Evaluation of Wind Tower Effectiveness in Rammed Earth Building

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Abstract

Due to global warming, the cooling requirements increase even in locations with broad heating periods. The integration of passive cooling systems, especially in buildings and settlements in hot-dry climates, contributes to the decay of energy consumption. The selection of the appropriate material and determination of the application technique is a significant issue since passive cooling systems significantly affect energy performance. In the study, a hypothetical residential building, assumed to be built with the rammed earth technique in Diyarbakır with hot-dry climate characteristics, is used to evaluate the suitability of wind towers in terms of natural ventilation and thermal comfort performance.

Key Innovations

- Wind Tower
- Hot-Dry Climate
- Rammed Earth
- Thermal Comfort

Practical Implications

Consider night ventilation in any case for massive buildings in hot climates. Avoid cross ventilation in day time in hot climates. Two openings on wind tower increases thermal comfort conditions.

Introduction

Today, with the effect of global warming, the increase in cooling requirements, even in settlements with more heating periods, increases the need for passive cooling systems. With natural ventilation, one of the most basic and effective passive cooling approaches, the need for mechanical systems in cooling and air conditioning required to provide indoor climatic comfort conditions reduce and, therefore, energy consumption decreases (Kumar et al., 2021; Melikoğlu and Bekleyen, 2021). Air circulation in natural ventilation systems is stimulated by temperature and/or wind pressure differences (Küçüker, 2019).

The characteristics of the environment and the building as district pattern, location, topography, climate, building form and dimensions, organization of the functions, user requirements, building envelope materials, and building typology have to be considered from the design stage for natural ventilation systems to be effective. Natural ventilation components, constructed to respond to the climatic conditions of the region where the buildings locate, meet the occupants' ventilation and cooling requirements and come forward as significant elements that reflect the architectural identity of the district.

Wind towers in regions with hot-dry climate characteristics are a decent example of this. Since the air flows from the outside to the indoor environment, air bulks with outdoor temperature also affect indoor temperatures. Because of this, from past to present, wind towers that allow the cooler air entrance in the elevations above the roof prevent the increase of interior temperature with outdoor temperature in hot-dry climate regions. Wind towers stimulate cross ventilation by catching upper cooler prevailing wind flows and orienting downwards to exit from the outlet openings located on the facade or roof. Cooler airflows decrease interior surface and air temperatures. Air circulation also enhances the passive cooling of the occupants by increasing heat loss by convection from the building and body surfaces.

The basic working principle of wind towers is based on the airflows stimulated by pressure difference due to buyancy effect and forced convection by wind (Figure 1). Wind towers are diversified in terms of opening directions and plan layout to use environmental factors effectively. In terms of aperture directions, they are classified as one-sided towers, two-sided and multi-sided towers. Clean, cool air is circulated to the interior space through the windward openings of the tower, placed with the consideration of the prevailing wind direction with one sided windcatchers (Ghadiri et al., 2011). The hot and polluted air inside the space is exhausted through the leeward openings of the building. The temperature difference supports the circulation under the effect of the wind and provides ventilation and cooling in the absence of wind (Kilci, 2005). Upper cool air gets in through tower openings during the day. In most of the examples the temperature of intaken airflow decreases by evaporation by cooling pads before reaching interior zones. This cool air is exhausted from the building openings; During the night, the need for ventilation and cooling is eliminated by letting the cool air in through the building openings and expelling the hot air from the tower openings by the stack effect.

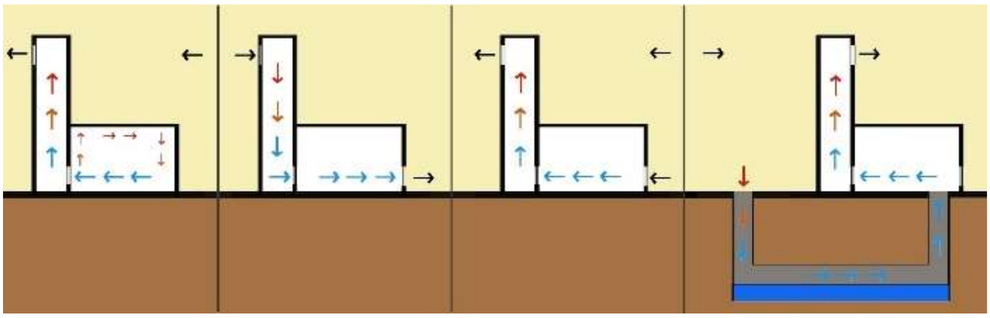


Figure 1: The basic working principle of wind towers.

