



Investigation of a novel windcatcher with passive tube heat recovery

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Abstract

Windcatchers are low-energy ventilation devices which can provide cooling and reduce buildings' energy use. However, during unfavourable climate conditions, windcatcher operation could cause thermal discomfort and ventilation heat loss. Limited research has been conducted on pre-heating the supply air in windcatchers to address the issue and potentially increase their adoption in mild-cold climates. Therefore, this research proposes a novel windcatcher ventilation system integration with tube heat recovery (THR). By combining with a solid tube bank heat recovery device, the windcatcher can be operated under winter conditions to improve indoor ventilation while reducing buildings' heating energy consumption.

A three-dimensional computational fluid dynamics (CFD) model was developed to investigate the performance of the proposed windcatcher in ventilation rate, thermal comfort, and indoor air quality (IAQ). The CFD model was validated against the previous literature. The longitudinal pitch (LP) and the transverse pitch (TP) of the THR device were optimised based on the ventilation rate and tube thermal performance. The tube thermal performance can be improved by reducing LP and TP, increasing the fresh air supply temperature by up to 6.4 °C. Furthermore, the proposed windcatcher can provide sufficient ventilation for a typical classroom occupied by 15 people when the external wind speed exceeds 3 m/s. In addition, this project also explored the feasibility of the year-round operation of the windcatcher with tube heat recovery (THR) using the validated CFD model.

The results showed that within the mild-cold months, the windcatcher with THR functioned as natural ventilation and improved the room temperature by an average of 3.1 °C. This extended the working period of the windcatcher throughout the year, especially during mild-cold months. During summertime, the highest indoor temperature observed in the space ventilated by the windcatcher with THR was 24.35 °C, which met the static overheating criteria. The windcatcher with THR reduced the ventilation heat loss by up to 8.1% in wintertime. It should be acknowledged that this windcatcher cannot provide satisfactory thermal comfort in months with outdoor temperatures below 9.41 °C, and more research should be done to improve the heat recovery efficiency. Furthermore, the CO₂ concentration and spatial distribution in the ventilated space were investigated, which represent the

IAQ. The effects of the occupant-influenced and external environment-influenced variables on the indoor CO₂ levels were analysed. The results highlighted that occupant activity levels greatly affected CO₂ levels in the ventilated space, with an increase of 44% from sedentary to medium working observed at the breathing heights based on the set conditions. For an occupancy density of 1.7-2.6 m²/p in the classroom model, the indoor above outdoor CO₂ levels were within 550 ppm at outdoor wind speeds above 3 m/s. The effect of heating/non-heating seasons on the indoor CO₂ levels may be negligible for locations with high wind speeds all year round. Based on the UK's year-round mean climate conditions, the CO₂ level in the space ventilated by the windcatcher with THR was expected to reach Category I or II, according to EN 16798-1:2019.

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Preface

The work presented in this thesis was carried out between October 2019 and July 2023 at the Department of Architecture and Built Environment, University of Nottingham. The following research outputs have been published or awarded as a result of the work:

Peer-reviewed articles:

1. **Liu, M.***, Nejat, P., Cao, P., Jimenez-Bescos, C. and Calautit, J.K., 2024. A critical review of windcatcher ventilation: Micro-environment, techno-economics, and commercialisation. *Renewable and Sustainable Energy Reviews*, 191, p.114048.
2. **Liu, M.**, Almazmumi, S., Cao, P.*, Jimenez-Bescos, C. and Calautit, J.K.. Can windcatcher natural ventilation beat the chill? A view from heat loss and thermal discomfort. *Building and Environment*, 247, p.110916.
3. **Liu, M.***, Jimenez-Bescos, C. and Calautit, J.K., 2023. Performance evaluation of wind tower natural ventilation with passive solid tube heat recovery based on CO₂ levels. *Journal of Building Engineering*, 72, p.106457.
4. **Liu, M.*** and Calautit, J.K., 2023. A parametric investigation of the heat transfer enhancement of tube bank heat exchanger with reversed trapezoidal profile fins. *Thermal Science and Engineering Progress*, 42, p.101914.
5. **Liu, M.***, Jimenez-Bescos, C. and Calautit, J.K., 2023. Passive heat recovery wind tower: assessing the overheating risk in summertime and ventilation heat loss reduction in wintertime. *Sustainable Energy Technologies and Assessments*, 58, 103310.
6. **Liu, M.***, Jimenez-Bescos, C. and Calautit, J.K., 2022. CFD investigation of a natural ventilation wind tower system with solid tube banks heat recovery for mild-cold climate. *Journal of Building Engineering*, 45, p.103570.

Conference papers:

1. **Liu, M.**, Jimenez-Bescos, C. and Calautit, J. Numerical analysis of a natural ventilation wind tower system with solid tube bank heat recovery devices for mild-cold climate. The 16th Conference on Sustainable Development of Energy, Water and Environment Systems (SDEWES), Croatia, Dubrovnik, 10-15 October 2021.

Awards:

1. First Place in Buildings, Energy and Environment Research Group Internal showcase 2021- 1st Year Presentation.

Nomenclature

Abbreviation

IAQ	Indoor air quality
LCA	Life cycle assessment
VOC	Volatile organic compound
HVAC	Heating, ventilation, and air conditioning
CFD	Computational fluid dynamics
CAD	Computer-Aided design
ASHRAE	American Society of Heating, Refrigerating and Air Conditioning Engineers
EAHE	Earth-air heat exchanger
RANS	Reynolds-averaged Navier-Stokes
SBS	Sick building syndrome
GHG	Greenhouse gas
LCC	Life cycle cost
SPP	Simple payback period
DPP	Discounted payback period
NPV	Net present value
IRR	Internal rate of return
SEA	Strategic Environmental Assessment
EIA	Environmental Impact Assessment
ERA	Environmental Risk Assessment
SDG	Sustainable Development Goal
LTD	Limited company
LES	Large eddy simulation
THR	Tube heat recovery
CO ₂	Carbon dioxide
ACE	Air change efficiency
CP	Plane near the ceiling
TBH	Teacher's breathing height
CBH	Children's breathing height
BP	Bottom plane
OD	Occupant density

Symbol

LP	Longitudinal pitch (mm)
TP	Transverse pitch (mm)
y ⁺	Mesh specification near the wall (dimensionless)
v	Inlet velocity (m/s)
p	Static pressure (Pa)
T	Temperature (K, °C)
g	Gravitational acceleration (m/s ²)
Q	Building heating loss (Watts)
A	Building component area (m ²)
U	U value (W/m ² K)
N	Air change rate (1/hour)
V	Volume of building (m ³)
m	Mass flow rate of air (kg/h)
c _p	Specific heat capacity of air (kJ/kg K)
W	Estimated ventilation heating energy (kWh)
D	Diameter of the tube
A _D	Dubois surface area (m ²)
w	Per occupant's weight (kg)
h	Per occupant's height (m)
M	Metabolic rate (met)
RQ	Respiratory quotient
G _{CO2}	CO ₂ release rate (L/s)
v	Airflow velocity (m/s)
W	Width (m)
L	Length (m)
H	Height (m)

Subscript

i	Inlet
o	Outlet
se	Required supply air temperature
sr	Supply air temperature after the THR

Chapter 1 Introduction

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. They are typically slender and tall structures, like a chimney, which are situated on a building's roof or wall. Windcatchers capture the wind at the roof level and induce it downwards into the building via openings or vents. This improves ventilation without using mechanical systems by facilitating air circulation and cooling via thermal mass. Windcatchers 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. Many studies, such as [1] and [2], have demonstrated that natural ventilation technology, such as windcatchers, has the potential to reduce energy use and improve IAQ; but this is not always the case. During unfavourable conditions, windcatcher operation could further cause thermal discomfort and poor ventilation.

However, there has been limited research into heat loss or overheating risk caused by windcatcher ventilation. Few studies have investigated the integration of passive heat recovery into windcatchers. While some research introduced heat transfer devices such as rotary thermal wheels [3] and heat pipes [4] into windcatchers, no studies have explored simpler heat exchange technologies that could be more cost-effective and reduce the need for moving parts, such as rotary wheels, and working fluids, such as heat pipes. The capability of windcatchers to operate effectively in mild-cold climates should be demonstrated in more depth [5]. Therefore, this study proposed a novel windcatcher incorporating passive tube heat recovery, highlighting its application potential in mild-cold climates. The tube heat exchanger operates without working fluids to transfer heat, is easy to operate, contains no moving or rotating parts, and is cost-effective [6].

1.1 Aims and objectives

The overall aim of this work is to develop a windcatcher ventilation device with passive tube heat recovery, which may offer a potential alternative to mechanical heating, ventilation, and air conditioning (HVAC) systems. The tube heat recovery collects the waste heat indoors and preheats supply air, thereby reducing ventilation

heat loss and providing satisfying thermal comfort during low-temperature conditions. The proposed windcatcher device is expected to enhance the applicability of windcatcher ventilation in low-temperature environments and extend its operation time throughout the year.

In line with the overall aim of the project, the following research objectives were identified:

1. Review recent developments in windcatcher natural ventilation and identify the research gaps.
2. Conceptualise the design of the windcatcher, tube heat exchanger and ventilated space.
3. Develop a validated CFD model against the experimental data in the previous literature.
4. Compare the overall airflow distribution in the windcatcher with and without the tube heat recovery.
5. Optimise the tube heat recovery device according to the ventilation rate and temperature distribution in the occupied space.
6. Investigate the year-round performance, such as ventilation rate and thermal comfort, of the proposed windcatcher in the UK climate, especially the summertime overheating risk and wintertime heat recovery.
7. Evaluate the IAQ performance in the occupied space ventilated by the proposed windcatcher based on the CO₂ level.
8. Analyse the overall performance of the proposed windcatcher and strike a balance across the indicators.

1.2 Project methodology

This study follows a systematic approach to achieve the research objectives. First, a thorough analysis and review of existing literature will be conducted, focusing on the recent developments in windcatcher integrations with cooling, heating, and dehumidification techniques. The commercialisation status of windcatchers in the UK will also be evaluated. The research gaps will be identified, and potential solutions, such as the introduction of tube heat recovery, will be proposed. Second, following the conceptualisation, a three-dimensional geometry model of the proposed windcatcher will be established using CAD software. The fluid domain will be extracted in ANSYS DesignModeler, and CFD modelling will be conducted

using commercial CFD software, such as ANSYS Fluent. The CFD model settings will be validated against experimental and numerical data from existing literature. The tube heat recovery device will be optimised to achieve a balance between ventilation rate and tube thermal performance. Finally, the overall performance of the proposed windcatcher will be evaluated, in terms of ventilation rate, thermal comfort, and IAQ. Fig. 1 shows the methodology flow chart for the progression of the PhD study.

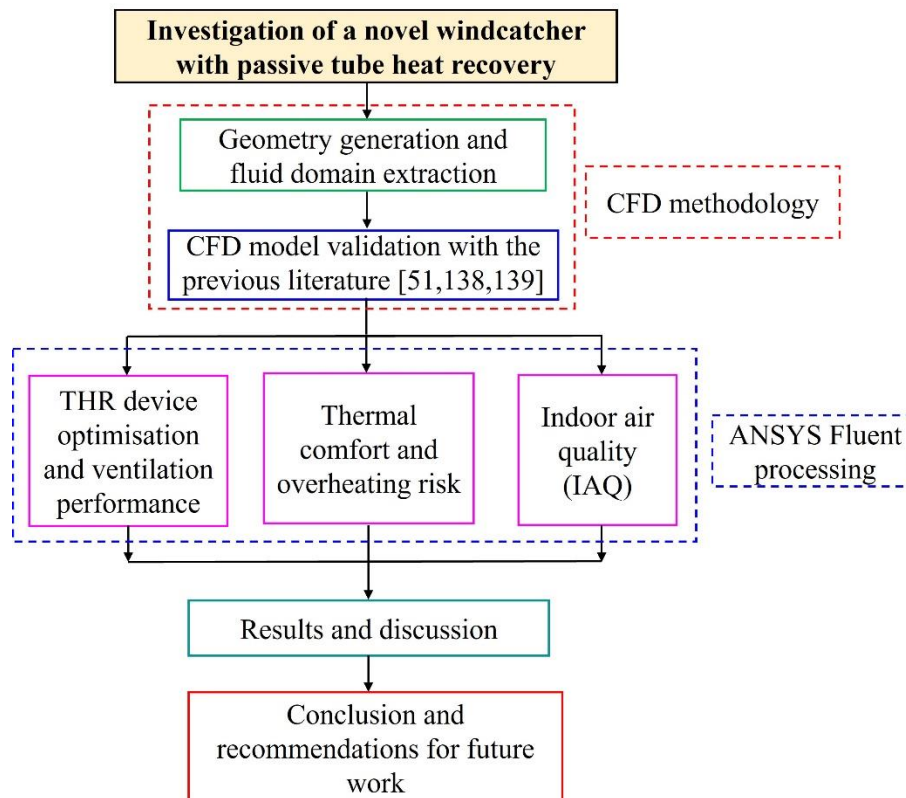


Fig. 1 Methodology flowchart for this research

1.3 Thesis structure

The aim of the study described in the thesis is to investigate the performance of windcatcher ventilation combined with passive tube heat recovery. The research adopts a systematic methodology to optimise the tube heat exchanger and predict the performance of the windcatcher combined with the optimal tube arrangement. The thesis consists of six chapters. The order and content of the chapters will guide readers through the research from concept to conclusion. A brief summary of each chapter is listed as follows.

Chapter 1 introduces the high-energy demand imposed on buildings for HVAC and

shows examples of alternative technologies, such as windcatchers. The chapter details the key objectives, structures, and methodology of this study.

