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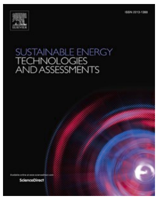

Passive heat recovery wind tower: Assessing the overheating risk in summertime and ventilation heat loss reduction in wintertime

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ABSTRACT

Wind towers are low-energy ventilation devices which can provide cooling and reduce buildings' energy use. However, during unfavourable climate conditions, wind tower operation could cause thermal discomfort and ventilation heat loss. There also has been very limited research into the overheating risk caused by wind tower ventilation. Therefore, this study explores the feasibility of the year-round operation of wind towers with solid tube heat recovery (THR) through computational fluid dynamics (CFD). The results show that within the mild-cold months, the natural ventilation wind tower with THR raised the room temperature by an average of 3.1 °C, based on the set conditions. This extended the working period of the wind tower throughout the year, especially during mild-cold months. During summertime, the highest indoor temperature observed in the space ventilated by the wind tower with THR was 24.35 °C, which meets the static overheating criteria. The wind tower with THR reduced the ventilation heat loss by up to 8.1% in wintertime. It should be acknowledged that the wind tower with THR cannot provide satisfactory thermal comfort in cold months with outdoor temperatures below 9.41 °C, and more research should be conducted to improve the heat recovery efficiency.

Introduction and literature review

The social and economic crisis caused by COVID-19 is hitting families, communities, and countries around the world [1,2]. A number of studies have emphasised the importance of indoor ventilation during the global pandemic [3,4]. As demonstrated by Wang et al. [5], passive ventilation, as a way of providing fresh air and thermal comfort to residents without consuming electrical energy, is recently attracting more attention.

Windcatchers or wind towers, also called badgir, are traditional architectural structures used for centuries in the Middle East and North Africa to provide natural ventilation and cooling in buildings [6,7]. They are typically tall structures, like a chimney, which are situated on a building's roof or wall. Wind tower captures the wind at the roof level and induces it downwards into the building via openings or vents. This improves ventilation without the use of mechanical systems by facilitating air circulation and cooling via thermal mass. Wind towers are effective in areas with strong and consistent winds, and they work better when used in conjunction with other natural ventilation strategies, such as windows and doors. It is a simple and zero/low-energy way to achieve free ventilation and cooling, which can help to reduce energy consumption and greenhouse gas emissions [8,9]. With the growing interest in net-zero and sustainability in the building sector, wind towers are gaining attention as a sustainable and eco-friendly solution for building ventilation.

Literature review

Many researchers have proposed new designs in combination with wind towers, mainly to improve their ventilation and cooling performance [10–17]. For example, Ghoulem et al. [10] designed a greenhouse with a passive downdraught evaporative cooling windcatcher (PDEC-WC) system to reduce the energy required for ventilating and cooling greenhouses in warm and hot climates. A range of outdoor temperatures (30–45 °C) and relative humidity (15–45%) were considered. It was found that the system reduced air temperature by up to 13.3 °C and increased relative humidity by 54%. Nejat et al. [11] measured the effect of a two-sided wind tower with an upper wing wall on indoor adaptive thermal comfort and indoor air quality (IAQ). At wind speeds above 2.5 m/s, the wind tower provided adequate thermal comfort at an external temperature of 29 °C and a relative humidity of 80%. As demonstrated by Foroozesh et al. [12], a good thermal comfort

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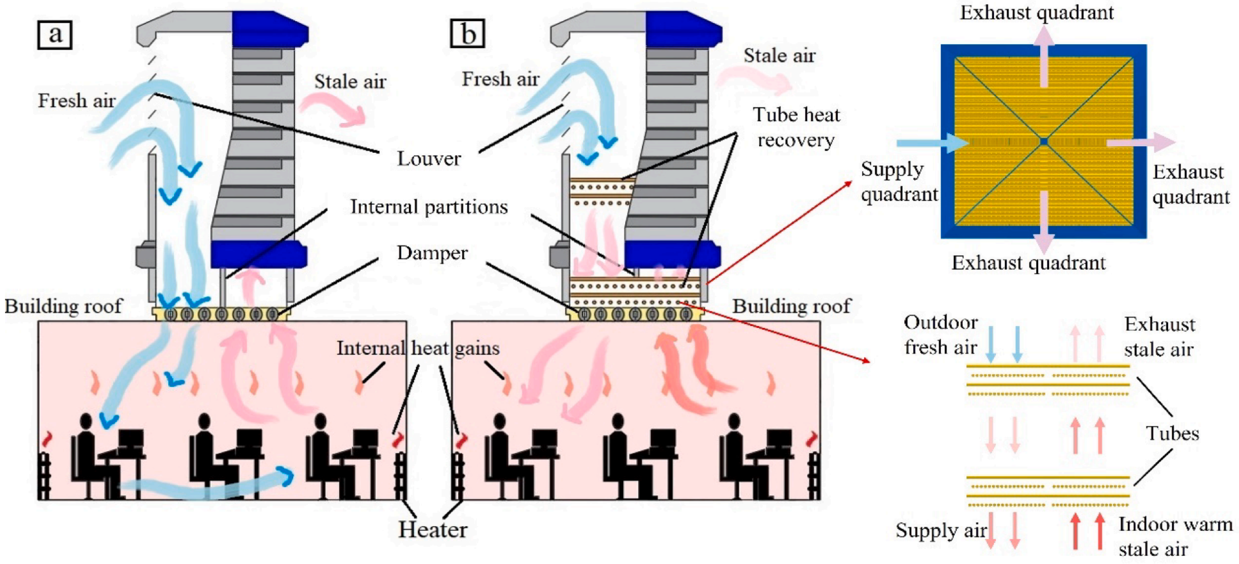


Fig. 1. Airflow through a space ventilated by a wind tower (a) without THR and (b) with THR.

level in accordance with ASHRAE 55-2020 can be obtained at the outdoor temperature of 39.2 °C, wind speed of 2.7 m/s and water spray rate at 0.004 kg/s. From this, an indoor temperature drop of up to 17.4 °C was observed. Jafari and Kalantar [13] explored the performance of the solar chimney, water spray and wind tower in terms of a three-story high-rise building. The modified wind tower can reduce the indoor temperature by 6–12 °C, increase the relative humidity on the third floor by 80%, and provide a cooling capacity of almost 3500 W. The wind tower provided good ventilation and a comfortable thermal environment even on windless days. Similarly, integrations such as a sustainable bio-inspired cooling unit [14], solar-assisted air heater [15] and rotary scoop [16] were proposed to combine with modern wind towers to enhance their ventilation and cooling performance in hot-arid areas.

As the passive building concept is gaining popularity, wind towers are being improved to cope with different climates ranging from hot to cold. From the literature, wind tower technology has been widely used in hot climates for building ventilation and cooling. However, its use in temperate and cold regions was limited because operating it at a low ambient temperature would result in great ventilation heat loss, increasing buildings' heating loads and causing thermal discomfort. With the development of wind tower technology to date, a group of researchers also have been working on promoting the use of wind towers in cold climates [18–23]. Calautit et al. [18] proposed the integration of a passive thermal wheel into a wind tower system to preheat the airflow entering a room in a mild-cold climate. Depending on conditions indoors and outdoors, the supply temperature can be increased by up to 3.7 °C. The results also showed that adding a thermal wheel could reduce the indoor air flow velocity by 14%-30%. Sakhri et al. [19] and Hughes et al. [20] also proposed combining wind towers with a ground-to-air heat exchanger and heat pipes heat recovery to improve their use in low-temperature conditions. The indoor temperature can be increased by 10 °C [19] and 3.3 °C [20] after the improvement, respectively. The heat pipe heat recovery in the windcatcher was further investigated by Calautit et al. [21] and Mahon et al. [22]. The supply air temperature was increased by 4.5 K [21] and 2.8 °C [22], respectively. A new hybrid wind tower with cold storage and a shallow geothermal system was further developed to address internal pathogen (e.g., COVID-19, seasonal flu, etc.) transmission problems caused by HVAC systems while reducing building energy consumption [23]. This hybrid wind tower uses a shallow geothermal system to cool the water that is then pumped into the ducts inside the tower. As warm outside air enters the tower, it comes into contact with the cold ducts, achieving low-energy cooling. Water condensed on the ducts' walls is collected at the bottom of the tower and used to collect particle pollutants, while a filter purifies the air before it enters the occupied space. The warm water from the cooling process is partly pumped back into the geothermal system and partly used for heat exchange with the ambient environment to reduce the water temperature for recycling. During cold climatic conditions, the geothermal system gains heat from shallow/deep sources and heats the cold water, which is then pumped into the wind tower ducts to preheat incoming air.