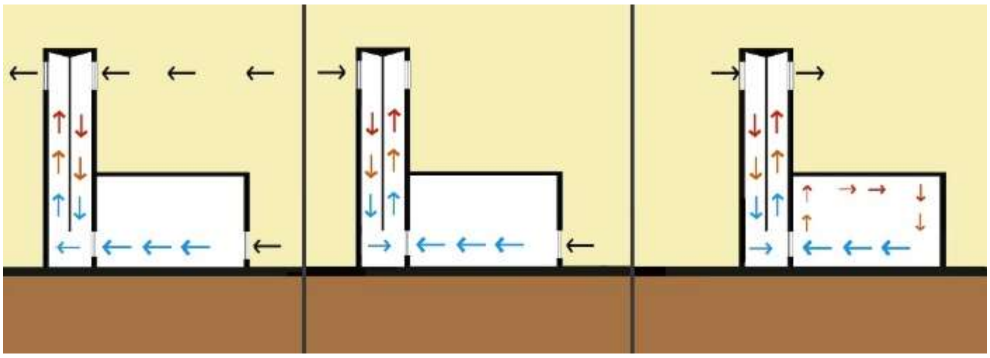
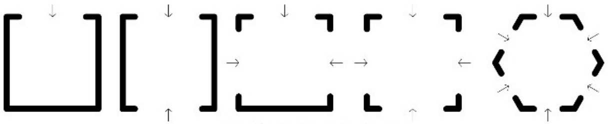


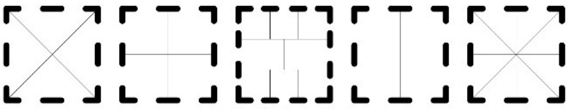
Figure 2: The basic working principle of two-way wind towers.

Two-way wind towers have 2 circulation paths provided by opposite openings one of which orients to prevailing winds (Figure2). Two-sided towers, which are more efficient in terms of ventilation performance, provide ventilation and cooling with opposing openings. Three-sided wind towers, which are not preferred outside of certain regions, are designed to take the wind from at least two places (Melikoğlu and Bekleyen, 2021).

Four-sided configurations are the most widespread wind tower types separated by vertical shafts. Wind flow is provided from all directions. Versatile wind towers have a more complex system with hexagonal and octagonal shapes with plan layouts, classified as X, +, H, I, and K types (Habıbzadeh, 2018) (Figure 3).



a- Classification by opening directions.



b- Classification by plan layouts.

Figure 3: Classification of wind towers, adapted of Habıbzadeh, 2018.

Ahmed et al. compared the air exchange rates provided by the cross and single-sided ventilation, formed by openings on the facades, with the wind tower and solar chimney setup, in hot climates. The study revealed that wind towers and solar chimneys provide better performance by producing higher ventilation rates (Ahmed et al., 2021). Hosseini revealed that in the climatic conditions of Yazd city of Iran, dimensional changes in the 4-way wind tower have a direct effect on the speed and distribution of air currents and, accordingly, indoor thermal comfort conditions (Hosseini et al., 2016).

Bahadori evaluated the disadvantages of the existing wind tower in the Middle East climate conditions and developed two wind tower design proposals suitable for areas where wind effects are sufficient or insufficient with various add-ons to improve thermal comfort conditions (Bahadori, 1994).

The rammed earthen building is a masonry construction system, the main material of which is soil, and a wall is built by compressing different, moistened soil layers in lateral forms between the temporary formwork panels and compacting it with the help of equipment to build monolithic walls (Alibeyoğlu and Ökten, 2021).

Rammed earthen buildings with widespread examples in the world have important potential in terms of aesthetics, durability, and energy efficiency. Building components constructed with this technic, have low embedded energy and carbon emissions due to their natural material content (Dong et al., 2014). Besides the researches on the durability and combination of rammed earth technic, there are some studies in which application of natural ventilation strategies in rammed earth buildings (Taylor et al., 2008; Fernandez, 2019; Dong et al., 2014). Taylor et al. (2008) investigated the effect of night ventilation on thermal comfort-and energy use in an office building constructed with rammed earth in a hot-dry climate zone. The study revealed that natural ventilation was insufficient to provide the thermal comfort conditions of the building, and insulation was required on the outer walls.