Chapter 2 offers a comprehensive review of recent developments in windcatchers, focusing on the integration of cooling, heating, and dehumidification techniques. The review analyses the latest literature on windcatchers in terms of ventilation rate, thermal comfort, overheating risk, IAQ, energy performance, economic analysis and LCA. The commercial windcatcher market in the UK is also reviewed, and the main research gaps will be identified.

Chapter 3 describes the numerical methods that will be adopted in the thesis. This chapter will detail the theoretical background of CFD, mesh generation, mesh independence study, boundary conditions, and convergence criteria.

Chapter 4 details the CFD model validation with experimental data from previous literature.

Chapter 5 presents the results and discusses the windcatcher's performance in terms of ventilation rate, thermal comfort, and IAQ. The overall airflow velocity, temperature, and pressure distribution in the windcatcher and ventilated space are discussed. The tube heat exchanger is optimised according to the windcatcher ventilation rate and tube thermal performance. Furthermore, this chapter evaluates the year-round performance of the proposed windcatcher using UK climatic data from 1990 to 2021, with an emphasis on evaluating summertime overheating risk and wintertime heat recovery. Lastly, the IAQ performance achieved in the ventilated space, as indicated by CO₂ levels, is investigated.

Chapter 6 draws conclusions from the analysis presented in the results and discussion. Areas for potential future work to further enhance the research are also identified and discussed.

Chapter 2 Literature Review

Chapter 2 provides an overview of the general principle of windcatcher ventilation and its previous developments. The recent integrations of cooling, heating, and dehumidification techniques into windcatchers will be reviewed. The windcatchers' performance in ventilation rate, thermal comfort, overheating risk, IAQ, energy efficiency, economic performance, and LCA will be discussed. Thermal comfort denotes the extent to which occupants are content with the thermal conditions in their environment [7]. In the UK, static overheating criteria commonly used are adopted from CIBSE guidelines and Technical Memoranda [8]. IAQ refers to the air quality within a building or enclosed space, especially concerning the health and well-being of the individuals inside [9]. This chapter also highlighted the current trends and future perspectives in the commercial market for windcatchers, including available options, opportunities, and threats. Following the review, the research gaps in the existing literature are identified.

For the literature review, the research articles published between 2008 and 2023, spanning a 15-year timeframe, were considered. The articles were sourced from three databases: Scopus, Web of Science and ScienceDirect. The main search keywords were “windcatcher” and “wind tower natural ventilation”. Other keywords, such as “wind scoop”, were excluded from the literature searching process since wind scoops can refer to a wider range of architectural elements related to natural ventilation and can have varying shapes. The identification of studies selected for review was accomplished by employing Mendeley, Zotero and VOSviewer. The literature screening process is illustrated in Fig. 2, and the visualisation of windcatcher research networks is shown in Fig. 3. As shown in Fig. 2, a total of 4,485 studies were initially obtained from those three databases, excluding any duplicates. To ensure the selected literature aligns robustly with the review's topic, I further narrowed down the initial pool by screening the papers based on the presence of the keywords in their titles and abstracts, resulting in 255 articles being shortlisted. Subsequently, 98 studies were chosen based on the availability of full-text PDFs. Finally, after adding an additional 63 studies manually, a total of 161 studies have been included in the literature review.

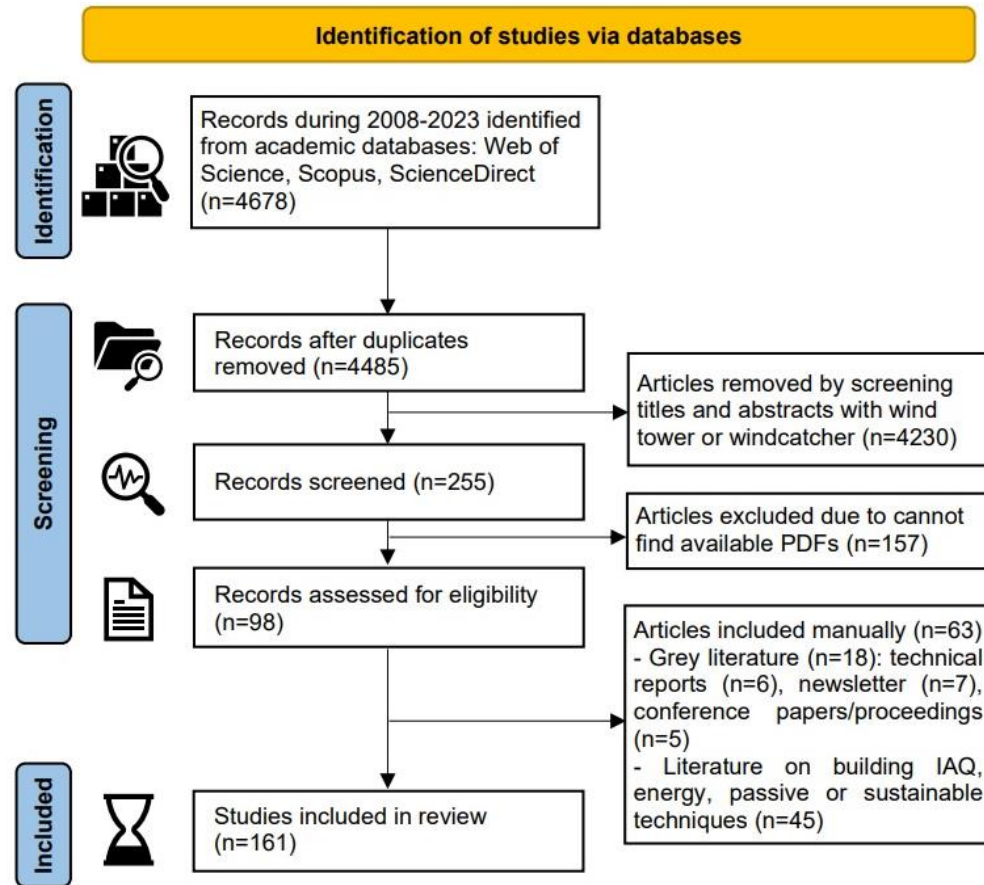


Fig. 2 PRISMA flow chart of literature screening for this review

Fig. 3 provides a more concise and intuitive network diagram of windcatcher research through VOSviewer. The Web of Science database was selected, and keywords such as “wind tower” and “windcatcher” were extracted from the titles and abstracts. The number of appearances of each related keyword was counted in binary, retaining those with at least five occurrences. The meaningless, irrelevant, and duplicate words were removed from the thesaurus file supported by VOSviewer. The circle sizes denote the frequency of each keyword’s occurrence, while the distance between circles represents the co-occurrence frequency of keywords. A closer distance indicates more frequent appearances in the same document. It can be found that wind towers/windcatchers are strongly linked to passive/natural ventilation. In the reviewed studies, windcatchers mainly target buildings with high occupancy, such as classrooms. The primary methodologies used in these studies are CFD or numerical analysis and wind tunnel tests.

The colours of the lines and circles correspond to the year legends at the bottom. Between 2014 and 2018, the main keywords related to windcatchers included “passive cooling”, “passive ventilation”, “summer”, and “dry climate”. During this

period, windcatcher research focused more on external climate conditions (e.g., wind velocity and direction) and ventilation performance (e.g., air change rate and air flow rate). Modifications to windcatchers were mainly aimed at improving or optimising the cooling function. From 2018 onwards, there have been a few studies conducted on windcatchers coupled with heat recovery systems, aiming to function in cold or mild-cold climates. More dimensions, such as humidity, have been considered when evaluating windcatchers' performance.

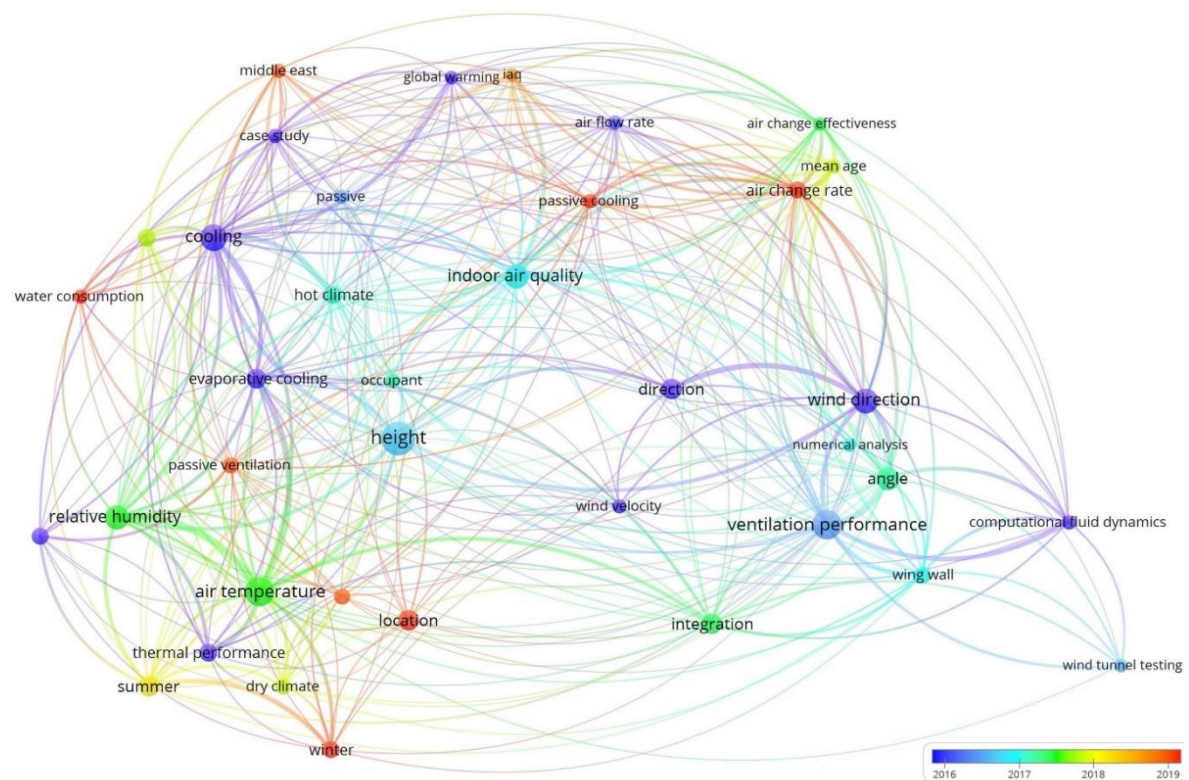


Fig. 3 Visualisation of wind tower/windcatcher research networks in the reviewed studies

2.1 Previous windcatcher's developments

Buildings contribute significantly to greenhouse gas (GHG) emissions due to ventilation, heating, cooling, construction, retrofitting, and waste disposal [10,11]. Natural ventilation relies on natural forces, such as wind and buoyancy, to ventilate buildings without using mechanical systems like fans or air conditioners. It has recently been combined with various heating, cooling, and dehumidification techniques to maintain good indoor environmental quality while reducing or eliminating the need for energy-intensive HVAC systems [12,13]. Natural ventilation can be particularly effective in buildings with a simple layout, few internal obstructions and areas with a mild or temperate climate. Methods of implementing natural ventilation include using openings like windows and doors to

facilitate airflow, and architectural features such as vents, louvers, passive chimneys, and windcatchers to direct and enhance indoor airflow. Windcatchers catch the wind and direct it downwards into buildings through a series of vents or openings (Fig. 4) [5]. As the wind passes through the building, it helps to increase ventilation and, in some cases, cool the air via thermal mass. Windcatchers have been used for centuries in hot, dry climates, particularly in the Middle East and North Africa, to create a comfortable indoor environment without the need for mechanical cooling systems [14]. Their effectiveness relies on strong, consistent winds, often complemented by other natural ventilation strategies like windows and doors to facilitate airflow throughout the building.