Many studies have demonstrated the potential of wind towers for wintertime use, but these integrations also have their own limitations. For example, in the case of a ground-to-air heat exchanger [19], it may not be suitable for large-scale renovation of existing buildings, due to their complex structure. The thermal heat recovery wheel [18] was relatively simpler than that in [19], but it had moving parts and may cause air cross-contamination. Likewise, heat pipes were usually costly and there could be refrigerant or liquid leakage risk. A potential solution may be simpler and less costly, such as the combination proposed by [24], which used THR to collect and transfer heat across the wind tower quadrants. The justification for using solid tubes is that it is simple in design, easy to install, maintain and operate, and easy to retrofit to wind towers. Table A.1 summarises the thermal performance and overheating analysis of different wind towers in the selected literature reviewed above. As can be observed, most studies only investigate the thermal effect of different integrations into wind towers while potential overheating risk has not been predicted. There is also very limited research into the year-round thermal performance of wind towers under different weather conditions. This study will therefore investigate the thermal performance of the proposed wind tower with THR under UK year-round climatic conditions. The overheating risk during summertime and ventilation heat loss reduction during wintertime will also be reported.

Research novelty and contributions to knowledge

Previous works have shown the potential of wind towers with THR to minimise heat loss, but at the same time, it also reduced ventilation rates [24]. Hence, this impact on indoor thermal comfort must be evaluated. This study will evaluate the impact of this by modelling the wind tower based on the solid tube arrangement introduced in [24], as illustrated in Fig. 1. The wind tower captures the outdoor wind and directs fresh air into the occupied space. At a wind angle of 0°, three of the four quadrants allow warm and stale air to escape the room. As the warm and stale

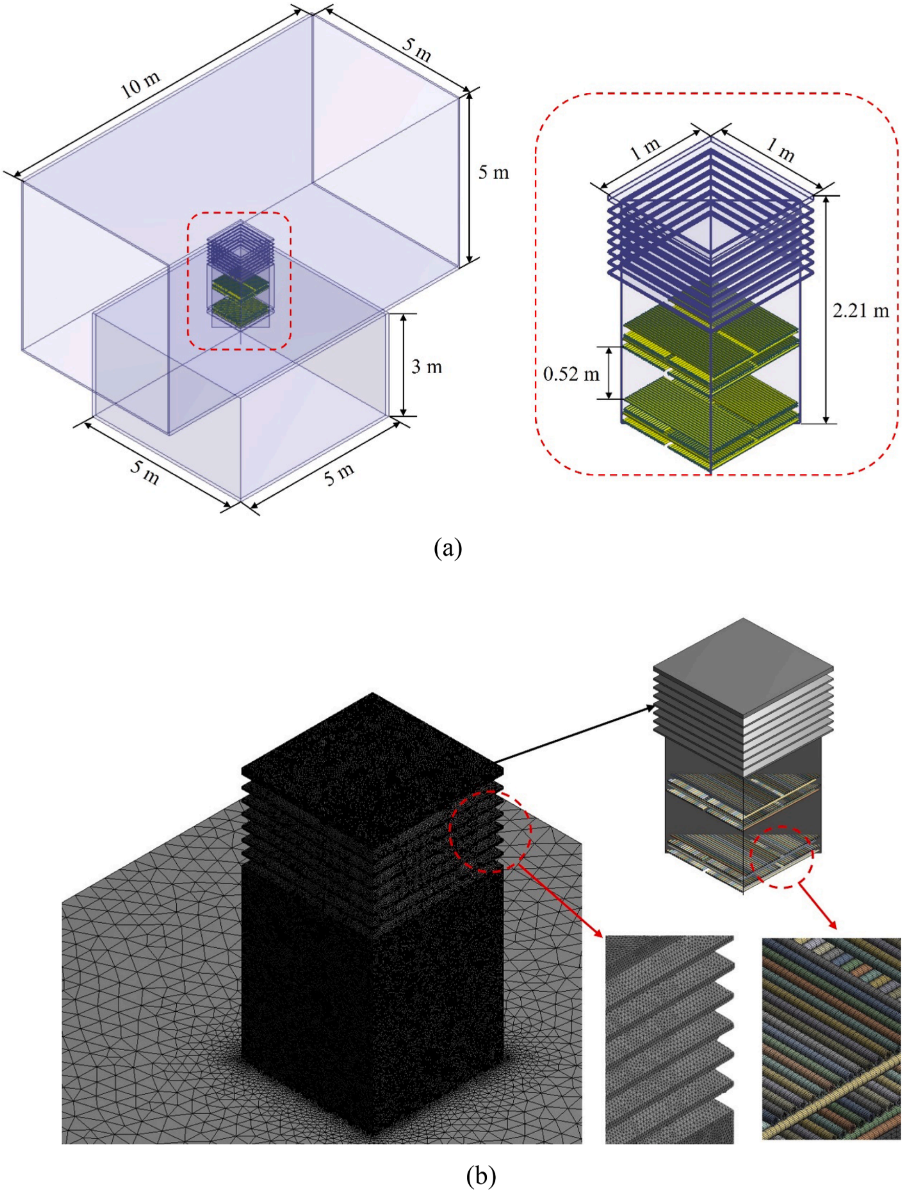


Fig. 2. (a) The computational domain of the CFD model and (b) a close-up of the surface mesh on the tubes and louvers.

air traverses through the solid tubes in the exhaust quadrants, heat is collected and stored in the tubes and then transferred into the supply quadrant, where the fresh air gets preheated before entering the occupied space.

One of the key gaps in the literature that we will address in this research is evaluating the ability of the wind tower with THR to ventilate, preheat in winter/mild-cold months and cool during summer months. Most studies typically evaluate its performance based on varying wind speeds and worst-case thermal conditions, while the study on its year-round thermal operations is limited. Another gap that this research will address is evaluating the risk of overheating in the space ventilated by the wind tower with THR, especially in areas with warm/hot summer conditions and increasing temperatures due to global warming. With the expected reduction in ventilation rate, the wind tower's capacity to passively cool the space will also be reduced. Hence, there can be an overheating risk which must be evaluated to ensure the wind tower can also function in these conditions. Finally, limited studies have evaluated ventilation heat loss and heat recovery amount from wind towers; this will be addressed here. This study will explore how the wind tower could perform effectively in different climatic conditions.

Aims and objectives

Using a three-dimensional CFD model, the natural ventilation potential of the proposed wind tower will be simulated and evaluated during summer, winter, and mild-cold months. The evaluation will focus on buildings with high occupancies, such as schools, that must create a healthy and productive work environment. The ability of the wind tower to provide a satisfactory fresh air rate and thermal environment indoors will be one of the most important considerations. The airflow velocity and temperature in the wind tower ventilation system with THR will be compared against a benchmark (without THR) to investigate the benefits of incorporating THR to extend its year-round operation in a temperate climate such as the UK. At the same time, potential issues will also be assessed, especially the potential risk of overheating during summertime. Finally, the ventilation heat loss and heat recovery amount by the THR will be estimated.

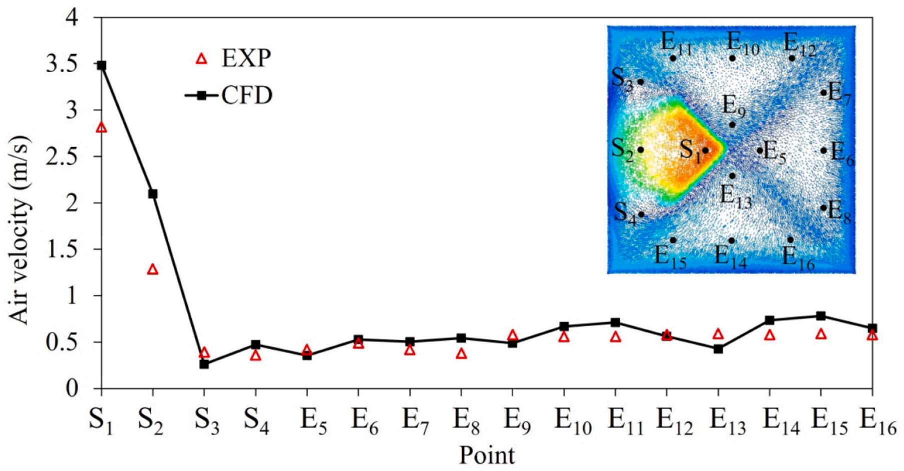


Fig. 3. The validation of the presented CFD model with experimental data from [25] in terms of supply and exhaust velocity.