There is limited study on rammed earth buildings with wind tower configuration in the literature. Wang (1992) investigated the thermal performance of an earthen tower building. However the building itself has a tower typology instead of seperate wind tower.

Adobe buildings constructed with soil bricks dried in the sun are common construction technics in the cities such as Tunceli, Diyarbakır, Şanlıurfa with hot climate conditions (İzgi, 2020). There are very few examples of rammed earth technique in Turkey. The application of rammed earth walls and wind towers, which are preferred especially for thermal comfort in hot-dry climatic regions, would have a significant potential to provide optimum indoor climatic conditions with lower energy consumption.

In cases where the ventilation and cooling performance of the openings on the facade are not sufficient, wind towers, which have been a common building component in regions with hot climates since ancient times, to benefit from the wind passing over the roof level, are also useful in reducing cooling loads and providing optimum indoor climatic comfort conditions in districts with hot climate conditions such as Diyarbakır in Turkey (Uslusoy, 2012). Diyarbakır, a city located in the Southeastern Anatolia region with hot climate conditions has similar architectural features to the Middle East region with fountains, pools for cooling by evaporation; courtyards, high walls, semi-open rooms for shading (3 sides closed), massive outer walls for delaying and decreasing the peak heat loads in traditional residential buildings. Wind towers and rammed earth buildings are prominent examples of vernacular architectural identity, designed to resist harsh hot-dry climatic conditions, in some of the neighboring countries in the middle east, such as Iraq and Iran (Bekleyen and Dalkılıç, 2011; Sözen and Gedík, 2007; Jafar Rouh, 2017; Jaquin, 2008). However, rammed earth building constructions with wind towers are not part of architectural applications in the old settlement in Diyarbakır though it is a common strategy in countries such as Iran with similar climatic conditions. Therefore, rammed earth buildings with wind towers for cooling effect by ventilation in summer can be constructed in newly built residential areas with small parcellation which does not permit courtyard design.

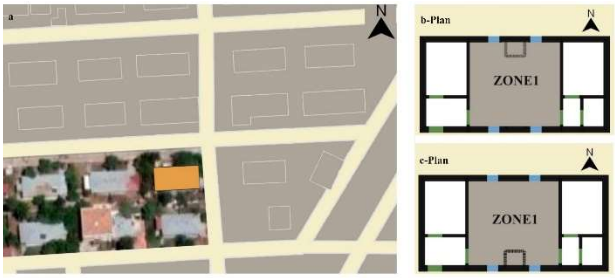
In this study, wind towers, one of the architectural approaches to natural ventilation systems, are investigated together with the rammed earth wall construction. The effect of wind towers, which are preferred in regions with hot-dry climates, on indoor climate comfort conditions is evaluated with the DesignBuilder simulation program for rammed earth building models derived from wind tower alternatives with different opening locations under the climatic conditions of Diyarbakır. Energy consumption and thermal comfort levels achieved by the alternatives are compared with the results of the sample model made of reinforced concrete and without a wind tower.

Method

This study investigates the effects of natural ventilation on energy performance; indoor climatic comfort levels that occur by the rammed earth buildings alternatives with wind towers assumed to locate in Diyarbakır with hot climatic conditions. Basic characteristics of Diyarbakır climate is low humidity and high temperatures. Temperature differences between day and night reach to high levels. Cooling needs require much more consideration in building design as summer conditions are dominant in a year with long periods.

An imaginary building is assumed to locate in 500 evler district with existing low rise buildings in Diyarbakır.

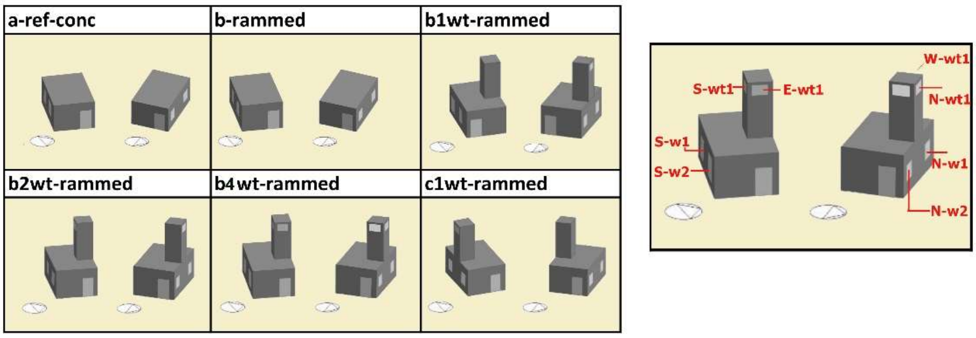
A low-rise building with 3 zones with 6 m x 12 m dimensions is assumed to locate in the area in question. The opening area rate is 15% for each of the South and North facades of the building. The simulations are conducted for the zone in the middle. Interior doors are assumed to be close for all simulations (Figure 4).



a-Layout plan of the exiting settlement b-Simulation model- Wind tower on north c-Simulation model- Wind tower on south

Figure 4: Layout and building plans.