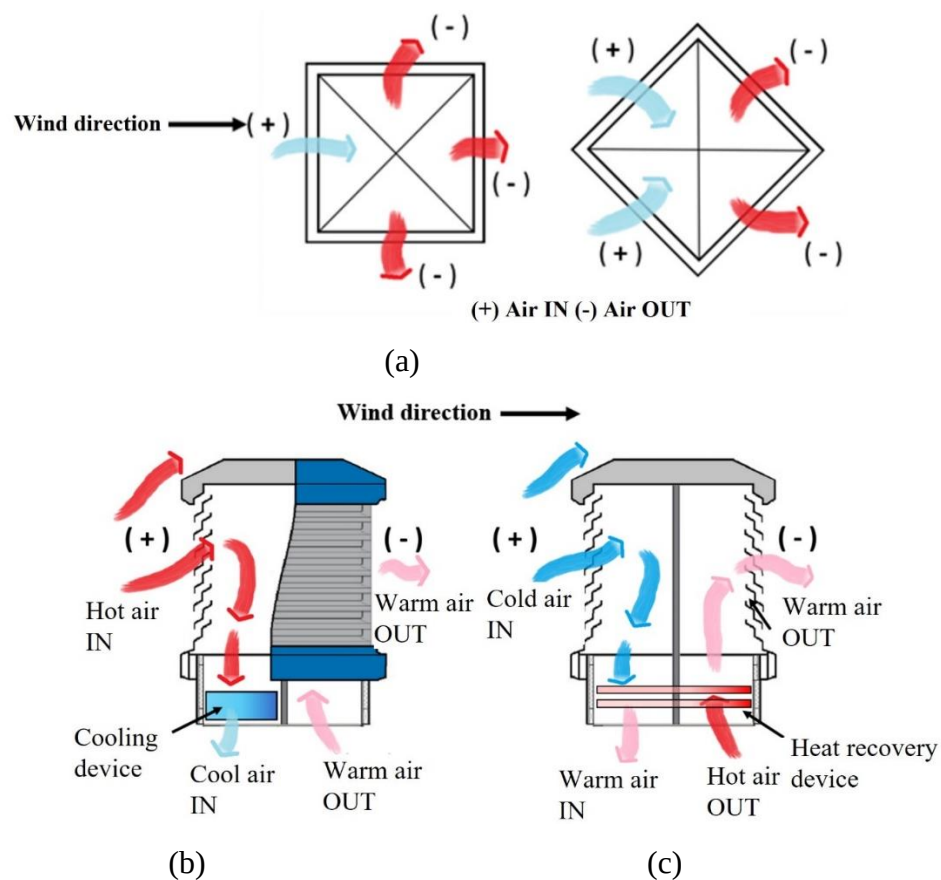


Fig. 4 Typical operation of a (a) standard windcatcher (from top view) (b) windcatcher with a cooling device (c) windcatcher with a heat recovery device

Like any natural ventilation strategy, windcatchers alone are insufficient to keep a building ventilated and comfortable at all times of the year. In some cases, it may be necessary to use mechanical HVAC systems together with natural ventilation to maintain a well-ventilated and pleasant indoor environment. Research has combined windcatchers with passive or low-energy strategies like solar design [15], thermal mass [16], evaporative cooling [17], and heat transfer devices [18]. Evaporative

Table 1 Coverage of review papers on natural ventilation windcatcher technologies

	[24]	[25]	Review articles
			Design and operation
			Modelling and simulation
			Experiment analysis
			Integration with technologies
			Ventilation performance
			Thermal performance
			Thermal comfort / overheating
			Urban context / integration
			Indoor air quality
			Energy performance
			Economic / LCA analysis
			Commercial aspects
			Case studies and real examples

[26]												
[27]												
[28]												
[5]												
[30]												
[29]												
[32]												
[31]												
Current												

The literature review aims to review the windcatchers' performance in IAQ, thermal comfort, energy saving, economic cost, and LCA, along with the current challenges and future prospects in the commercial market. The review is structured according to the following aspects.

- (1) Provides an overview of the recent advancements in windcatchers combined with low-energy cooling, heating, and dehumidification techniques. The review will not look into the details of traditional and modern windcatcher designs or operations, as these points have already been extensively covered and discussed in great depth in previous studies [24–26].
- (2) Discusses the potential challenges in the windcatcher studies, such as overheating risk, inadequate IAQ evaluation tools and limited adaptations. Although earlier works have reviewed the windcatchers' performance in thermal comfort [5,33], few have explored the potential overheating risk.
- (3) Investigates the techno-economic assessment of windcatchers, including energy performance, economic analysis, and LCA, which typically have not been covered previously.
- (4) Identifies the current and emerging trends in the commercial market of windcatchers, including their utilisation in the built environment. To the best of

the author's knowledge, no studies have thoroughly reviewed windcatchers' commercialisation status and case studies.

(5) Highlights the potential research gaps in windcatcher developments.

2.2 Recent integrations of cooling, heating, and dehumidification technologies with windcatchers

Windcatchers can provide a comfortable and fresh indoor micro-climate using renewable wind energy in favourable weather conditions [34,35]. However, windcatchers also have some drawbacks. For example, it is difficult to provide enough ventilation on windless days, and their use has been limited in mild-cold or cold climates due to significant heat loss [36,37]. An increasing number of studies have suggested incorporating windcatchers with cooling, heating, or dehumidification technologies to enhance their applicability in various climates [30,38].

2.2.1 Windcatchers integrated with cooling techniques

A few cooling techniques have been proposed to be combined with windcatchers to enhance their cooling performance, including water evaporation [33,39,40], earth-air heat exchangers (EAHE) [41–43], heat pipes [21], phase change materials (PCM) [44,45], and solar chimneys [46,47]. Water evaporation has been employed in many forms to reduce the air temperature provided by windcatchers, such as water spray [17,19,39], wetted surfaces/columns/pads/blades [15,16,33], and an underground water tank [40]. The EAHE operates by capturing warm air with the windcatcher, transporting it through buried ducts, where its heat is dissipated by the surrounding low-temperature soil, and further delivering it indoors [41]. Another cooling enhancement strategy involving heat pipes has been proposed by Calautit and Hughes [20]. In this method, one end of the heat pipes is placed in a water tank that is constantly maintained at lower temperatures. When the other end comes into contact with the warm air entering the windcatcher from outside, heat transfer occurs along the heat pipes and between the air and the heat pipes, thereby reducing the temperature of the air supplied to the occupied space. Fig. 5 shows the selected windcatchers incorporated with cooling enhancement technologies.

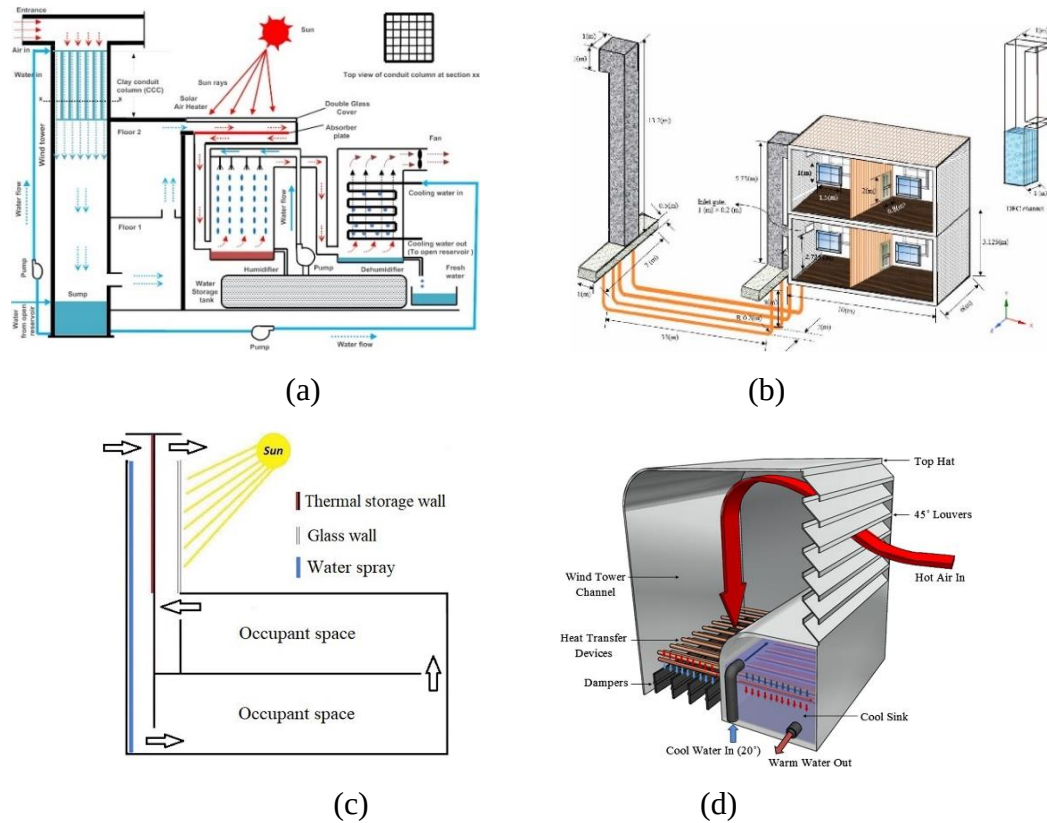


Fig. 5 Diagrams of the selected cooling enhancement technologies for windcatchers: (a) wetted columns [14]; (b) EAHE and water tank [45]; (c) solar chimney and water spray [43]; (d) heat pipes and water tank [18]

Table 2 summarises different cooling techniques combined with windcatchers in the selected papers. Windcatchers, when combined with cooling technologies, are expected to achieve effective ventilation and cooling, thereby reducing failed or unsatisfactory ventilation under unfavourable weather conditions. However, there are also some disadvantages. For example, water spray may not be suitable for water-stressed areas. Mould or bacteria can develop more easily on wet surfaces. EAHE may result in high pressure drop and require high airtightness.

Table 2 Different cooling enhancement techniques combined with windcatchers

Techniques		Ref	Methodology	Cooling potential
Water evaporation	Water spray	[17]	CFD	The average indoor temperature can be reduced by up to 17.13 °C.
		[19]	CFD	The temperature inside the building can be reduced by up to 17.4 °C.
	Wetted surface	[15]	Mathematical modelling	A 5 m-height-column can reduce the indoor air temperature by 29% and increase the

	s/columns/pads			relative humidity by 40%.
		[16]	Field test	An average temperature drop of 14.6 °C and a 57.5% increase in relative humidity can be obtained.
	Underground water tank	[40]	CFD	The inlet air temperature can be reduced by 15.4 °C, and the relative humidity can be increased by 52%.
EAHE		[43]	Mathematical modelling	The supply air temperature can be reduced by 12.5-20 °C.
		[48]	Field test	The indoor temperature can be reduced by up to 12 °C.
Heat pipes		[18]	CFD, wind tunnel and field test	The indoor temperature can be reduced by 12 °C.
		[21]	CFD and wind tunnel test	The indoor temperature can be reduced by 10 °C.
PCM		[44,45]	Laboratory experiment	A full cover of PCM can achieve a temperature reduction of 3.61 °C.
Solar chimney and water spray		[46]	CFD and laboratory experiment	The temperature in the occupied space can be reduced by up to 5.2 °C, and a 9 ACH ventilation rate can be provided during peak hours, which can reduce 75% of the cooling load and 90% of the ventilation energy cost.
Solar chimney		[47]	Theoretical calculation	At a wind speed of 1 m/s, the combination of the solar chimney can improve ACH from 35 to 73.

2.2.2 Windcatchers integrated with heating techniques

The use of windcatchers in cold/mild-cold climates is limited due to significant ventilation heat loss, which can increase buildings' heating loads and lead to thermal discomfort [49,50]. To address this limitation, studies have explored integrating heat recovery devices into windcatchers to improve their applicability in mild-cold climates. Various heat recovery methods, including heat pipes [51], rotary thermal

wheels [52], fixed plate heat exchangers [53], and tube heat exchangers [54], have been proposed for combination with windcatchers, some of which are illustrated in Fig. 6.

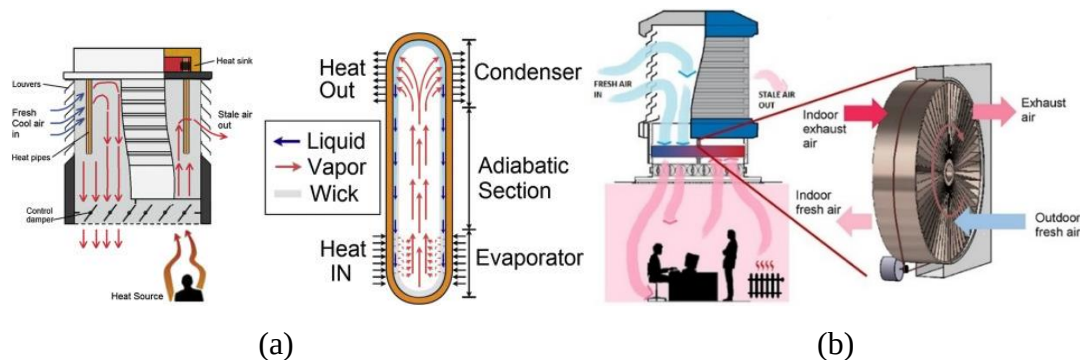


Fig. 6 Schematic examples of heating technologies combined with windcatchers: (a) heat pipes [21]; (b) rotary thermal wheel [46]

Table 3 summarises the heat recovery technologies combined with windcatchers in the selected papers. Windcatchers equipped with heat recovery techniques can improve the supply air temperature and reduce ventilation heat loss. However, the addition of heat recovery devices can generally lead to higher airflow resistance and potentially poor indoor ventilation. Heat recovery units, such as rotary thermal wheels, may cause air cross-contamination and are not suitable for places with high IAQ requirements, such as hospitals and food factories.

Table 3 Different heating techniques combined with windcatchers

Ref	Combined technology	Methodology	Main conclusions
[3]	Rotary wheel	CFD and wind tunnel test (1:10 scale)	A fresh air supply rate higher than 10 L/s/person can be provided at wind speeds as low as 1.5 m/s. The indoor temperature can increase by up to 3.7 °C. However, the indoor average velocity can be reduced by 4% as the rotation speed increases from 0 to 25 rpm.
[52]		CFD and wind tunnel test (1:10	The supply temperature can increase by up to 3 °C, which can save 20% on

		scale)	heating costs. A pressure drop of up to 45.4 Pa was observed across the rotary wheel at an inlet air velocity of 10 m/s.
[51]	Heat pipe	CFD and full-scale wind tunnel test	The supply air temperature can be increased by 2.8 °C, and the heating energy demand can be reduced by up to 860.7 W. The ventilation rate requirement of 8 L/s/person cannot be satisfied at an inlet speed of 1 m/s or lower.
[2]		CFD and wind tunnel test (1:10 scale)	The supply air temperature can be improved by 4.5 K, but the ventilation rate can be reduced by 8%-17%.
[53]	Plate heat exchanger and water drop spray	CFD and laboratory test (1:16 scale)	Under the combined effect of the plate heat exchanger, solar radiation and air humidification, indoor thermal comfort levels of 21.7% in winter and 12.4% in summer can be achieved.
[54]	Tube heat exchanger	CFD	The supply temperature can increase by up to 6.4 °C, depending on the external wind speeds. However, the ventilation rate requirement can only be met at a wind speed of 3 m/s or higher.