Methodology

Geometry

The model was based on the CFD-wind tunnel research method, whereby the wind tower ventilation system combined with a tested room was assumed to be put in a wind tunnel, using weather data as input boundary conditions [25]. The CFD-wind tunnel approach has been used in a few studies to examine the effects of natural ventilation on indoor airflow patterns [26,27]. The wind tower (W × L × H = 1 × 1 × 2.21 m^3) was installed in the middle of the occupied space's roof [21], as shown in Fig. 2a. Two stages of heat recovery were arranged, consisting of four interlaced layers of tubes. The tubes were modelled based on copper material with a diameter of 0.02 m and a length of 1 m, respectively. The horizontal (0.025 m) and vertical (0.06 m) pitches of adjacent tubes were based on the previous study [24]. The vertical distance between the two stages was 0.52 m. Table A.2 summarizes the dimensions of the model. The fluid domain was extracted from the CAD model using Ansys Design Modeler.

Mesh generation, mesh independency analysis and boundary conditions

Non-uniform mesh was used to discretise the fluid domain. Mesh refinement was implemented around the louvers and THR with a face sizing of 0.01 m [24]. Curvature refinement was also applied to the sharp edges such as the louvers. To ensure that the CFD results are independent of the mesh, mesh independency analysis should be conducted. As demonstrated, a range number of mesh elements from 11.5 million to 21.2 million, representing mesh from coarse to fine, were generated respectively. From the simulation results, variation in the supply air velocity and temperature was significant with the number of mesh elements increasing from 11.5 million to 14.2 million; but the results changed by less than 4% from 14.2 million to 21.2 million. Hence, a total of 17.0 million mesh elements were enough to capture the airflow patterns. Table A.3 shows the mesh independence analysis results. Fig. 2b depicts a close-up of the surface mesh of tubes and louvers.

The inlet of the fluid domain was set as a velocity inlet, with temperature and speed set depending on the external weather data. The velocity inlet was kept constant and Reynolds number (Re) at the entrance was between 1.87 × 10^6 and 1.37 × 10^6 based on the maximum and minimum external wind speed throughout the year. The inlet turbulence intensity was 1% [28], and the wind direction at the inlet was perpendicular to the wind tower, i.e., wind angle was 0̊. The outlet was set to the atmospheric pressure outlet. The sides had symmetrical boundary conditions. All walls were non-slip [21]. A heat flux of 30 W/m^2 was applied to the room floor [24], representing the indoor heat gains. Semi-Implicit Method for Pressure-Linked Equations (SIMPLE) scheme with a second-order discretisation was used. RNG *k*-epsilon model with a standard wall treatment was used to solve the governing equations [29–31]. The governing equations are described in depth in the ANSYS User's Guide [32], thus they are not shown here.

Validation of the CFD model

The presented CFD model was validated with the experimental measurement data by Calautit et al. [25]. Fig. 3 shows the supply and exhaust air velocity (represented by points S_1-S_4 and E_5-E_{16}, respectively) obtained from the presented CFD model and experiment [25]. As can be seen, the CFD results fluctuated up and down around the experimental data with an average error of 25%. The main difference between the CFD and experimental data was observed at points S_1 and S_2 in the supply quadrant. This could be caused by the large flow disturbances at those points. The RNG model cannot fully capture the flow patterns around intense flow separations, jets, etc. in terms of simulating natural ventilation [29,31]. A more detailed and comprehensive validation can be found in [24]. Overall, the presented CFD model was considered to provide a reliable simulation for this study.

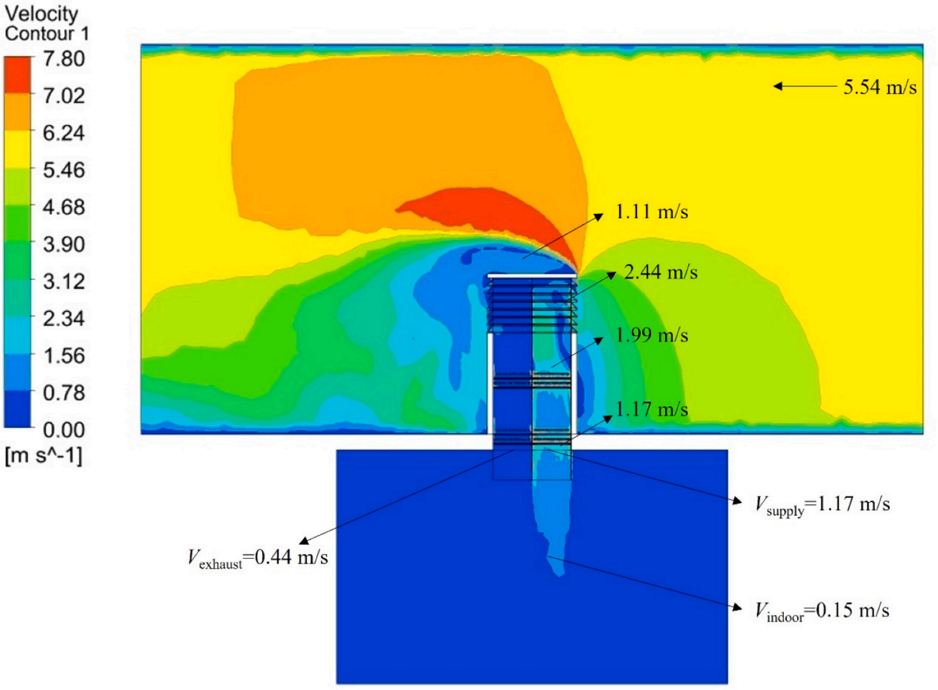
Climatic data of the UK

By modelling the average monthly wind speed and temperature in the UK, we were able to obtain the annual ventilation performance and preheating/cooling potential of this wind tower under various climatic conditions. Variation in wind direction was not considered because the wind tower was multi-directional and can capture air regardless of the wind direction; instead, the focus was on the influence of adding the THR on the airflow behaviours in different months. The monthly weather data for the UK from 1990 to 2021 was obtained from the Met Office [33] (as shown in the Appendix Fig. A.1). Overall, the cold months outside were mainly from November to December and from January to March, when the maximum temperatures did not exceed 10 °C. High outdoor temperatures were recorded from June to August (summertime), when the maximum temperature can reach around 20 °C. The rest of the year was mild-cold (April-May and September-October), with average temperatures varying between 8 °C and 13 °C. The average monthly wind speed was between 4.04 m/s and 5.54 m/s.