5 types of alternative configurations with and without wind towers on the terraced roof of middle zone are generated for the CFD simulation process conducted with Designbuilder program in order to present the natural ventilation and cooling performance and variation of thermal comfort sensation by Fanger method for summer design day 21 July for the morning and afternoon hours. The wind acts from the Northeast with a velocity of 1.60 m/s at 10:00 and from the Northeast with a velocity of 1.58 m/s at 16:00 on 21 July due to the Energyplus weather data for Diyarbakır. The alternative [a-ref-conc] as the reference building is a reinforced concrete building without a wind tower. The second alternative is a rammed-earth building also without a wind tower. Primarily the combined effect of natural ventilation and building envelope thermo-physical properties on thermal comfort is investigated with the second alternative. The alternatives [b1wt-rammed], [b2wt-rammed], and [b4wt-rammed] have wind towers located on the middle part of the roof in the North with a different number of openings for each. The effects of the number of openings on thermal comfort conditions are investigated by these alternatives. The alternative [c1wt-rammed] has a wind tower on the middle part of the roof in the South. The effect of the location of the wind tower is examined by this alternative (Figure 5). The wind towers, which are 3 m high from the terraced roof, have an area of 1.6 m2. Alternatives are derived for wind towers with a wall thickness of 0.3 meters, where 0.7m *1m in size, single, two, and four openings are present. Two-way and multi-direction wind towers are divided into compartments in the plan. These partitions are formed with 3 cm thick wooden. It is assumed that the wind towers extend to the ceiling level of the space.



	S-w1	S-w2	N-w1	N-w2	N-wt1	S-wt1	W-wt1	E-wt1
a-ref-conc	100%	100%	100%	100%	-	-	-	-
b-rammed	100%	100%	100%	100%	-	-	-	-
b1wt-rammed	100%	100%	0	0	100%	-	-	-
b2wt-rammed	100%	100%	0	0	100%	100%	-	-
b3wt-rammed	100%	100%	0	0	100%	100%	100%	100%
c1wt-rammed	0	0	100%	100%	-	100%	-	-

Figure 5: Simulation alternatives and operation of openings.

The metabolic rate of the seated occupants in the sitting position was set as 1.0 met and clothing insulation value as 0.5 clo, at 40% relative humidity for Fanger thermal comfort calculations with CFD. Interior obstructions in the room are not considered.

Calculation Parameters and Boundary conditions for CFD with Designbuilder

K-e turbulence model based on Navier-Stokes equations is used for the calculations. The Power Law discretisation method was selected. Maximum mesh spacing is 0.3m, Maximum dependent variable residual is 10-6 and cell aspect ratio is 13. Simulation results obtained by Energyplus for 21 July were used as CFD boundary conditions (Table 1).

Openings on north and South facades are assumed to be full open for cross ventilation for the reference alternatives, [a-ref-conc] and [b-rammed].

Table 1: CFD boundary conditions.

INPUT/OUTPUT	**10:00**	**16:00**
	˚C	**˚C**
External Temperature	37.50	41.70
Initial Air Temperature	20.00	20.00
Average Zone Air Temperature	36.72	38.78

Thermal comfort PMV-PPD outputs are plotted on plan view obtained by horizontal slice set at a height of 1.2 m. Air temperature and velocity plots are presented below.

Results

Morning Hours

Relevant wind acts from 74° northeast at 10:00 in the morning hours. The effect of indoor airflow distribution and velocity on the variation of the operative temperatures, accordingly thermal comfort levels in the zone were compared for the six alternative situations (Figure 6).