2.2.3 Windcatchers integrated with dehumidification techniques

The role of dehumidification in windcatchers is also important. High humidity levels along with moderate to high air temperatures may cause discomfort among occupants, as the high humidity can hamper sweat evaporation from human skin [55]. Prolonged exposure to such conditions can also foster the growth of mould inside windcatchers, especially for those using water evaporation cooling technology, which can pose risks to human health [56]. This issue could be more significant in tropical and subtropical coastal cities [57].

To address the limitations of windcatcher dehumidification, O'Connor et al. [58] proposed a solution involving a desiccant rotary wheel with radial plates coated in

desiccant silica. CFD simulations and lab experiments have demonstrated that this approach can achieve a moisture adsorption rate of up to 65% for the incoming airflow. However, [58] did not evaluate the adsorption and desorption performance of silica gel particles over a long period of time. The dehumidification unit was not fully integrated into a windcatcher, and its impact on ventilation rate, air quality, and energy performance was unclear.

Other dehumidification methods include the use of solid desiccants (e.g., silica gel, alumina) or liquid desiccants (e.g., bromide solution), as well as electrochemical and membrane separation techniques [59]. It should be noted that many studies have identified several common challenges with current dehumidification technology: (1) significant pressure drops, which can increase by up to 100 Pa [59]; (2) high regeneration temperatures ranging from 80 °C to 120 °C [60]; (3) other constraints including limited water sorption capacity, long-term stability, adsorption/desorption kinetics and high cost [61,62]. The above discussions regarding concerns about dehumidification technologies also raise doubts about their compatibility with windcatcher systems. One key concern is that the additional pressure drop resulting from the dehumidification device may reduce overall ventilation efficiency. Second, high regeneration temperatures may require additional energy input to maintain continuous effective dehumidification. Third, other factors, such as the limited water absorption capacity of the current desiccant materials and the ease of integration, may further offset the energy-saving benefits of windcatchers. In the work of [58], the exhaust stream temperature used as the regeneration temperature in the rotary desiccant wheel was not high enough, and additional energy was required to drive the motor. While solar energy could be used to partly compensate for the energy consumption, it may complicate the system. Other methods, such as liquid desiccants, could be more effective but are also more complex and may require more maintenance. These challenges may have kept dehumidification technology from receiving widespread interest for windcatchers. Achieving the goals of low cost, simple structure, high durability, and improved adaptability in windcatcher dehumidification remains a significant challenge.

2.3 Performance evaluation of windcatcher ventilation

Section 2.3 highlights the performance evaluation of innovative windcatcher designs. This evaluation covers aspects such as ventilation performance, thermal

comfort, overheating risk, IAQ, energy performance, economic cost, and LCA.

2.3.1 Ventilation performance

Ventilation rate, often measured in L/s/person or L/s per m² of floor area, is frequently used to assess windcatcher performance, indicating the efficiency of outdoor air distribution in occupied spaces [63]. Another common metric is air change rate (ACR) or air changes per hour (ACH) [64].

Numerous studies have been carried out to enhance windcatchers' ventilation rates. For example, Nejat et al. [65] introduced a wing-wall design into a two-sided windcatcher to increase the induced airflow rate and facilitate efficient mixing of the supplied air with indoor air. The results indicated that at a wind speed as low as 0.5 m/s, the proposed windcatcher could provide 180 L/s of fresh air, which exceeds the required ventilation rate specified in ASHRAE 62.1 by at least three times. More recently, Moosavi et al. [46] incorporated a solar chimney and water spray system into a windcatcher, which achieves an average temperature reduction of 5.2 °C and an ACH of 9. Table 4 summarises the reviewed articles focusing on the evaluation of windcatchers' ventilation performance. It is well recognised that windcatchers alone may exhibit inadequate ventilation under low external wind speeds. Therefore, ongoing efforts are being made to optimise the structural design of windcatchers or combine them with additional installations, such as wing walls, chimneys, etc., to address this issue. With the advancements in windcatcher technology to date, modern windcatchers have developed to not only enhance ventilation performance but also improve the indoor thermal environment, as will be discussed in Section 2.3.2.

Table 4 Summary of the reviewed windcatcher studies focusing on ventilation performance

Ref	Windcatcher			Method			Integration	Building scenario	Ventilation standard followed	Key findings
	One-sided	Two-sided	Four-sided	CFD/Theoretical	Wind tunnel test	Field test				
[66]			✓	✓			/	Office	/	Combining the windcatcher with leeward-side windows can improve the ventilation rate.
[67]	✓				✓ (1:40 scale)		/	/	/	The windcatcher with a curved top induced more airflow than the flat (10%) and inclined ones at a 0° wind angle. As the wind angle increased to 60°, the windcatcher with a flat top experienced the highest reduction in airflow velocity (63%), followed by the curved top (54%) and inclined top (35%).
[68]		✓			✓ (1:50 scale)		/	House	/	At a wind speed of 10 m/s, the airflow rate entering the house decreased from 0.015 m ³ /s to 0 as the wind angle increased from 0° to 55°.
[69]		✓		✓	✓ (1:12 scale)		/	Single zone with an opening	/	As the wind angle increased from 0° to 80°, the airflow volume rate induced by the windcatcher with a frontal opening decreased from 0.0103 m ³ /s to 0.0019 m ³ /s. RANS models cannot accurately capture airflow patterns in regions with high flow separation.

[70]	✓			✓			Helical coil heat transfer device	Single zone	/	At wind speeds of 1-4 m/s, the indoor temperature can be reduced by 8.6-14.25 K, and a minimum ventilation rate of 18 L/s can be provided.
[71]			✓	✓			/	Semi-closed courtyard	ASHRAE 62.1-2013	A ventilation rate of 6056 L/s, corresponding to an ACH of 108.62, can be achieved at a wind speed of 4 m/s and a 45° wind angle, which is at least 100% higher than the ventilation rate required by ASHRAE 62.1-2013.
[65]		✓		✓	✓ (1:10 scale)		Wing wall	Classroom	ASHRAE 62.1- 2007	Ventilation rates exceeding three times the ASHRAE 62.1-2007 requirements can be achieved at wind speeds above 0.5 m/s.
[46]		✓		✓	✓ (1:10 scale)		Solar chimney and water spray	Two-story office	/	An average temperature reduction of 5.2 °C and an ACH of 9 can be achieved.
[71]			✓	✓			/	Low-rise house	/	At a wind speed of 3 m/s, the average supply velocity in the windcatcher with a windward window was 79%, 67% and 80% higher than without a window, with a leeward window and with a lateral window, respectively.

2.3.2 Thermal comfort and overheating risk

As described in ASHRAE 55 [7], thermal comfort shows occupants' satisfaction with the thermal environment, which is influenced by factors like thermal radiation, humidity, air velocity, and clothing insulation. The evaluation of thermal comfort is based on both static and adaptive criteria [72]. In the UK, static overheating criteria commonly used are adopted from CIBSE guidelines and Technical Memoranda. According to CIBSE Guide A 2006, for offices, the acceptable indoor operative temperature is 25 °C in the warm summer months [73]. Early CIBSE TM36 states that for offices and schools, the comfortable temperatures for occupants are 25 °C and 28 °C, respectively [74]. In CIBSE Guide J, temperatures above 28 °C should be less than 80 hours of the occupied time in the year [75]. Adaptive thermal comfort criteria are detailed in standards such as ASHRAE Standard 55 [7] and EN 15251 [76].

Many studies have investigated various modifications to windcatchers to enhance thermal comfort in occupied spaces. Abdo et al. [45] introduced the PCM into windcatchers, reducing the average room temperature by 2.5 °C within 25% of the test time. Nejat et al. [77] studied a two-sided windcatcher with a wing wall and identified thermal discomfort at wind speeds below 2.5 m/s. Harrouz et al. [78] proposed integrating a solar chimney and dew point indirect evaporative cooling into a windcatcher, maintaining indoor temperatures within the comfort zone. Sadeghi et al. [79] compared three scenarios for thermal comfort: (a) an isolated windcatcher, (b) a windcatcher at a building complex corner, and (c) a windcatcher surrounded by a building complex. In scenario (c), indoor temperatures were more comfortable than the cross ventilation through windows. For scenario (b), the indoor temperature was within the thermal comfort zone. For scenario (a), when the outdoor temperature reached or exceeded 23 °C, the windcatcher reduced the indoor temperature by 3.19 °C compared to cross ventilation.

Table 5 summarises the windcatcher studies focusing on thermal comfort and overheating risk assessment. It is notable that most of the reviewed studies did not evaluate the potential overheating risk caused by windcatchers. Overheating assessment is particularly important for multi-storey buildings or when integrated technologies reduce airflow rates. Furthermore, many thermal comfort studies have been conducted based on single-ventilated zones or hypothetical scenarios,

highlighting the need for more field experiments to validate these findings. Given global warming trends and extreme weather conditions, it is crucial to evaluate the effectiveness of windcatcher ventilation under such challenging conditions.

Table 5 Summary of the reviewed windcatcher studies focusing on assessing overheating risk and improving thermal comfort

Ref	Windcatcher			Method			Integrati on	Building scenario	Thermal comfort standard	Thermal comfort analysis	Overheat ing criteria	Overheating risk analysis
	One- sided	Two- sided	Four- sided	Theor etical/ model ling	Wind tunnel test	Fiel d test						
[80]			✓			✓	/	Three- story classroom	CIBSE Guide A- 2006	The temperatures in the teaching spaces during the winter were 19-21 °C, which did not meet CIBSE thermal comfort requirements.	BB101- 2006	Indoor temperatures of 28-38 °C could occur at full occupancy, which was outside the thermal comfort zone.
[81]	✓			✓			Solar chimney and water evaporation	Single zone with an opening	ASHRAE Standard 55-2002	At least an 80% range for thermal comfort with an optimal ventilation rate of 414 m ³ /h can be achieved.	/	/
[82]		✓		✓			/	Single zone with an opening	ASHRAE standard - 1985	Optimal thermal comfort was achieved in the windcatcher with a width of 2.5 m. Thermal discomfort may occur when the windcatcher's width is less than 1.5 m.	/	/
[83]		✓		✓			/	Five-storey apartment	EN15251-2007	Under the optimal ventilation strategy, the maximum operating temperature, which remained within the range of 80% to 90% acceptability, was recorded for 1% of the cooling period. The minimum operating temperature, falling within the	CIBSE Guide A-2006	The optimal ventilation strategy resulted in 47% of the cooling period above 26 °C and 17% above 28 °C (overheated).

										80%-90% acceptability range, occupied 48% of the cooling period.		
[77]		✓		✓	✓ (1:10 scale)		Wing wall	Classroom	ASHRAE Standard 55 - 2017/CIB SE Guide A -2006	At wind speeds between 2.5-4 m/s, 50%-80% of the indoor area was within the comfort zone. At wind speeds less than 2.5 m/s, the thermal comfort criteria cannot be met.	/	/
[84]	✓			✓			/	Classroom	ASHRAE Standard 55-2017	Occupants felt neutral and the thermal comfort complied with ASHRAE Standard 55-2017 at wind speeds of 0.1-0.5 m/s.	/	/
[85]	✓			✓			Solar chimney and water spray	Three-story building	ASHRAE Standard 55-2002	The midday temperatures on the first, second and third floors were 304 K, 303 K and 302 K respectively, which met the thermal comfort requirements.	/	/
[19]	✓			✓			Water spray and baffle	Single zone	ASHRAE 55-2020	At a baffle angle of 60°, a water spray of 0.004 kg/s provided indoor thermal comfort from neutral to slightly cool to cool at an outdoor temperature of 39.2 °C and a wind speed of 2.7 m/s.	/	/

2.3.3 Indoor air quality (IAQ)

Besides good ventilation rate and thermal comfort, healthy IAQ is also important and has always been highly valued by nations, especially considering the COVID-19 pandemic and the post-pandemic era [86].

There are 39 main sources of indoor emissions, including formaldehyde, CO, PM_{2.5}, PM₁₀, NO₂, SO₂, ozone, CO₂, airborne bacteria, and visible mould [87]. Measuring the concentrations of these emissions can help evaluate IAQ. It should be noted that CO₂ is not a reliable IAQ metric but indicates ventilation adequacy. Higher indoor CO₂ concentrations at lower outdoor CO₂ levels reflect poorly ventilated rooms and potentially higher levels of indoor pollutant concentrations. Indoor CO₂ concentrations are also associated with occupants' bioeffluents and body odours. Finally, excessive CO₂ levels, such as 800 ppm [88,89] or 1000 ppm [90,91], may reduce the cognitive abilities of exposed occupants and increase the risk of Sick Building Syndrome (SBS) symptoms such as headache, dizziness, and fatigue. However, it has been paradoxical that CO₂ concentrations can influence occupants' health conditions and working/studying performance. Studies have yielded conflicting results on whether CO₂ concentrations can impact occupants' health and performance. Zhang et al. [92,93], for example, stated that 2.5 hours of exposure to up to 5000 ppm CO₂ did not increase the health symptoms reported by the tested people, nor did it reduce their performance on cognitive tests. The inconsistency in these results indicates that more future research should be conducted to clarify the influence of CO₂ concentrations on occupants. From the above discussion, CO₂ can still serve as a tool to evaluate IAQ, but its limitations should be fully understood.