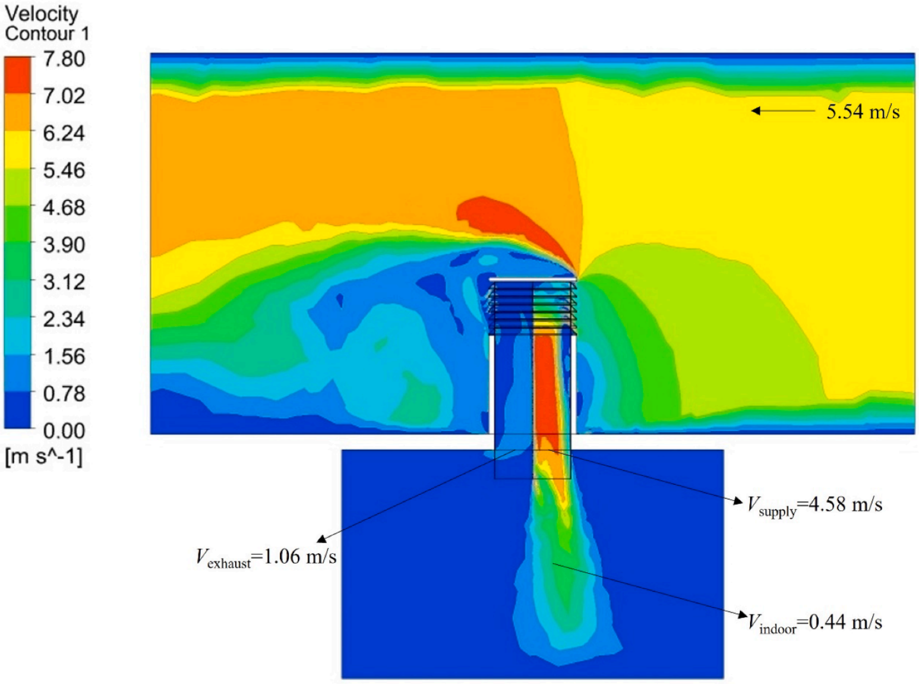
Results and discussion

Airflow velocity and temperature patterns

Fig. 4 shows the airflow velocity pattern at the cross-sectional plane



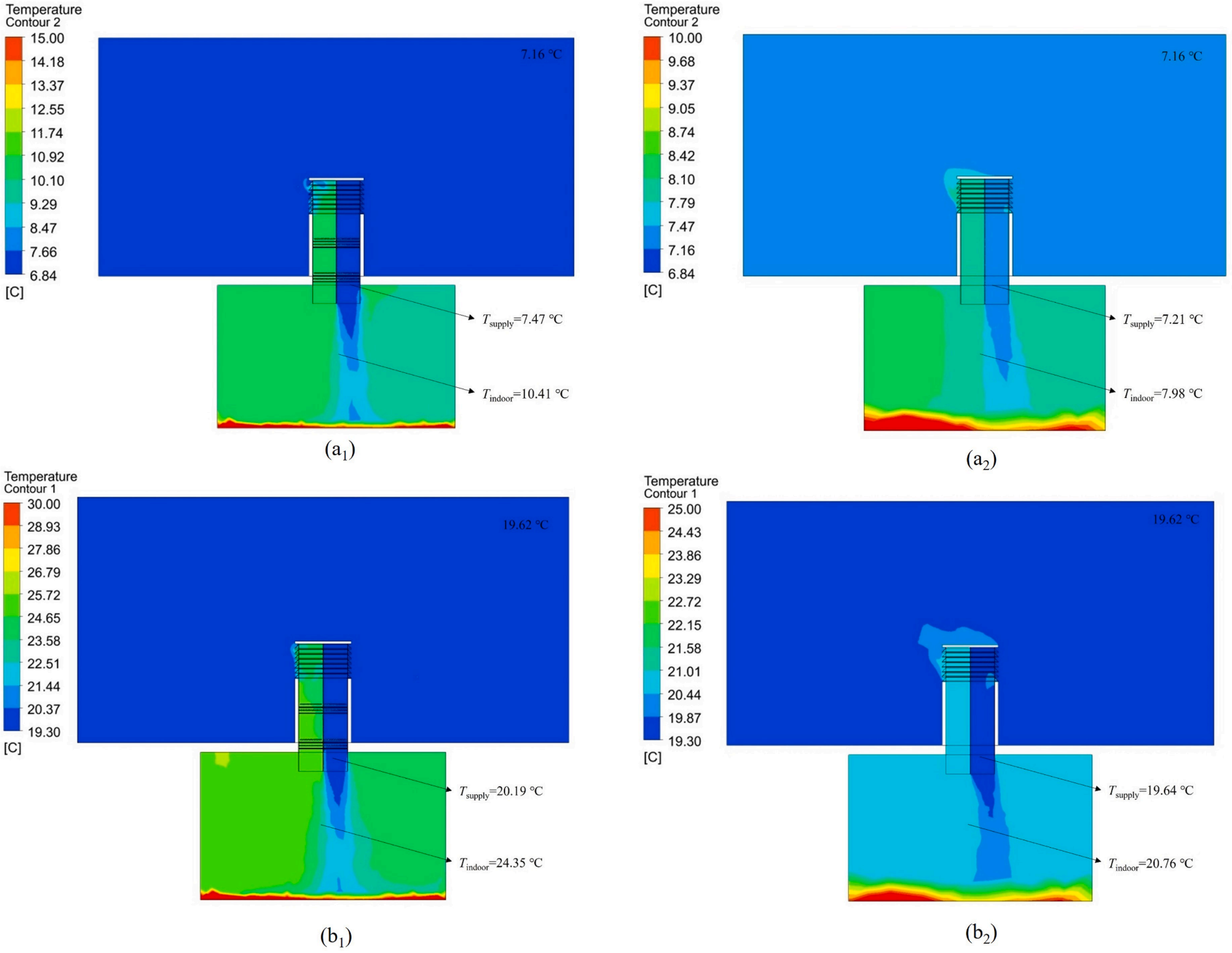
(a)



(b)

Fig. 4. The airflow velocity distribution at the cross-sectional plane x = 0 for the wind tower (a) with THR and (b) without THR in February.

x = 0 for the wind tower with and without THR in February. As shown in Fig. 4a, the average velocity of the entering flow was 5.54 m/s, but it dropped to around 2.44 m/s near the wind tower. A portion of the air moved towards the leeward side along the top (1.11 m/s), creating a flow recirculation zone. The average airflow velocity upstream of the THR was 1.99 m/s, and after the THR was 1.17 m/s. The average airflow velocity in the room was 0.15 m/s. In the wind tower without THR, the overall airflow features were similar, as shown in Fig. 4b. However, as can be seen, a higher air velocity inside the wind tower without THR was observed. The supply air velocity of 4.58 m/s was four times higher than that in the wind tower with THR. A higher average indoor velocity of 0.44 m/s was also obtained which was almost two times higher than with THR. The average exhaust air velocity was 1.06 m/s, whereas in the wind tower with THR, the velocity was 0.44 m/s. Introducing THR had a dampening effect on the exhaust velocity, but nevertheless, the indoor stale air had sufficient capacity to leave the wind tower. The pressure



(a_1) (a_2)

(b_1) (b_2)

Fig. 5. The air temperature distribution at cross-sectional plane x = 0 for the wind tower with (subscript 1) and without (subscript 2) THR in (a) February and (b) July.

pattern was described in the Appendix, as shown in Fig. A.2.

Fig. 5 shows the air temperature distribution at cross-sectional plane x = 0 for the wind tower without and with THR in February and July. In February, at a maximum outdoor temperature of 7.16 ℃, the average supply air temperature was 7.47 ℃ while the indoor average temperature was 10.41 ℃. In the wind tower without THR (Fig. 5a2), the two values were 7.21 ℃ and 7.98 ℃, respectively. As the outdoor temperature dropped to a minimum value of 1.13 ℃, the supply and indoor temperatures in the wind tower without THR were 1.19 ℃ and 1.95 ℃, respectively. With the addition of THR, the indoor temperature and supply temperature increased by 2.44 ℃ and 0.26 ℃, respectively. In the warm months like July, the average indoor and supply temperatures varied between 15.75 and 24.35 ℃ and 11.60–20.19 ℃ respectively, as shown in Fig. 5b1. In the wind tower without THR (Fig. 5b2), the indoor and supply temperature were lower, varying between 12.14–20.76 ℃ and 11.06–19.64 ℃. From all the scenarios, the high temperature was mainly observed near the floor of the room which was set as a heat flux to simulate the effect of indoor heat gains from occupants, radiators, lights, etc.