Higher operative temperatures and less air movement velocities are obtained at the point “R” in the indoor environment with all alternatives except [b2-wt-rammed] according to the reference situation [ref-conc]. The interior mean operative temperatures with all alternatives are above the comfort temperatures due to the size of the opening, the transfer of hot outdoor airflows, and the effect of solar gains by closed windows. The interior operative temperature increased in the [b4-wt-rammed] alternative depending on the increase in opening sizes. However, the same effect did not occur with [b2-wt-rammed] with lower indoor operative temperature values by the effect of air velocities with lower temperatures (Figure 7).

The homogeneous distribution of the air flows in the zone is provided most with [b2-wt-rammed], according to the reference situations. However, vortices can be observed at the locations, [X2, X3; S-w1, N-w1] with [a-ref-conc]; [X2, X3; S-w1, N-w1] with [b-rammed]. [b-rammed] alternative was created to observe the effect of material differentiation on indoor air movement velocity, distribution, and operative temperatures compared to [a-ref-con] reference alternative formed with concrete material. The massive wall effect, which delays the sensation of the outdoor peak temperature effects in the indoor environment and, also reduces the indoor temperature oscillations, could not provide a temperature decrease due to the ventilation carried out during the day with high temperature airflows. Although there is not much difference between them in terms of these parameters, indoor operative temperatures have reached higher values with the [b-rammed] alternative. The air flows at the user sitting level are homogeneously distributed in the [b2-wt-rammed] and [a-ref-conc], [b-rammed] but stagnated at the rear. Although the PPD values were low in a few limited areas near the windows, they were at a near rate of 96% throughout the place, even with these alternatives.

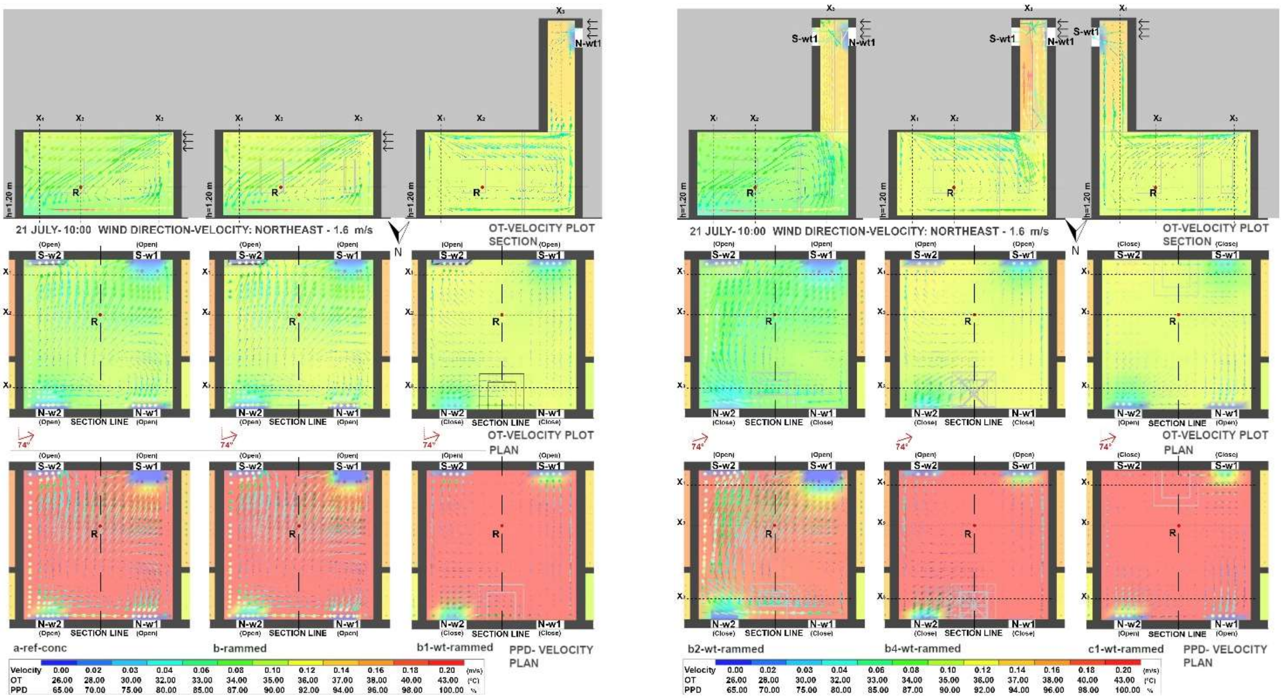
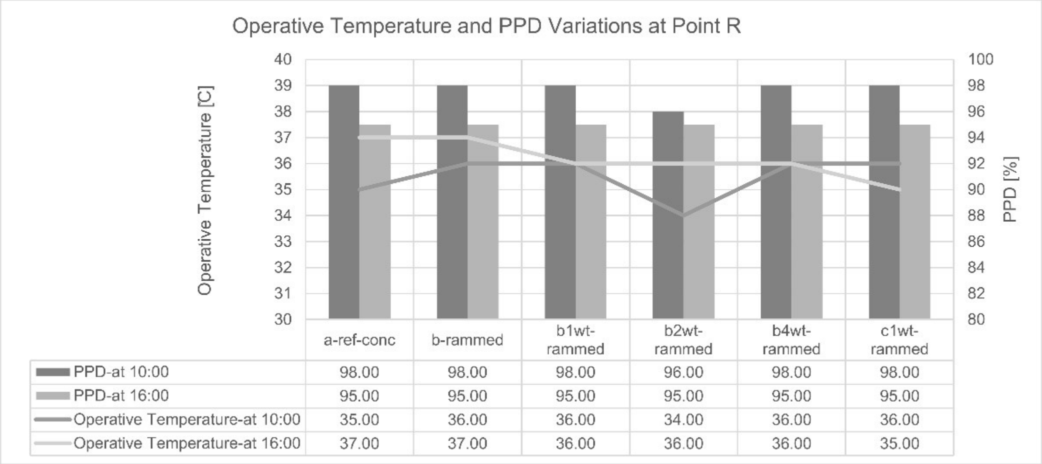