Most studies on the IAQ performance of windcatcher ventilation have focused on CO₂ concentrations. For instance, Mavrogianni and Mumovic [80] found that CO₂ levels in a London school with windcatcher ventilation were below 1500 ppm during the day, with fresh air rates below 8 L/s/person. Abdallah et al. [81] reported indoor CO₂ levels below 1000 ppm in a windcatcher-solar chimney system. Calautit et al. [21] investigated CO₂ levels in a heat pipe-assisted windcatcher, assuming 12 human manikins as CO₂ sources. The average indoor CO₂ levels were below 1000 ppm at wind speeds over 1 m/s. Nejat et al. [77] observed an 8% reduction in CO₂ levels in the windcatcher with wing walls. Liu et al. [94] assessed CO₂ levels in a hypothetical classroom ventilated by a four-sided windcatcher with tube heat

recovery and found that the IAQ met Category I or II criteria under UK climate conditions according to EN 16798-1:2019. It is important to note that the statement claiming that indoor CO₂ concentrations below 1000 ppm indicate good or acceptable IAQ has been controversial. As pointed out by Persily [95,96], ASHRAE [97], Lu et al. [98], Kapalo et al. [99], and Lara-Ibeas et al. [100], indoor CO₂ levels below 1000 ppm cannot guarantee good or acceptable IAQ.

Other parameters used to evaluate IAQ include mean age of air (MAA) and air change effectiveness (ACE). MAA represents the average time it takes for air to move from the supply point to any location within a ventilated space, where lower values indicate better IAQ [101]. ACE is the ratio of nominal time to MAA. Nominal time is the ratio of occupied space volume to the incoming air flow rate, and an ACE equal to or greater than 1.0 indicates perfect air mixing. ASHRAE 129 [102] recommends a minimum ACE value of 0.95 at the breathing height (1.1 m above floor level) to ensure acceptable IAQ. Calautit and Hughes [103] observed that in a single zone ventilated by a four-sided windcatcher at a wind speed of 3 m/s, the average indoor ACE was about 1.0, and the MAA at the breathing height level was 100 s. Ameer et al. [104] indicated that the occupied space with a “narrowed”-type roof resulted in lower MAA and higher ACE for the windcatcher ventilation. Montazeri and Montazeri [105] showed that a single-sided windcatcher was more effective in ventilating a space with a single ceiling opening, resulting in an indoor ACE of 98%. Nejat et al. [77] reported a reduced MAA of 57 s with a two-sided windcatcher and a wing wall. Mohamadabadi et al. [106] measured an average MAA of 66 s for a typical house using windcatcher ventilation in dry summer conditions in Iran.

Table 6 summarises the windcatcher studies reviewed that focused on IAQ evaluation. Whether these studies use CO₂, MAA, or ACE to measure IAQ, they mainly relied on CFD modelling or wind tunnel tests with controlled environmental conditions. In areas with high pollution or population density, the risk of cross-contamination from the outside should not be overlooked, and air purification may be needed. Moreover, future studies could investigate the effects of air pollutants, such as VOCs.

Table 6 Summary of the reviewed windcatcher studies focusing on IAQ evaluation

Ref	Windcatcher			Method			Integr ation	Building scenario	IAQ indicator	Guideli ne	IAQ analysis
	One- sided	Two- sided	Four- sided	Numeric al modellin g	Wind tunnel test	Field test					
[80]			✓			✓	/	Three- story classroom	CO ₂ level	BB101	The monitored classrooms had an average CO ₂ level of no more than 1500 ppm throughout the day, but none of them achieved a continuous ventilation rate of 8 L/s/person.
[81]	✓						Solar chimney	Single zone with an opening	CO ₂ level	ASHRA E Standar d 62.1 (2010)	The optimised system can achieve CO ₂ levels below 1000 ppm during the daytime.
[94]				✓ (full- scale)			Tube heat recovery device	Single classroom	CO ₂ level	EN 16798- 1(2019)	Under the average UK climatic conditions, the CO ₂ levels in the occupied space can reach Category I or II.
[103]			✓	✓	✓ (1:10 scale)		/	Classroom	MAA and MCE	ANSI/A SHRAE Standar d 129- 1997	A MAA of 100 s was obtained in the middle of the 1m-height plane, while a MAA of 200 s was obtained near the walls at a wind speed of 3 m/s. The ACE was between 0.86 and 2.1 at the breathing height, with an indoor average ACE of about 1.0.

[104]			✓	✓	✓ (1:16 scale)		/	Classroom	MAA and ACE	ASHRAE 129 (1997)	The ventilated space with a “narrow”-shaped roof performed best in terms of IAQ, achieving a minimum MAA and maximum ACE in compliance with ASHRAE 129.
[105]	✓	✓		✓			/	Single zone with openings	ACE	/	The combination of the windcatcher and a ceiling opening in the occupied space achieved a maximum ACE of 98% indoors.
[21]	✓			✓	✓ (1:10 scale)		Heat pipes with extended surfaces	Classroom	CO ₂ level	ASHRAE Standards 62.1	The average indoor CO ₂ levels were less than 1000 ppm at wind speeds above 1 m/s and outdoor CO ₂ levels of 250-350 ppm.
[77]		✓		✓	✓ (1:10 scale)		Wing wall	Classroom	MAA	ASHRAE Standard 55/CIBSE Guide A	At wind speeds higher than 2.5 m/s, the MAA was below 100 s. The worst-case scenario occurred at a wind speed of 0.5 m/s, with the MAA peaking at 679 s, indicating potential risks of poor IAQ.
[106]			✓	✓	✓ (1:25 scale)			A parlour and a courtyard	MAA and ACE	ANSI/ASHRAE Standard 129-1997	The average MAA at the breathing height was 66 s. The ACE was greater than 0.95 at the wind angles of 0°-135°, indicating an acceptable IAQ.

2.3.4 Energy performance

Windcatcher energy performance can be evaluated based on its potential for providing free cooling or heating and electricity savings. According to Moosavi et al. [46], energy savings are equal to the ratio of the free cooling capacity provided by the windcatcher to the overall cooling load required. It was found that by incorporating a solar chimney and a water spray system, the windcatcher could achieve significant cooling energy savings of up to 75% during the peak cooling season in warm and arid climates. Ji et al. [105] examined the energy-saving potential of the four-sided windcatchers in various Chinese cities during months with average outdoor temperatures ranging from 20.73 °C to 33.13 °C. The results indicated cooling energy consumption reductions of 35% and 28% in Harbin and Beijing, 13% and 15% in Shanghai and Chongqing, and 8% in Guangzhou, respectively.

Benhammou et al. [107] studied the energy performance of a windcatcher integrated with the EAHE, finding a daily cooling capacity of 30.7 kWh with a 70 m duct. Increasing the duct diameter from 20 to 60 cm enhanced the daily cooling capacity from 13.08 to 89.59 kWh. Nejat et al. [77] demonstrated that a two-sided windcatcher with wing walls can provide free cooling power of up to 9.6 kW in Malaysia's climate. Gilvaei et al. [108] evaluated the energy savings achieved by a windcatcher, EAHE, and evaporative cooling system in a two-story apartment. Compared to the split inverter and evaporative cooler, the proposed windcatcher system can reduce the cooling load of 0.0194 kWh/m² and 0.0081 kWh/m², respectively. The annual electricity savings can be reduced by 20.952 kWh/yr.m² and 8.748 kWh/yr.m², respectively.

Table 7 provides an overview of windcatcher energy-saving performance in various climates. Due to the climate-dependent nature and different criteria used, it is challenging to compare the windcatcher energy performance across all the studies. From Table 7, it can be observed that under favourable weather conditions, windcatchers can offer effective ventilation and reduce the cooling load of buildings. However, many of the studies have relied on numerical/analytical modelling or laboratory experiments, which involved various assumptions or controlled environmental conditions. More in-depth and long-term field studies on windcatcher energy savings across different climate zones should be conducted. Factors such as

surrounding contexts and dynamic wind patterns should be further considered when evaluating windcatchers' energy performance.

Table 7 An overview of the energy savings by using the windcatchers across different climates

Ref	Location	Climate	Key findings
Ji et al., 2012 [105]	(1) Kunming and (2) Guangzhou, China	(1) Temperate highland tropical; (2) humid subtropical	64% and 8% of the free cooling load can be provided in Kunming and Guangzhou, respectively, across the spring, summer, and autumn seasons.
Benhammou et al., 2015 [107]	Algeria	Hot and arid	An annual free cooling capacity of 333.14 kWh can be provided.
Moosavi et al., 2020 [46]	Tehran, Iran	Arid and semiarid	A free cooling capacity of 1612 kWh (75%) can be provided during the typical occupied hours (8am-5pm) in the cooling season.
Calautit et al., 2020 [3]	UK	Humid, temperate, and oceanic	The heating energy can be saved by up to 45% over a 5-hour period at wind speeds of 1-4 m/s and an outdoor temperature of 10 °C.
Nejat et al., 2021 [77]	Malaysia	Hot, humid, and tropical	The free cooling power ranged from 1 to 9.6 kW at outdoor temperatures of 23 °C and from 0.2 to 1.6 kW at outdoor temperatures of 28 °C, both at wind speeds ranging from 0.5 to 4 m/s.
Gilvaei et al., 2022 [108]	/	/	The electricity consumption can be reduced by 0.0194 kWh/m ² and 0.0081 kWh/m ² , respectively, compared to the split inverter and evaporative cooler.
Liu et al., 2022 [54]	UK	Humid, temperate, and oceanic	The estimated heating energy demand can be reduced by 76% at a wind speed of 5 m/s and an outdoor temperature of 5 °C.

2.3.5 Economic analysis and life cycle assessment (LCA)

Economic analysis and life cycle assessments (LCAs) of windcatcher ventilation systems are critical for assessing their long-term cost-effectiveness. However, academic literature on these topics is very limited. Mostafaeipour et al. [109] compared the annual cost of owning, operating, and maintaining an underground warehouse with an absorption chiller and a windcatcher, respectively. The annual cost of the warehouse with the absorption chiller was 184% more than that of the windcatcher. Goudarzi et al. [110] demonstrated that using windcatchers in residential buildings located in an arid Köppen climate zone led to energy cost savings of 16,371 USD and a life cycle cost (LCC) of 876 USD over a 20-year period. The study indicated that the construction, operation, and maintenance costs of the windcatcher accounted for only 5.5% of its energy cost savings.

Despite these insightful studies, the overall body of research conducting economic analysis and LCAs of windcatchers remains significantly underdeveloped. This gap in the literature requires further in-depth investigations to provide a more comprehensive understanding of the economic and environmental implications of windcatcher ventilation systems. The economic analysis of windcatchers can be approached through several performance indicators, including life cycle cost (LCC) [111], simple payback period (SPP) [112], discounted payback period (DPP) [112], net present value (NPV) [113], and internal rate of return (IRR) [114], as summarised in Table 8. LCC provides a holistic view, while SPP and DPP offer insights into the payback period. NPV and IRR consider the time value of money and profitability. Policymakers may use a combination of these indicators to make well-informed decisions about windcatcher installations based on their financial and environmental objectives.

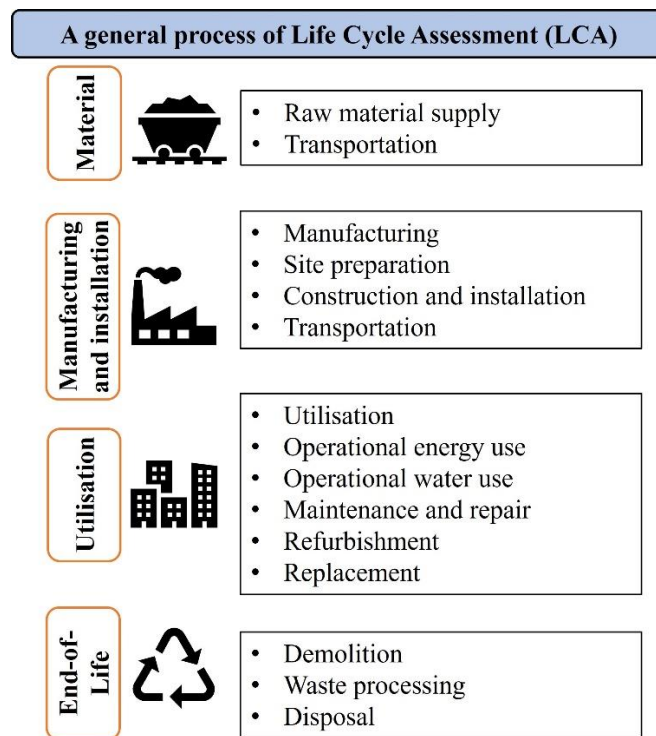
Table 8 Commonly used indicators in economic analysis

Indicator	Definition	Method
LCC [111]	The total costs that encompass the design, construction, operation, maintenance, and end-of-life disposal expenses over the lifetime of a windcatcher.	$LCC = I + Repl + E + EOL$ Where, I=Investment costs, Repl=Replacement costs, E=Operational energy costs, EOL=End-of-life costs.
SPP [112]	The time it takes for the initial investment in the windcatcher	$SPP = \text{initial investment} / \text{net cash flows per period}$

	system to be recovered through cumulative energy savings and other financial benefits.	
DPP [112]	The time it takes for cumulated discounted net cash flows to offset the initial investment of installing windcatcher systems.	$DPP = \frac{\ln\left(\frac{I_0 \times (r - d)}{C_s} + 1\right)}{\ln\left(\frac{r + d}{r - d}\right)}$ Where, I_0, r, d and C_s are initial investment cost, inflation rate, discount rate and cost savings, respectively.
NPV [113]	The difference between the present value of cash inflows and the present value of cash outflows over a period of time. It helps assess whether the benefits, such as energy savings and improved indoor air quality, outweigh the initial investment and ongoing operational costs associated with windcatcher systems.	$NPV = \sum_{i=1}^n \frac{C_i}{(1+r)^i} - TIC$ Where, C_i is the net cash flows in the year i, r is discount rate, TIC is total investment cost.
IRR [114]	This metric estimates the profitability of potential investments in windcatcher systems. IRR is a discount rate that makes the net present value (NPV) of all cash flows equal to zero in a discounted cash flow analysis.	$0 = NPV = \sum_{i=1}^n \frac{C_i}{(1+IRR)^i} - TIC$ Where, C_i is the net cash flows in the year i, TIC is total investment cost.