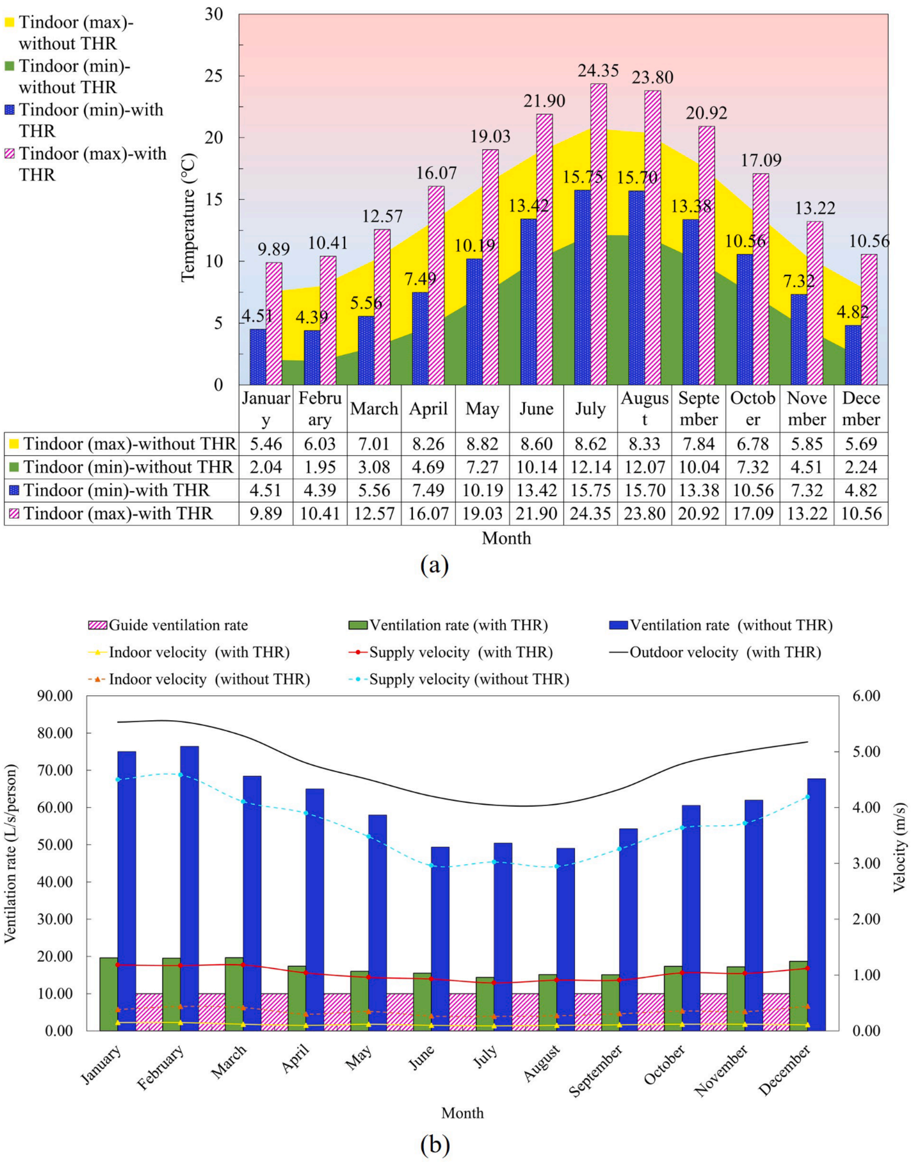
Performance of the wind tower with THR throughout a year

Indoor thermal performance

Air temperature is one of the most essential factors for ensuring indoor comfort and thus can be used as an indicator to evaluate thermal performance [34]. The UK government considers a pleasant living room temperature of 21 °C; for other areas of a dwelling, the acceptable temperature is 18 °C [35].

Fig. 6a shows the predicted indoor temperature for the wind tower with and without THR throughout the year. The annual indoor temperature of the wind tower with THR was overall higher than that without THR. During the months when the maximum outdoor temperature did not exceed 10 °C (i.e., November-December, January-March), the indoor temperature with THR ranged between 4.39 °C and 13.22 °C, showing an average increase of 2.56 °C compared to without THR. Although the temperature did not meet the criteria for indoor thermal comfort in the winter, the inclusion of THR will be beneficial for reducing ventilation heat loss and extra heating demand.

During the mild-cold months (i.e., April-May and September-October), the average indoor temperature of the wind tower with THR varied between 11.78 °C and 17.15 °C, while that in the wind tower without THR was 8.82–13.96 °C, an average of 3.1 °C lower. The combination of THR could extend the wind tower's operation periods for a few months, such as in April, May, September, and October. This indicated that introducing THR could be a low-energy strategy to reduce ventilation energy loss and improve thermal comfort for occupants in mild-cold climates. For the warmer summer months, June to August, the maximum indoor temperature fluctuated between 21.90 °C and 23.80 °C for the wind tower with THR and from 18.74 °C to 20.75 °C for that without THR. According to the static overheating criteria (CIBSE Guide A [36], CIBSE Guide J [37], TM36 [38], TM59 [39]), the temperature in the space ventilated by the wind tower with THR was within



	January	February	March	April	May	June	July	August	September	October	November	December
Tindoor (max)-without THR	5.46	6.03	7.01	8.26	8.82	8.60	8.62	8.33	7.84	6.78	5.85	5.69
Tindoor (min)-without THR	2.04	1.95	3.08	4.69	7.27	10.14	12.14	12.07	10.04	7.32	4.51	2.24
Tindoor (min)-with THR	4.51	4.39	5.56	7.49	10.19	13.42	15.75	15.70	13.38	10.56	7.32	4.82
Tindoor (max)-with THR	9.89	10.41	12.57	16.07	19.03	21.90	24.35	23.80	20.92	17.09	13.22	10.56

Fig. 6. (a) The year-round indoor temperature for the wind tower with and without THR and (b) the annual ventilation rate in the wind tower with and without THR.

the acceptable limit. However, it should be noted that in the summertime, we suggest using additional ventilation methods, such as opening windows and vents to increase the ventilation and cooling capacity.

The effect of adding THR on the year-round ventilation performance of the wind tower

Fig. 6b shows the predicted ventilation rate and airflow velocity for the wind tower with and without THR throughout the year. Overall, the ventilation rate was lower in summer than in winter, mainly due to the lower outdoor wind speed during summertime. For the wind tower with THR, the ventilation rate was lowest in July at 14.35 L/s/person, when the outside wind speed was also the lowest of the year. The yearly maximum ventilation rate of 19.69 L/s/person was obtained in March. The difference in the ventilation rate from January to March was not significant and the values were all at a high level (19.55–20.04 L/s/person) throughout the year. Supply air velocity throughout the year ranged from 0.86 m/s to 1.18 m/s, and indoor air velocity was essentially 0.12 m/s. For the wind tower without THR, the overall trends in supply velocity and ventilation rate were similar, but with higher values of 2.95–4.58 m/s and 49.09–76.41 L/s/person, respectively. The wind tower with THR can provide a 14.35–19.69 L/s/person of ventilation rate throughout the year, 44%-97% more than the suggested value of 10 L/s/person [34]; while the wind tower with THR can provide a much higher annual ventilation rate of 49.38–76.41 L/s/person. As can be seen, in the UK climate of this study, the wind tower system with THR had the potential to operate all year round. We should acknowledge that the wind speed at roof level in real life may be lower than the data used here. This is because wind speed can be related to many factors such as surrounding buildings and vegetation and may vary depending on the microenvironment in which the wind tower is located.

Summertime overheating analysis

As mentioned earlier, the inclusion of THR, while can potentially improve occupant thermal comfort in winter, also results in a reduced airflow rate. This means that one potential pitfall of the wind tower with THR was the lack of ventilation and cooling capacity in the summertime, which may lead to indoor overheating. Inappropriate thermal conditions can affect occupants' health and cognitive performance and also increase the cooling demand. Therefore, it was important to evaluate the overheating risk during summertime.