Figure 6: Operative temperature and PPD variations for the alternatives on 21 July at 10:00.



	a-ref-conc	b-rammed	b1wt-rammed	b2wt-rammed	b4wt-rammed	c1wt-rammed
PPD-at 10:00	98.00	98.00	98.00	96.00	98.00	98.00
PPD-at 16:00	95.00	95.00	95.00	95.00	95.00	95.00
Operative Temperature-at 10:00	35.00	36.00	36.00	34.00	36.00	36.00
Operative Temperature-at 16:00	37.00	37.00	36.00	36.00	36.00	35.00

Figure 7: Operative temperature and PPD variations at point R.

Afternoon Hours

Relevant wind acts from 42.75° northeast at 16:00 in the afternoon hours. The effect of indoor airflow distribution and velocity on the variation of the operative temperatures, accordingly thermal comfort levels in the zone were compared for the six alternative situations (Figure 8).

It is seen that the internal operative temperature values obtained in the evening at the point, "R" are at higher levels for [b1-wt-rammed], [b4-wt-rammed], [c1-wt-rammed] alternatives compared to morning hours. Higher internal operative temperatures are observed for [a-ref-conc], [b-rammed], [b2-wt-rammed] alternatives compared to morning hours.

Operative temperatures above the comfort threshold temperature 26 °C were observed at the reference point and in other regions with all alternatives. Although desired comfort temperatures are achieved in a limited area in front of the window, it is insufficient to provide climatic comfort throughout this zone.

Airflow distributions are provided homogeneously with all alternatives. This distribution and velocity effects are dominant with [b1-wt-rammed], [b2-wt-rammed], [b4-wt-rammed], [c1-wt-rammed]. However, stagnant air flow conditions among vortices are observed at the locations, [X2, X3; S-w1, N-w1] with [b1-wt-rammed]; [X2, X3; S-w1, N-w1] with [b2-wt-rammed]; [X1, X2; S-w1, N-w1] with [c1-wt-rammed]. The [c1-wt-rammed] model, in which the wind tower locates in the south orientation, has a slightly lower temperature than the other models at the point, "R" due to the fact that the building openings are located in the north.

The [b2-wt-rammed] seems to be the most effective alternative with homogeneous air circulation. The highest airflow velocities are obtained with the [b4-wt-rammed].

In the [b2-wt-rammed] alternative, the air currents reach the upper levels of the interior space through the wind tower opening. Then, as it orientates towards the south façade and returns from the user-level parts of the zone to the north façade openings, it creates an effect that lowers the operative temperature in the interior environment. Even if, airflows reach all parts of the zone for all models, a more effective circulation is obtained with [b2-wt-rammed] and [c-1wt-rammed]. For this reason, PMV-PPD values are lower with these models.