To comprehend the environmental footprint of windcatcher systems, a LCA can be conducted. A LCA involves evaluating environmental impacts and resource usage throughout a windcatcher's entire lifecycle, from raw material sourcing, manufacturing, utilisation, to waste management [115,116], as illustrated in Fig. 7a. Other similar evaluation tools, including Environmental Impact Assessment (EIA), Strategic Environmental Assessment (SEA), and Environmental Risk Assessment (ERA), could also be applied [117]. These evaluation tools play an important role in facilitating informed decision-making and promoting the environmentally sound

deployment of windcatcher technology. Fig. 7b shows a brief description of the EIA evaluation tool [118]. EIA is a systematic process for evaluating the potential environmental impacts associated with the planning, development, and execution of windcatchers. This evaluation aims to identify any adverse effects on the natural environment, local communities, and ecosystems that may result from windcatcher installations. While LCA aims to understand the overall life cycle impacts, EIA focuses more on assessing site-specific effects to ensure that windcatcher installations align with the environmental and social characteristics of the chosen site.



(a)

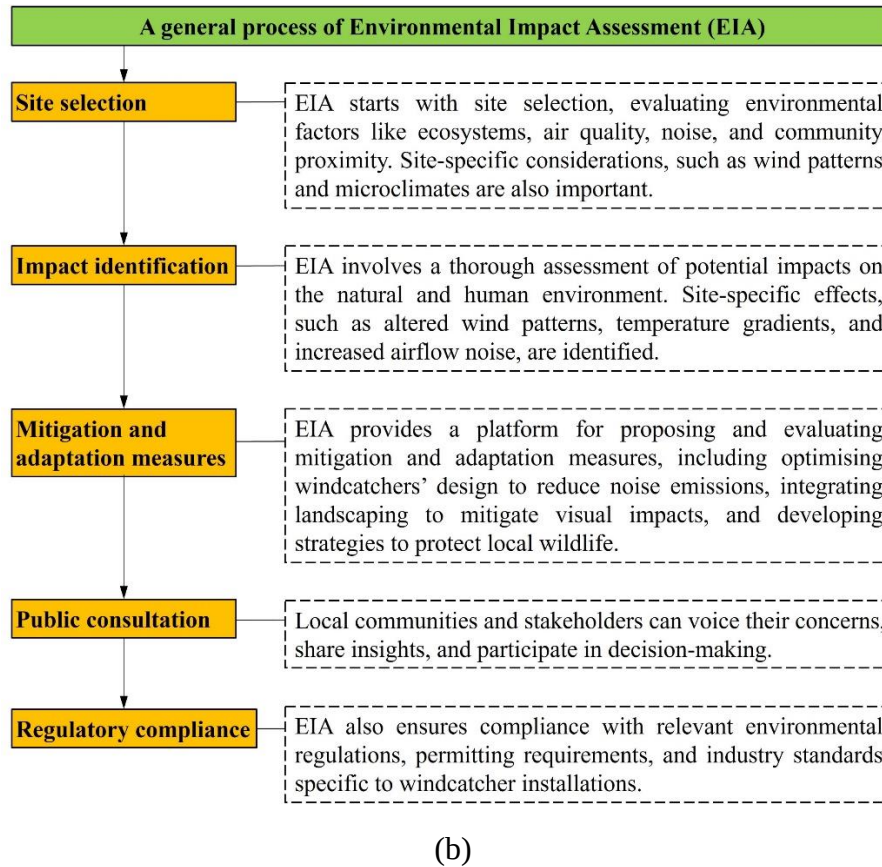


Fig. 7 A brief description of the environmental impact evaluation tools: (a) LCA (adapted from [116]) and (b) EIA (adapted from [118])

2.4 Commercial applications and case studies

Windcatcher ventilation deals with various aspects of Sustainable Development Goals (SDGs) [119], including thermal comfort, climate action, good health and well-being and clean energy, all of which are key issues within the UN 2030 Agenda [120]. It is important to explore current and emerging trends in the commercial market regarding windcatcher developments. This section will provide a review of these topics. In the UK, the current market for windcatcher products includes five companies, i.e., Monodraught LTD [121–123], Breathing Buildings LTD [124], Passivent LTD [125], Free Running Buildings LTD [126], and Midtherm Engineering LTD [127].

(1) Monodraught LTD

Monodraught LTD offers five main windcatcher products, i.e., Windcatcher Classic, Windcatcher X-Air, Windcatcher Zero, Sola-Boost Classic, and Sola-Boost X-Air [121]. These products are designed to provide sustainable and low-carbon passive ventilation strategies for new or refurbished commercial buildings like offices,

classrooms, canteens, and lecture halls. Windcatcher X-Air features a double-step louver pattern that allows for maximum ventilation when fully open and provides protection from rain, dust, and insects when closed. To reduce the risk of under-ventilation, Monodraught LTD proposed an enhanced ventilation control system which uses a fan driven by a variable-optimised photovoltaic power supply, as proposed in [122]. The fan speed can be controlled based on the intensity of the light captured on the photovoltaic unit and the indoor temperature [123]. Building upon this principle, Windcatcher Zero, Sola-Boost Classic and Sola-Boost X-Air have been further released.

(2) Breathing Buildings LTD

Breathing Buildings LTD designed a windcatcher called the S-Series, which is specifically suitable for areas with significant internal heat gains. This windcatcher can improve supply air temperature by mixing the cooler outside air with the warmer indoor air, thereby reducing the heating energy load when the windcatcher operates during wintertime [124].

(3) Passivent LTD

Passivent LTD offers a range of windcatcher products, including Airscoop, Airstract iat, Airstract, Hybrid Plus Airstract, and Litevent Airstract Rooflight/Ventilator. Airscoop captures prevailing wind and directs it to the occupied space through four chambers. It provides control over airflow volume, reduces air short circuits, and offers protection against rain/insects/debris. Airstract iAT can improve the buoyancy effect by using internal heat gains to facilitate windcatcher ventilation. Airstract provides night ventilation for buildings, and Hybrid Plus Airstract can be adapted to different modes depending on external conditions. They can provide warm supply air during winter, intensive cooling in summer, and ensure a healthy IAQ. Litevent Airstract Rooflight/Ventilator combines natural ventilation and natural light in one unit, reducing the reliance on artificial lighting and mechanical ventilation [125].

(4) Free Running Buildings LTD

Free Running Buildings LTD developed a multi-directional windcatcher known as FREECOOL, which captures wind at roof levels and provides natural ventilation and cooling to the occupied space. This technology reduces the need for air conditioning and improves buildings' energy rating. Another multi-directional windcatcher designed for building ventilation heat recovery is called FREEHEAT.

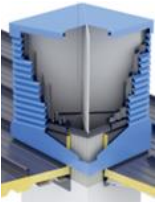
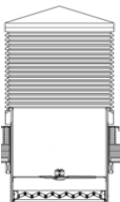
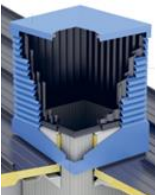
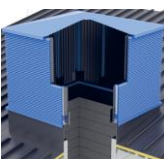
FREEHEAT uses heat pipes to increase the supply air's temperature and can achieve up to 3.4 °C of heat recovery, corresponding to a 20% reduction in heating energy demand [126].

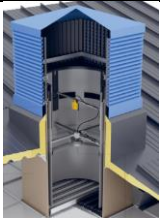
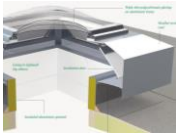
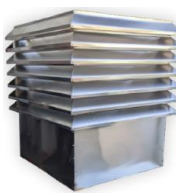
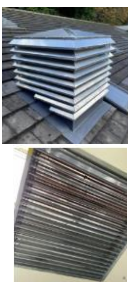
(5) Midtherm Engineering LTD

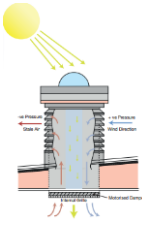
Midtherm Engineering LTD developed the Windvent series products, including Windvent, Windvent SV, Windvent FV and Windvent VL. Windvent has adjustable dampers that allow for airflow control and can facilitate night cooling. Windvent SV incorporates solar panels to convert photovoltaic energy into electrical energy to drive the fan and increase airflow. Windvent FV is combined with hard-wired fans to increase airflow volume. In addition to natural ventilation, Windvent VL can provide natural lighting to further reduce energy demand [127]. Table 9 summarises the main windcatcher products along with their key features currently on the market.

Table 9 Summary of the main windcatcher products and their key features currently on the market

LT D	Windcat cher products	Pictures	Key features	Ref
Mo nod rau ght	Windcat cher classic		• Provides day-time fresh air and night-time cooling. • Low power consumption for damper control. • Compatible with temperature and CO₂ control.	[121 – 123]
	Windcat cher X- air		• Provides day-time fresh air and night-time cooling. • Low power consumption for damper control. • Compatible with temperature and CO₂ control. • Wind load reduction and rain prevention.	
	Windcat cher zero		• Windcatcher classic with counterflow heat exchanger to improve ventilation and thermal comfort. • Solar panel boosted fan can enhance ventilation during low wind speeds.	
	Sola- boost classic		• Provides day-time fresh air and night-time cooling. • Low power consumption for damper control. • Compatible with temperature and CO₂ control. • Solar modules drive fans to enhance ventilation.	

	Sola-boost X-air		• Provides day-time fresh air and night-time cooling. • Low power consumption for damper control. • Compatible with temperature and CO₂ control. • Wind load reduction and rain prevention. • Solar modules drive fans to enhance ventilation. • Additional features include air collectors, relief vanes, and solar lighting.	
Breathing Buildings	S-Series		• S-Series uses hybrid ventilation to preheat fresh air in winter. • Buoyancy effect can facilitate indoor warmer air to escape.	[124]
Passive	Airscoop		• Auto damper control to adjust airflow rates. • Sectional design maximises airflow and minimises pressure drop. • Separated chambers prevent air short circuits. • Dual louvers provide 100% rain protection. • Resistant to 51 m/s wind loads. • Protection against insects and debris.	[125]
	Airsttract iat		• Electrical-controlled dampers control airflow rates. • Intelligent systems-controlled fans to adjust temperature or CO₂ levels. • Dual louvers provide rain protection. • Resistant to 51 m/s wind loads. • Protection against insects and debris.	
	Airsttract		• Resistant to 51 m/s wind loads. • Motorised dampers provide thermal and airtight performance. • Dual louvers provide complete rain protection. • Protection against insects and debris.	
	Aluminium Airsttract		• Suitable for all flat and pitched roofs. • Powder-coated extruded aluminium louvers with a welded aluminium lid for crane access. • Robust two-part wind-resistant construction with motorised dampers. • Available in larger square and rectangular sizes. • Dual bank louvers with rain and insect protection. • Resistant to 51 m/s wind loads.	
	Hybrid		• Recirculation mode provides warm fresh air in	

	Plus Airstract		cooler weather. • Intensive mode for peak summer months to avoid overheating. • Night cooling strategy to reduce thermal mass temperature. • Unaffected by wind direction. • Resistant to continuous wind loads of 51 m/s. • Protection against insects and debris. • Controlled by ventilation control systems.	
	Litevent Airstract Rooflight/Ventilator		• Provides natural lighting. • Insulated aluminium brackets and triple polycarbonate glazing minimise heat loss.	
Free Running Buildings	FREECOOL		• Can work with other heating and cooling systems, reducing the need for air conditioning. • No moving parts, resulting in minimal maintenance requirements. • Easy to install.	[126]
	FREEHEAT		• Reduces air conditioning needs, energy costs, and carbon emissions. • Works well with other heating and cooling systems. • Requires little maintenance and is easy to install.	
Midtherm Engineering	Windvent		• Automatically adjustable dampers. • Control system allows for night cooling with full damper opening.	[127]
	Windvent SV		• PV solar panels power the fan batteries via an internal charge controller unit. • Intelligent control systems regulate solar vents and fan operation, humidity, temperature, air quality, and CO₂ levels.	
	Windvent FV		• Windvent FV and an integral hard-wired fan to increase internal air velocity and improve thermal conditions during summer.	

				
	Windvent VL		• Natural lighting function added to the Windvent. • A low-voltage MID-2012 controller monitors and adjusts the input and discharge ventilation rates accordingly.	

Over the years, these companies have utilised their windcatcher products to develop natural ventilation strategies at various locations, such as Windcatcher X-Air in the Paulton's Family Theme Park [121], Airscoop at the Tesco Ramsey eco-store [125], FREECOOL at the Khalifa International Stadium in Doha, Qatar [126], and Rainbow Windvent Terminals in Castle Hill Primary School [127]. It can be found that windcatcher ventilation is primarily used in commercial buildings (e.g., retail stores, office buildings, and warehouses), institutional buildings (e.g., schools), and recreational buildings (e.g., sports stadiums), which typically have high occupancy rates. High occupancy rates can improve internal heat gains, which contributes to a larger buoyancy effect and facilitates windcatcher ventilation.