Thermal performance in summer is usually measured against a

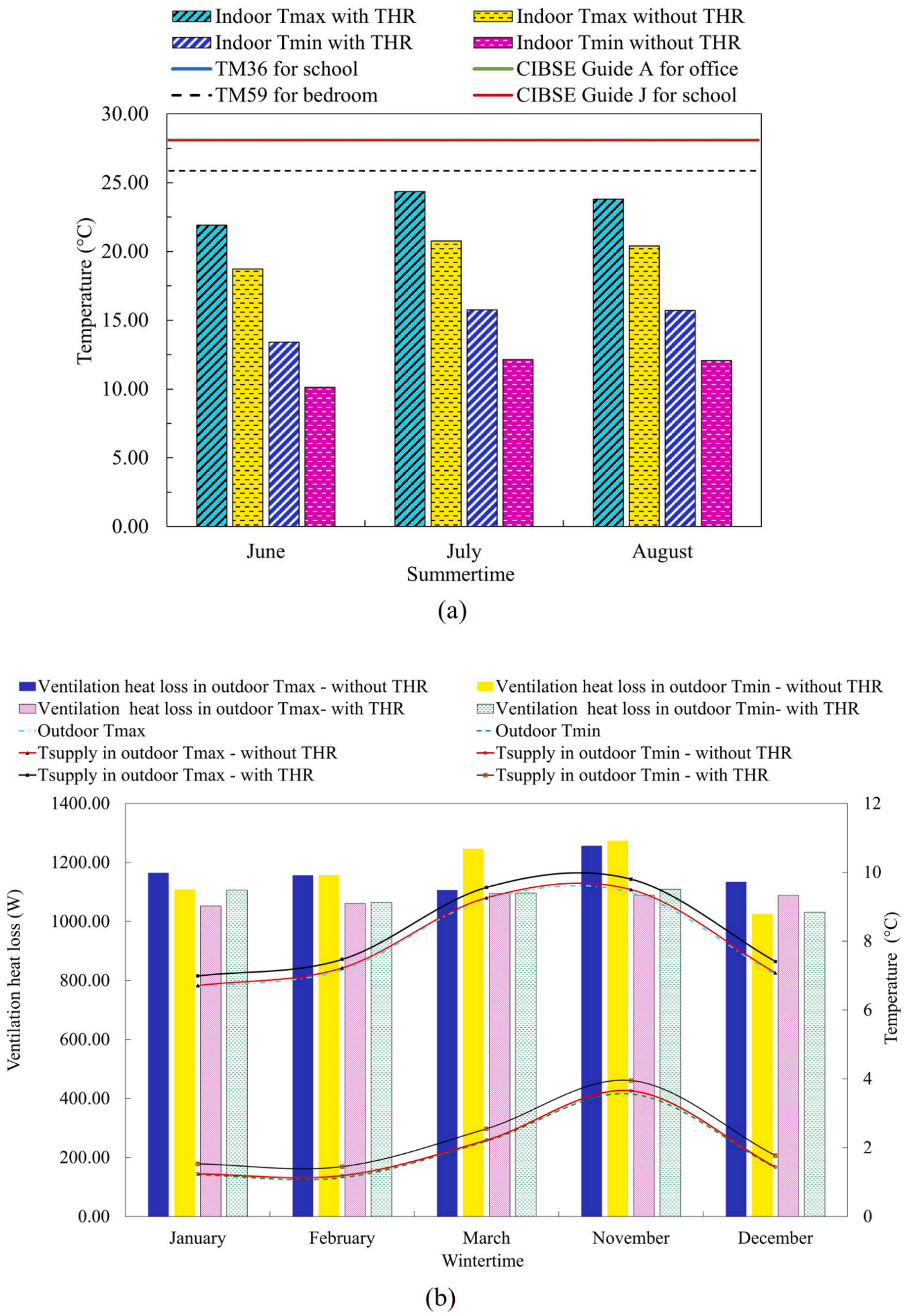
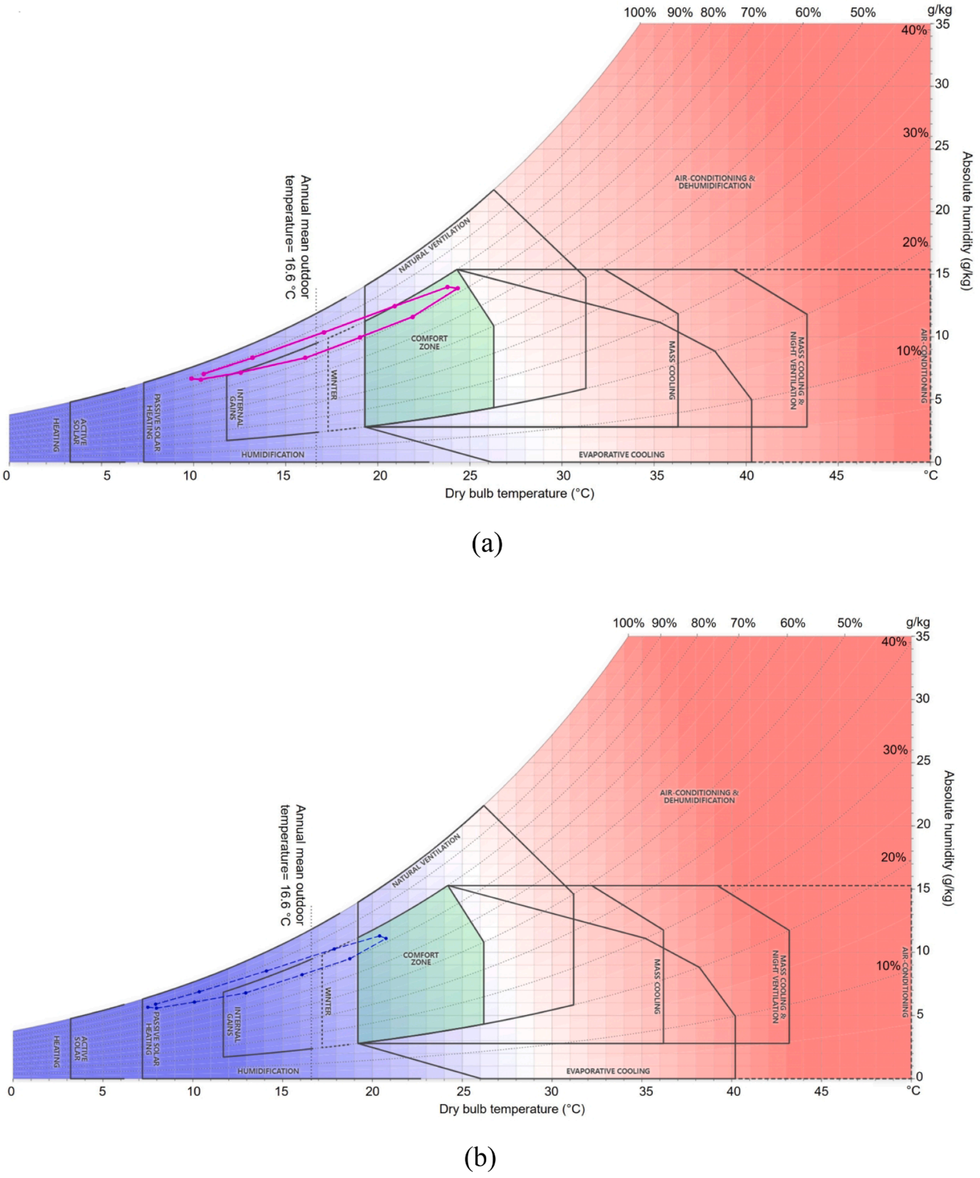


Fig. 7. (a) Indoor overheating evaluation in the wind tower with and without THR during the summertime (June-August) and (b) ventilation heat loss prediction in the wind tower with and without THR during the wintertime.

criterion, which is a benchmark temperature that should not be exceeded at a particular time or period of the year. Static criteria are widely used to assess the indoor thermal environment. In the UK, the most commonly used static overheating criteria are adopted from CIBSE guidelines and Technical Memoranda [36]. Early CIBSE TM36 [38] states that for offices and schools, the comfortable temperatures for occupants are 25 °C and 28 °C, respectively. According to CIBSE Guide A 2006 [36], for offices, the acceptable indoor temperature is 26 °C in the warm summer months. In CIBSE Guide J [37], the comfortable temperature for schools must not exceed 28 °C. Table A.4 details the commonly used static overheating criteria.

Fig. 7a shows the indoor overheating evaluation in the wind tower with and without THR during the summertime (June-August). For the wind tower with THR, the average indoor temperature in June, July, and August ranged from 13.42 °C to 24.35 °C. The maximum outdoor temperature of 19.62 °C was observed in July, with a corresponding maximum indoor temperature of 24.35 °C. As can be observed, the indoor temperatures over summertime were all within the static overheating threshold TM36 [38], CIBSE Guide A [36], TM59 [39] and CIBSE Guide J [37]. This indicated that the wind tower with THR met the thermal comfort criteria for summer use, and if combined with other passive ventilation methods, the indoor thermal environment can be further improved. It should be noted that including THR is detrimental to the passive cooling effect in summer, as the average room temperature is 24% higher than without THR.



(a)

(b)

Fig. 8. Psychrometric chart (represented by Givoni bioclimatic chart) for the wind tower with THR (a) and without THR (b) throughout the year in the UK.