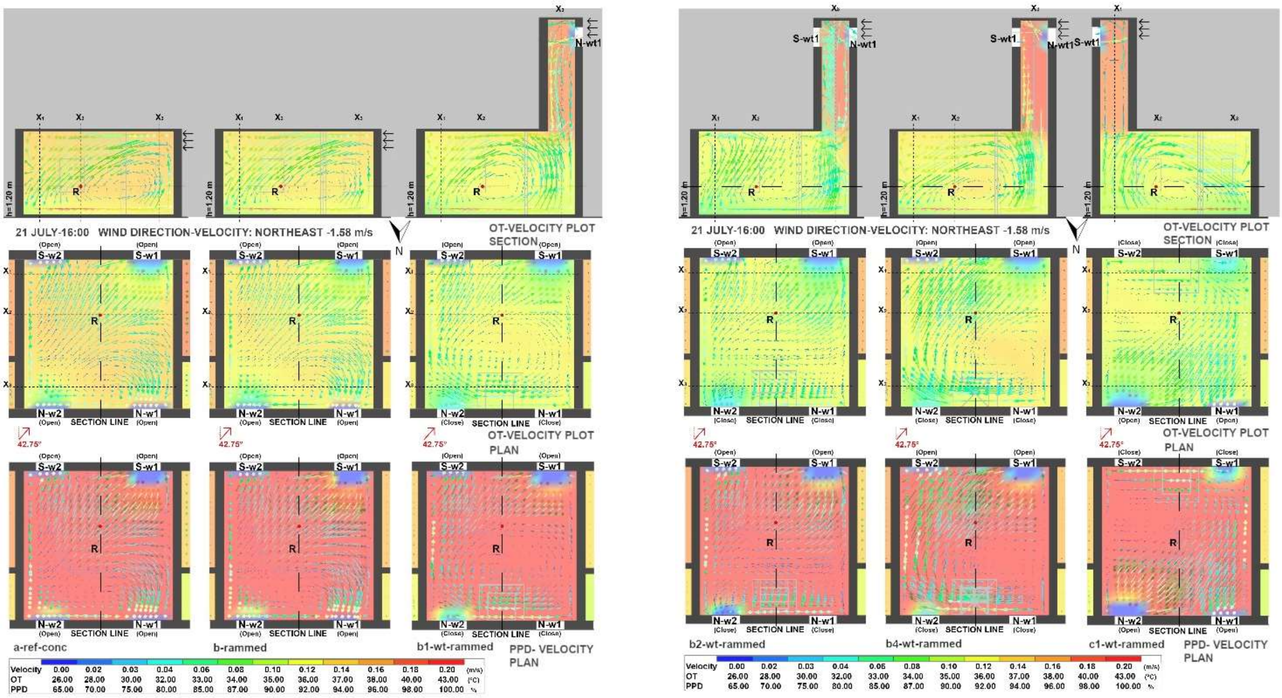


Figure 8: Operative temperature and PPD variations for the alternatives on 21 July at 16:00.

Conclusion

According to the analysis, the operative temperature values obtained in the reference and alternative models were insufficient to provide comfortable conditions during the warm period. However, it is an appropriate approach to ventilate at night when the outdoor temperature is lower in hot climate conditions. The fact that the operative temperatures are above the comfort limit values, especially in the [a-ref-conc] and [b-rammed], is an expected issue due to the cross-ventilation with large opposing windows and the transfer of air currents with high outdoor temperatures to the indoor environment among these time intervals. Even in these conditions rammed earth alternative created a lower operative temperature at the reference location compared to other models during afternoon hours. When the applicability of the wind tower in hot climate conditions is evaluated within the scope of the study, it is observed that the wind tower has the potential to affect the comfort conditions positively in Diyarbakır conditions and to meet the ventilation and cooling needs of the space to some extent when the openings are operated correctly. When the two time periods are evaluated together, [b2wt-rammed] comes to the fore as the optimum model among all models due to its positive effect on ventilation performance and thermal comfort conditions. Also in afternoon hours [c1-wt-rammed] also provides lower operative temperature in the reference location compared to other alternatives. Therefore, as the location of the wind tower on south increases the thermal comfort sensation, simulations with similar configurations as north location can present the potential of wind tower location change in terms of increasing thermal comfort and ventilation efficiency. The determination of the position of the inlet, outlet openings, optimum wind tower location, height, and integration of night ventilation, especially in hot climate regions where massive walls are widely used, appears to be of great importance in improving interior microclimatic conditions. Therefore, the studies on these parameters have to increase.

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