To further analyse the performance of windcatchers in the commercial market, the profits of five companies over the years have been discussed here. It was found that Monodraught LTD, one of the most active companies, reported its operating profits (£) during 2015-2019 as follows: 116,723 (2015), 411,327 (2016), 469,545 (2018), 586,937 (2019), with no profit data available for 2017. This data demonstrated a potentially increasing trend in the windcatcher market, especially from 2015 to 2016 (253% increment). However, the operating profits (£) showed a decreasing trend after 2019, with 460,901 in 2020 and 335,417 in 2021. Although these profits are derived from a variety of products associated with natural ventilation/daylight/cooling, they can partially reflect the market response to windcatcher ventilation products. It can be observed that before 2020 (prior to the COVID-19 outbreak), there was a potentially promising market trend for windcatchers. However, from 2020 and onwards, the company's profits have shown a downward trend. The stagnant market of windcatcher adoption in the UK is the reverse of the anticipated growth of global ventilation systems. The global

ventilation system market size stood at USD 27.61 billion in 2022 and is projected to expand from USD 29.65 billion in 2023 to USD 50.26 billion by 2030, exhibiting a compound annual growth rate (CAGR) of 7.8% over the estimated period [128].

Although the reasons behind this trend are complex and multi-dimensional, several potential factors could contribute to this decline:

(1) Lack of awareness and regulatory incentives: many people may not be aware of the benefits and functionality of windcatchers. They may be unfamiliar with the concept and its potential advantages in terms of natural ventilation and energy savings. The COVID-19 pandemic has highlighted the importance of enhanced ventilation to reduce infection risk, and the UK government has emphasised the need to open doors or windows to improve IAQ [129]. However, this method may not be continuously effective, especially for buildings with high occupancy such as retail stores, schools, and sports stadiums, which are at risk of poor ventilation and IAQ. The limited popularity of windcatchers can also be attributed to the absence of regulations or incentives promoting their use. Government policies, building codes, and incentives that prioritise sustainable building practices and energy-efficient solutions can play a crucial role in driving greater adoption of windcatchers. By creating a supportive framework and encouraging their integration into construction projects, these measures can help increase awareness and facilitate the widespread implementation of windcatcher technology.

(2) Cost considerations: the cost of installing windcatchers can pose a challenge, especially for residential buildings, where most installations are for individual homeowners. Depending on the design, materials used, and installation requirements, windcatchers may involve higher upfront costs compared to conventional ventilation systems. Higher initial investments may discourage their adoption, especially if potential users prioritise immediate cost savings over long-term benefits.

(3) Other considerations: the distinctive architectural appearance of windcatchers may clash with the aesthetic preferences of certain individuals or organisations. The prevalence and reliability of established ventilation systems like air conditioning pose a challenge for newer alternatives like windcatchers. Some people may have misconceptions or concerns about the effectiveness or practicality of windcatchers under various weather conditions. Addressing these concerns and misconceptions

would require more significant innovations in the windcatcher commercial market.

To verify the findings regarding the challenges and opportunities observed in the windcatcher commercial market, Table 10 further shows the stakeholders' perceptions of windcatcher use based on a range of surveys and questionnaires. As can be observed, according to Elmualim (2006) [130] and Mavrogianni and Mumovic (2010) [80], summer overheating was highly likely to occur in the educational spaces ventilated by the windcatchers. As further stated by [80], the summer overheating problem observed in the secondary school classrooms can be attributed, in part, to the inappropriate user control of the windcatcher, which was configured in "winter mode". As surveyed in [130], 75% of the participants were supportive of installing windcatchers in buildings. However, the importance of occupant training in understanding and effectively managing windcatcher systems should not be underestimated before their commercial promotion. Routine maintenance and trained teams responsible for windcatcher operations may also be necessary.

In the questionnaires conducted by Foruzanmehr (2012) [131], the primary concerns about windcatchers were their lack of filtration against dust, birds, and insects, followed by cost and limited adaptability to new buildings. Other considerations included low space efficiency, high repair/construction cost, structural weaknesses, noise, and a lack of aesthetic appeal. Mohamed and Nayer (2018) [132] noted that a significant constraint to windcatcher use was the general lack of awareness regarding its potential for providing effective natural ventilation in favourable conditions. In Priya (2019) [133], it was found that 98% and 84% of the surveyed occupants reported feeling comfortable in the windcatcher house during the winter and summer, respectively. However, occupants resorted to using electric fans to lower indoor humidity levels. These observations raise the critical questions about using windcatchers: Are occupants aware of the energy-saving benefits associated with windcatcher use? Can windcatchers effectively mitigate humidity and adapt to different climate zones or types of buildings?

Moreover, Baeumlea and Hunt (2017) [134] surveyed a group of international MA/MSc/MArch student architects regarding their perceptions of designing naturally ventilated buildings, including windcatchers. It was observed that 85% of the students expressed their concerns about pollution and noise when implementing

natural ventilation strategies in buildings, and 70% were worried about stringent building regulations and standards. Clearly defining building codes and standards for the installation and operation of windcatchers could further promote their use in buildings.

Table 10 Stakeholders' perceptions of windcatcher use in a range of surveys/questionnaires

Ref	Location	Scenario	Surveyed month/season	Key findings
Elmualim, 2006 [130]	University of Reading, UK	Seminar room	August	Half of the occupants felt significantly or slightly warm to the indoor temperature, while 41.7% felt neutral.
Mavrogianni and Mumovic [80]	London, UK	Secondary school classroom	July	26% of the occupants felt warm, while 40% felt hot. 33% were dissatisfied with the IAQ, while 75% were pleased with the acoustic comfort.
Foruzanmehr, 2012 [131]	Yazd, Iran	Residential buildings	Summer	Positive comments about windcatchers: (1) cooling and ventilation (33.2%); (2) energy and money saving (22.2%); (3) benefits from "natural" cooling (19.2%); (4) beautiful (16.8%). Negative comments about windcatchers: (1) unfiltered against dust, birds, and insects (33%); (2) costly (11.7%); (3) inapplicable to new buildings (11.4%); (4) low space efficiency (9.5%); (5) ineffective (8.3%).
Mohamed and Nayer, 2018 [132]	Jeddah, Saudi Arabia	Residential buildings	/	83% of the participants were in favour of implementing natural ventilation in buildings. However, only 10% could see the relationship between windcatchers and natural ventilation.
Priya, 2019 [133]	Nagappattinam, India	Residential buildings	May-June (summer); Nov.-Dec. (winter)	High levels of temperature comfort were observed in the windcatcher house during summer (84%) and winter (98%). However, 40%-50% of the surveyed people tended to use fans to reduce air humidity.

Currently, global climate action and the post-pandemic impact have created an opportunity to adopt natural ventilation, such as windcatchers, in buildings to reduce energy use when the weather conditions are favourable. The International Energy

Agency (IEA) issued the “REPower EU” plan to mitigate the impact of fossil energy shortage in Europe [135]. This plan emphasises energy saving and accelerating the clean energy transition. Although the efforts required to achieve these goals are complex and multi-faceted, this policy presents a potential opportunity to promote the utilisation of low-energy products like windcatchers in the building ventilation sector. However, it is crucial to address the potential constraints to fully capitalise on this opportunity.

Overall, this section has covered current and emerging trends in the market and commercial aspects of windcatchers, as well as the potential reasons behind these trends. However, there are some limitations in the discussions. For example, Free Running Buildings LTD and Midtherm Engineering LTD have not provided any profit or loss reports over the years. Passivent LTD officially dissolved in 2021, and Breathing Buildings LTD has been dormant since 2019. Furthermore, the profit reports from Monodraught LTD did not clearly indicate the profitability of the windcatcher products. The lack of detailed and comprehensive data may limit the analysis of the commercial market.

2.5 Summary

Chapter 2 summarises the recent developments of windcatchers with various heating/cooling/dehumidification integrations and identifies the research gaps. The performance evaluation of the existing windcatcher studies has been carried out, focusing on ventilation performance, thermal comfort, overheating risk, IAQ, energy performance, economic analysis, and life cycle assessment (LCA). The challenges and research gaps related to windcatchers’ commercialisation have been detailed.

A Sankey diagram, as shown in Fig. 8, summarises the literature reviewed on windcatcher ventilation, considering different influencing factors. As can be observed, the effects of various structure- and environment-related factors have been widely investigated in windcatcher studies. However, factors such as occupants’ density, activity level, and adaptive behaviour have rarely been studied, even though they are important considerations. In practical applications, it is essential to consider the surrounding microenvironment and building designs/operations. For instance, in areas prone to severe dust storms, preventing dust or other pollutants from entering the windcatchers is essential. Few studies have

considered the entry of rain or snow into occupied spaces. Only several earlier works [77,136,137] have mentioned the rain protection of windcatchers. Moreover, the acoustic comfort and ease of windcatcher installations or integrations have not been thoroughly evaluated. Lastly, modern windcatchers should be equipped with control capabilities that allow for controlled ventilation according to different wind speeds, temperatures, CO₂ levels, etc. Those are typically not covered in previous studies and are suggested for future works. The research methodology has primarily involved numerical modelling and wind tunnel tests, with the building models always being hypothetical or simplified. Conducting field experiments is highly recommended to facilitate more comprehensive and in-depth research into these aspects.

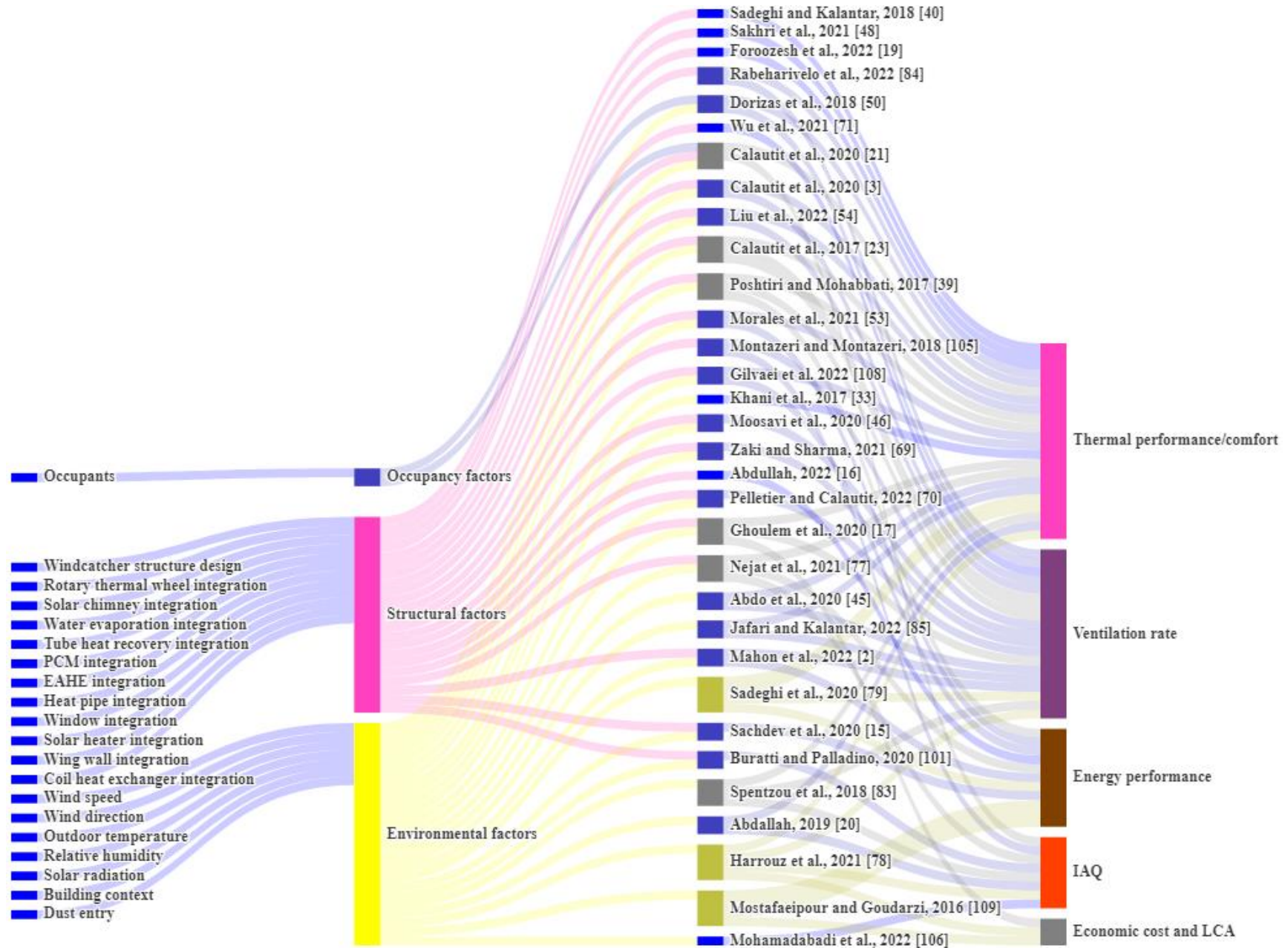


Fig. 8 Sankey diagram about the influencing factors and evaluation indicators in the windcatcher studies during 2017-2022

2.6 Research gap

Windcatchers were originally built for ventilation and cooling in hot regions such as ancient Egypt and Iran. They were designed to capture and direct wind from high locations into the interior, providing free ventilation and cooling. However, windcatchers' usage in low-temperature conditions may cause significant ventilation heat loss and thermal discomfort, which always results in the devices being shut off or left unused. Although some research has introduced heat transfer devices, such as rotary thermal wheels and heat pipes, into windcatchers, no work has investigated simpler types of heat exchange technologies that could reduce costs and operate without using moving parts.