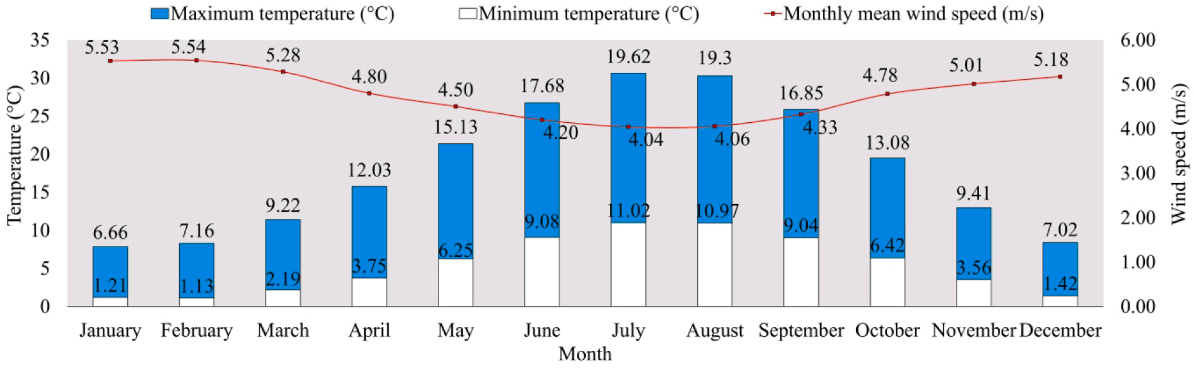


Fig. A1. Velocity and temperature data of UK from 1990 to 2021. Figure created by the data from Met Office [33].

Wintertime heat recovery and ventilation heat loss prediction for the wind tower with and without THR

Fig. 7b shows the reduction in ventilation heat loss during the wintertime (November-December and January-March) for the wind tower with THR and without THR. Building ventilation heat loss can be estimated using Eq. (1) [18],

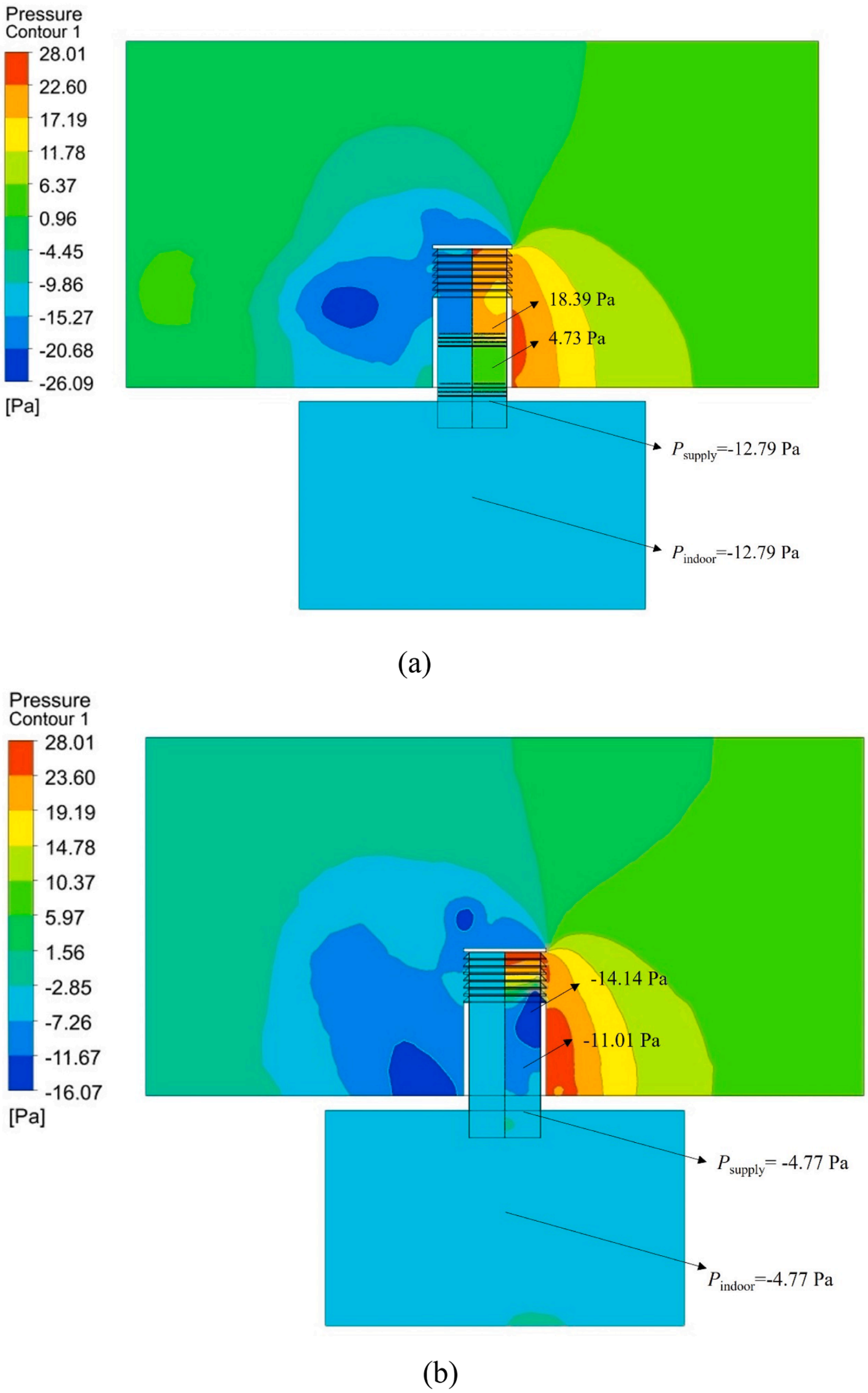


Fig. A2. The static pressure distribution at the cross-sectional plane x = 0 for the wind tower with THR (a) and without THR (b) in February.

$$Q = c_p \times \rho \times q \times (T_{indoor} - T_{supply}) \quad (1)$$

where, c_p is the specific heat capacity of air, ρ is the air density, q is the air volume flow rate, T_{indoor} is the indoor temperature, and T_{supply} is the supply temperature.

The heat loss from the wind tower ventilation was reduced in the cold months after the inclusion of THR, with an average reduction of 7.3% to 8.1%. When the external temperature peaked at 9.41 °C during the wintertime, the ventilation heat loss in the wind tower with THR was 1089.57 W, compared to 1256.72 W for the wind tower without THR, resulting in a reduction of 15.3%. When the external temperature was at a minimum of 3.56 °C, the ventilation heat loss in the wind tower with THR was 1109.18 W, compared to 1273.51 W in that without THR, a reduction of 14.8%. From January to March, THR can reduce ventilation heat loss by 0.2%-10.7%, 8.7%-9.0% and 1.1%-13.6%, respectively. The amount of heat recovery was mainly reflected in the increase in the supply air temperature. As seen from Fig. 7b, THR can preheat the incoming outside air by 0.28–0.33 °C compared to that without THR. However, adding THR in the wind tower still cannot provide occupants with good thermal comfort in cold/mild-cold months.

Fig. 8 shows the psychrometric chart (represented by Givoni bioclimatic chart) for the wind tower with and without THR throughout the year in the UK. Givoni bioclimatic chart is based on expected indoor temperatures and is mainly applicable to residential scale buildings

Table A1
Summary of the thermal performance and overheating investigation in the selected literature.

Ref	Wind tower			Integration		Thermal performance	Over heating	Key findings
	One-sided	Two-sided	Four-sided	Cooling	Heat recovery			
[10]	✓			✓	×	✓	×	The wind tower integrated with the water evaporation can reduce the indoor temperature by up to 17.13 °C.
[11]		✓		✓	×	✓	×	At wind speeds of 2.5–4 m/s, 50%-80% of the indoor area was defined as a “comfort zone” by using the wind tower combined with a wing wall. Wind speeds less than 2.5 m/s caused thermal discomfort indoors.
[12]	✓			✓	×	✓	×	The wind tower with the water evaporation can reduce the indoor temperature by 17.4 °C.
[13]	✓			✓	×	✓	×	The combination of the wind tower, solar chimney and water spray can provide satisfactory thermal comfort for the three-story building during the midday period.
[17]			✓	✓	×	✓	✓	By utilising the internal openings, shaft and wind tower, the period during which the temperature remained within the comfort range of 18–22 °C occupied only 6% of the time from 6 a.m. to noon. The most effective ventilation strategy resulted in 47% of the cooling period being above 26 °C, with 17% exceeding 28 °C (considered overheated).
[18]			✓	×	✓	✓	×	By introducing the rotary thermal wheel into the wind tower, indoor temperature can be increased by up to 3.7 °C.
[20]		✓		✓	✓	✓	×	A pre-cooling by 15.58 °C and preheating by 3.3 °C were achieved in the wind tower assisted with the heat pipes.
[21]			✓	×	✓	✓	×	By introducing the heat pipes into the wind tower, the supply air temperature can be improved by 4.5 K.
[22]			✓	×	✓	✓	×	The supply air temperature can be increased by 2.8 °C under the effect of the wind tower with heat pipes.

Table A2
The dimensions for the wind tower model.

Critical dimensions	**Value**
Room length, width, and height	5, 5, 3 m [21]
Wind tower with THR length, width, and height	1, 1, 2.21 m [24]
Louver angle	45° [21]
THR longitudinal pitch (SL)	0.025 m [24]
THR transverse pitch (ST)	0.06 m [24]
THR diameter	0.02 m [24]
THR length	1 m [24]

Table A3
The mesh independence analysis.

The number of mesh elements (million)	Supply temperature (°C)	Error (±%)	Supply air velocity (m/s)	Error (±%)
11.5	7.59	/	0.26	/
12.2	10.69	40.8	0.22	15.4
14.2	10.85	1.5	0.23	4.5
17.0	11.28	3.9	0.22	4.3
21.2	11.63	3.1	0.23	4.5

Table A4
The commonly used static overheating criteria.

Static criteria	**Applicable space**	**Comfort threshold temperature**	**Overheating Criteria**	**Ref**
TM36	Office	25 °C	Temperatures above 25 °C should be less than 5% of the year	[38]
	School	28 °C	Temperatures above 28 °C should be less than 5% of the occupied time of the year	
	Sleeping area	21 °C (night)	The upper limit of acceptable temperature for good sleep quality is 21 °C	
CIBSE Guide A	Office	25 °C	Acceptable indoor operative temperature is 25 °C	[36]
		28 °C	Operative temperatures above 28 °C should be limited to 1% of the occupied time	
TM59	Bedroom	26 °C (10 pm-7am)	Operative temperatures above 26 °C should be less than 1% of the year	[39]
CIBSE Guide J	School	28 °C	Temperatures above 28 °C should be less than 80 h of the occupied time in the year	[37]

[40,41]. It can present the boundaries of comfort zones and heating/cooling, or dehumidification/humidification strategies required for different zones [42]. In addition, we plotted the average of the occupants’ votes on a seven-point heat-sensitivity scale, i.e., PMV. The background colour changes left to right from blue to red to represent votes from cold, cool, slightly cool, neutral to slightly warm, warm, and hot [43]. The presented PMV classification is based on the EN 15251 standard released by the European Committee for Standardisation (CEN) for buildings without mechanical heating/cooling systems [44]. PMV is related to the occupants’ activity level, air velocity, clothing insulation level, etc. In this study, it was assumed that occupants’ clothing level was 1.0 clo and metabolic rate was 1.0 met (i.e., occupants wearing a business suit or casual dress with a sweater in sedentary activity) [45].

In the wind tower with and without THR, the predicted indoor air velocity in CFD was 0.12 m/s and 0.35 m/s, respectively. From the comparison of Fig. 8a, b, the inclusion of THR expanded the comfort zone for wind tower use (mainly from June to September) whereas the comfort ranges in the wind tower without THR were mainly in July and August. During January to May and October to December, THR helped to increase PMV from cold to cool or from cool to slightly cool. It should be noted, however, that the wind tower assisted by THR during the cold months such as January, February and December may still require additional heating input to provide satisfactory thermal comfort; during some extreme weather in the summertime, THR may cause the indoor thermal environment to reach warm.

Comparison with the previous studies

To evaluate the comparability of the wind tower with THR in terms of thermal performance, this section compared the present results with the previous related studies [18–22]. The studies [19,20,22] that did not do a parametric study of environmental factors such as wind speed/temperature were excluded. Comparisons were made based on indoor and outdoor temperature differences to enable the results obtained from different studies more comparable. A larger difference represented the potential of the heat recovery's capability to increase the indoor temperature at cold/mild-cold conditions. It was found the present tube heat recovery performance was competitive compared to the heat pipes [21] and rotary thermal wheel [18]. For example, at a wind speed of 4 m/s, the indoor temperature increase in the current study can reach 4.73 °C, 5 °C indoor temperature improvement obtained from the rotary thermal wheel in [18] and 3 °C from the heat pipes in [21]. In addition, the tube heat recovery is passive, i.e., the waste heat indoors is collected and stored in the tubes to preheat incoming air, while the rotary thermal wheel requires electrical power to control the rotary motor.

Conclusions and future work

The presented work was to further explore the annual thermal performance of the wind tower with passive heat recovery technology. The ability of THR to ventilate, cool during summertime and preheat during wintertime was evaluated by simulating monthly wind speed and temperature in the UK for the years 1990–2021. ANSYS FLUENT 18.1 was used for steady-state RANS simulations and the RNG k-epsilon model to simulate turbulent properties. The CFD model analysed the air pressure, velocity and temperature in the wind tower ventilation system based on the weather data provided by Met Office. Based on the simulated conditions, the highest indoor temperature (24.35 °C) and supply temperature (20.19 °C) were observed in the summer month of July, with a supply air velocity of 0.86 m/s. The lowest indoor temperature (4.51 °C) and supply temperature (1.54 °C) occurred in the winter month of January with a supply air velocity of 1.18 m/s. During the summertime, the average temperatures in the supply and the below room were 23.35 °C and 19.40 °C, respectively, an increase of 7.64 °C and 4.77 °C compared to the wind tower without THR. According to the static overheating criteria, during the summertime (June-August), the risk of overheating in the room was low, but additional ventilation strategies were recommended to improve thermal comfort during the summer months. During the wintertime (November-December and January-March), the wind tower with THR reduced ventilation heat loss by an average of 7.3%–8.1% and increased supply temperature by 3.7%–18.2% compared to that without THR. Furthermore, throughout the year, the wind tower with THR can provide a satisfactory ventilation rate for a small classroom with 15 occupants, ranging from 14.35 L/s/person to 19.69 L/s/person, which was 43.5%–96.9% above the recommended value of 10 L/s/person.

This research showed that the previously proposed wind tower with THR may not cause overheating in the ventilated space in warm conditions and can reduce ventilation heat loss in cold/mild-cold climates. The modelling approach here can be used to assist architects and building engineers in retrofitting wind towers into buildings. However, there are some limitations in this work. For example, the ventilated space in this study was assumed to be fully closed and isolated. The influence of microenvironment and different building stocks should be investigated carefully on a case-by-case basis in practical situations. It also should be noted that the wind tower assisted by THR during the cold months such as January, February and December may still require additional heating input to provide satisfactory thermal comfort; during some extreme weather in the summertime, THR may cause the indoor thermal environment to reach warm. The wind tower's resilience in thermal comfort during possible extreme weather conditions and global warming scenarios could also be evaluated in future studies.

CRediT authorship contribution statement

Miaomiao Liu: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization. **Carlos Jimenez-Bescos:** Writing – review & editing, Supervision. **John Calautit:** Conceptualization, Resources, Methodology, Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A

Fig. A.2 depicts the pressure pattern in the cross-sectional plane x = 0 for the wind tower with and without THR in February. As can be seen from Fig. A.2a, the pressure on the windward side was higher, with a maximum pressure of 24 Pa. The pressure inside the ventilated space was −12.79 Pa. The upstream air pressure for the first-stage heat recovery was 18.39 Pa and dropped to −12.79 Pa after the second stage. For a four-sided wind tower, when the wind direction angle was 0°, the room was usually under negative pressure because three of the four quadrants of the wind tower were used for exhaust and only one for supplying air. In the wind tower without THR, the air pressure inside the wind tower (−11.01 Pa) and at the supply (−4.77 Pa), was lower than the pressure after the THR was added. As can be observed in Fig. A.2, after incorporating the THR, the air pressure inside the wind tower increased, leading to a decreased airflow rate.

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