Tube heat exchangers do not rely on working fluid to transfer heat, are easy to operate, do not have moving or rotating parts and are relatively more cost-effective. Therefore, this study proposed a windcatcher incorporating solid tube heat recovery (THR). A validated CFD model was developed against the existing literature [51,138,139]. The proposed windcatcher's performance in ventilation rate, thermal comfort and IAQ was evaluated. The research gaps are identified as follows:

- (1) No investigations exist that have adapted passive tube heat recovery for a windcatcher ventilation system.
- (2) Limited work has evaluated the ability of a windcatcher with passive heat recovery to ventilate, pre-heat and cool spaces, focusing on its year-round operation.
- (3) Very few studies considered the overheating risk in spaces with passive heat recovery windcatchers during summer conditions.
- (4) Limited studies have evaluated ventilation heat loss caused by windcatchers.
- (5) The IAQ performance in the occupied space ventilated by a windcatcher with passive tube heat recovery has rarely been studied.
- (6) Few studies have explored how occupant-influenced variables, such as activity levels, affect windcatchers' performance in terms of CO₂ levels.
- (7) The effects of external CO₂ levels and heating/non-heating seasons on the CO₂ levels in the windcatcher ventilation system are unclear.

Chapter 3 CFD Methodology: Theory and Modelling

CFD is a computational technique employed to simulate fluid flow conditions by iteratively solving partial differential equations. The fluid domain is divided into discrete cells, creating a mesh structure, where these equations are solved to understand fluid behaviour. Data exchange occurs between adjacent cells until a stable solution is reached, indicated by either constant values within the cells or minimal change between iterations. Within this chapter, a concise overview of the theoretical principles underlying CFD modelling is offered, and steps involved in conducting CFD analysis are detailed.

3.1 CFD theory

3.1.1 Governing equations

CFD solvers are responsible for generating solutions to partial differential equations that describe characteristics of fluid flow. In this study, the widely used commercial CFD software, ANSYS Fluent, is employed. The governing equations presented here can be found in the ANSYS Fluent Theory Guide [140]. The mass and momentum equations are solved for all flow types, while the inclusion of the energy equation is necessary to account for heat transfer. The governing equations employed in the CFD model are presented below:

- Continuity equation
- Momentum equation
- Energy equation
- RNG k-epsilon model equation
- Species transport equation

(1) Continuity equation

The continuity equation governs the conservation of mass within fluid flow simulations. It accounts for variations in fluid density and velocity throughout the computational domain. By solving the continuity equation alongside the momentum and energy equations, ANSYS Fluent can predict fluid flow behaviour, ensuring mass conservation at each computational cell. The continuity equation is shown below:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{u}) = S_m \quad (1)$$

Where, ρ is air density, u is the fluid velocity, S_m is the mass added to the continuous phase from the dispersed second phase [141]. The airflow is considered incompressible in this study, so the first term on the left is 0.

(2) Momentum equation

The momentum equation governs the motion of fluid particles within the computational domain. It accounts for the interaction between various forces acting on the fluid, including pressure, viscous forces, and body forces such as gravity. By solving the momentum equation along with continuity equations, ANSYS Fluent can predict fluid velocities, flow patterns, and shear stresses under various flow conditions. The momentum equation is expressed as:

$$\frac{\partial}{\partial t}(\rho \vec{u}) + \nabla \cdot (\rho \vec{u} \vec{u}) = -\nabla p + \nabla \cdot (\bar{\bar{\tau}}) + \rho \vec{g} + \vec{F} \quad (2)$$

Where, p is the static pressure, $\bar{\bar{\tau}}$ is the stress tensor, $\rho \vec{g}$ and $\vec{F}$ are the gravitational body force and external body forces, respectively, which are not modelled in this work [142].

(3) Energy equation

The energy equation plays a fundamental role in simulating heat transfer phenomena within fluid flow problems. The energy equation governs the distribution of thermal energy throughout the computational domain and accounts for various heat transfer mechanisms, including conduction, convection, and radiation. By solving the energy equation along with the fluid flow equations, users can predict temperature distributions, heat transfer rates, and thermal behaviours within complex geometries and boundary conditions. The energy equation is described as:

$$\frac{\partial}{\partial t} \left[\rho \left(e + \frac{u^2}{2} \right) \right] + \nabla \cdot \left[\rho u \left(h_f + \frac{u^2}{2} \right) \right] = \nabla \cdot \left(k_{eff} \nabla T - \sum_j h_j \vec{J}_j + \tau_{eff} \cdot \vec{u} \right) + S_h \quad (3)$$

Where, e is the internal energy; h_f is the fluid enthalpy; k_{eff} is the effective thermal conductivity; T is the air temperature; h_j is the sensible heat of species j and $\vec{J}_j$ is the diffusion flux of species j , which are not modelled in the simulation work; τ_{eff} is the effective stress tensor; S_h includes the heat of chemical reaction, and any other volumetric heat sources that users have defined. S_h describes the internal heat

generation within the computational domain, which is not considered in this work [143].

(4) RNG k-epsilon model equation

The RNG k-epsilon model was employed for the CFD modelling, and the transport equations are shown in Eqs. (4) and (5). Several researchers have demonstrated the superiority of the RNG k-epsilon turbulence model over other models in simulating flow over tube heat exchangers. For instance, Nakhchi and Esfahani [144] found that numerical results obtained with RNG k-epsilon were more accurate in simulating the heat transfer performance of tube heat exchangers. Other studies also showed that the RNG model had higher accuracy in terms of heat transfer prediction [145,146]. Regarding natural ventilation, large eddy simulation (LES) was demonstrated to be more accurate in predicting airflow velocity and volume flow rate, as mentioned by Blocken [147]. However, LES also requires more computational resources and time. Many studies have highlighted that the RNG k-epsilon model improved the calculation efficiency while ensuring simulation accuracy and reliability, making it suitable for various engineering flow problems [148–150]. As for the windcatcher simulation, the RNG k-epsilon model also represented sufficient accuracy when compared with the experimental results [151–153]. Therefore, the RNG k-epsilon model was chosen for this research.

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j} \left(\alpha_k \mu_{eff} \frac{\partial k}{\partial x_j} \right) + G_k + G_b - \rho \varepsilon - Y_M + S_k \quad (4)$$

$$\frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial x_i}(\rho \varepsilon u_i) = \frac{\partial}{\partial x_j} \left(\alpha_\varepsilon \mu_{eff} \frac{\partial \varepsilon}{\partial x_j} \right) + C_{1\varepsilon} \frac{\varepsilon}{k} (G_k + C_{3\varepsilon} G_b) - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k} + S_\varepsilon \quad (5)$$

Where, k is the turbulence kinetic energy; ε is the dissipation rate; G_k represents the generation of turbulence kinetic energy due to the mean velocity gradients; G_b is the generation of turbulence kinetic energy due to the buoyancy; Y_M represents the contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate; the quantities, α_k and α_ε , are the inverse effective Prandtl numbers for k and ε , respectively; S_k and S_ε are the user defined source terms, which are not considered [154].

(5) Species transport equation

The species transport equation governs the advection, diffusion, and reaction of

individual chemical species as they move through a computational domain. It accounts for the convective transport of species due to fluid flow, as well as the diffusive transport resulting from concentration gradients. ANSYS Fluent predicts the local mass fraction of each species, Y_i , through the solution of a convection-diffusion equation for the i th species. The conservation equation for species transport is shown as Eq. (6), which is only switched on when investigating CO₂ transport.

$$\frac{\partial}{\partial t}(\rho Y_i) + \nabla \cdot (\rho \vec{v} Y_i) = -\nabla \cdot \vec{J}_i + R_i + S_i \quad (6)$$

Where, R_i is the net rate of production of species i by chemical reaction. S_i is the rate of creation by addition from the dispersed phase plus any user-defined sources [140].

3.1.2 Flow solvers: solution algorithm

Flow solvers employ various numerical methods, such as finite volume, finite element, or finite difference methods, to discretise and solve the partial differential equations representing the conservation laws of mass, momentum, energy, and species transport. One of the primary flow solvers used in Fluent is the pressure-based solver, which is generally used to simulate incompressible fluid flows. This solver iteratively solves the continuity, momentum, and energy equations coupled with appropriate turbulence models to accurately predict flow behaviour. Fluent also provides density-based solvers suitable for compressible flow regimes, including high-speed and supersonic flows, in which variations in fluid density significantly influence flow behaviour. These solvers solve the compressible Navier-Stokes equations and provide insights into phenomena such as shock waves and boundary layer interactions. In this study, pressure-based solvers are utilised as the air flow is considered incompressible.

Pressure-based solvers can calculate equations using two different approaches. The first approach is the segregated algorithm, where each governing equation is solved sequentially. The second approach is the coupled algorithm, which solves the equations simultaneously. Although the coupled algorithm enhances solution convergence rates, it comes with a higher memory requirement, which can be up to 2-3 times that of the segregated algorithm. In this study, the segregated algorithm was utilised.

As mentioned earlier, the segregated algorithm in pressure-based solvers solves the governing equations in a sequential manner, with the solution from each equation being used in the subsequent calculations. This approach proves efficient in terms of computational memory usage, as only a single equation needs to be stored at a time. However, it leads to longer solution convergence times since each equation is solved individually. Moreover, due to the non-linear nature of the governing equations, iterative loops are necessary until a converged solution is obtained. There are four different segregated pressure-based algorithm solvers in Fluent. SIMPLE (Semi-implicit method for pressure-linked equations), SIMPLEC (SIMPLE-consistent), PISO (Pressure-implicit with splitting operators), and FSM (Fractional step method). The SIMPLE algorithm is adopted in this study. This algorithm utilises the relationship between velocity and pressure corrections to enforce mass conservation and obtain the pressure field. The flowchart of the algorithm is shown in Fig. 8, constituting a single iteration in the workflow.

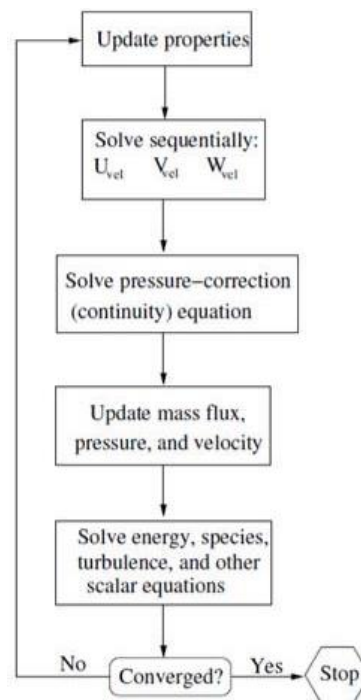


Fig. 8 Pressure-based segregated algorithm flowchart [140]

3.1.3 Solution convergence

The evaluation of solution convergence mainly involves assessing the difference in residuals between iterations. By default, ANSYS Fluent sets a convergence criterion of 10^{-6} for energy and 10^{-3} for the remaining residuals. Ideally, the residuals should

fall below these threshold values, which is generally accepted for most applications to determine convergence. However, it is important to note that reaching the set criteria for residuals still does not guarantee full convergence. Alternatively, a common approach involves monitoring specific parameters relevant to the problem, such as velocity or temperature. If these monitored parameters have reached a plateau, it is acknowledged that the solution has stabilised.

3.1.4 Mesh quality

Ensuring a high-quality mesh is important for obtaining accurate results and reducing computational time. Key factors to evaluate mesh quality include smoothness, skewness, and y^+ values. Skewness is a fundamental metric for assessing mesh quality. In a high-quality mesh, the transition in size between adjacent faces or cells should demonstrate a gradual and smooth change. A skewness value of 0 indicates an equilateral cell, representing the highest quality, while a value of 1 denotes a fully degenerate cell, indicating the lowest quality. Poorly categorised or degenerate cells are typically unacceptable because the equations assume cells are equilateral. Such cells can significantly impact solution accuracy or cause results not to converge. A skewness value of 0.75 suggests fair or acceptable mesh quality, and it is generally recommended that the maximum skewness value should not exceed this value. Another important parameter to assess mesh quality is the boundary layer resolution, also known as the y^+ value. Boundary layer meshes near solid walls are important for accurately modelling near-wall flows. The mesh should have adequate resolutions to capture the boundary layer and resolve flow features within it. Since the flow problem in this research is considered fully turbulent, y^+ values between 30 and 300 are generally acceptable for standard wall functions to capture the turbulent boundary layer profile. For enhanced wall treatment, the y^+ value should be less than 1 to capture flow patterns in the viscous sub-layers [140].

3.2 CFD modelling

The section discusses the creation of CAD geometry and extraction of the fluid domain, along with boundary conditions, mesh generation, and mesh independence analysis. It also includes the validation of the CFD model against existing experimental or numerical data from the literature.

3.2.1 Problem identification

The schematic of the proposed windcatcher system with a solid tube heat recovery (THR) device is shown in Fig. 9a. A four-sided windcatcher was selected as it can catch wind from all directions [31]. The windcatcher was designed with a height of 2.2 m, width of 1 m and length of 1 m. Louvers were located at the openings of the windcatcher, angled at 45° with a regular interval of 0.1 m. The windcatcher was considered fully open, and the dampers at the bottom were not modelled. It was mounted on the roof of a space with a height $\times$ width $\times$ length of 3 m $\times$ 5 m $\times$ 5 m, representing a hypothesised classroom occupied by 15 people. As shown in Fig. 9b, the THR device consisted of 8-layer solid copper tubes in a staggered arrangement. Each tube had a diameter and length of 0.02 m and 1 m, respectively. LP and TP represented the longitudinal pitch and transverse pitch, set at 25 mm and 60 mm, respectively. The dimensions of the solid THR device are presented in Fig. 9c.

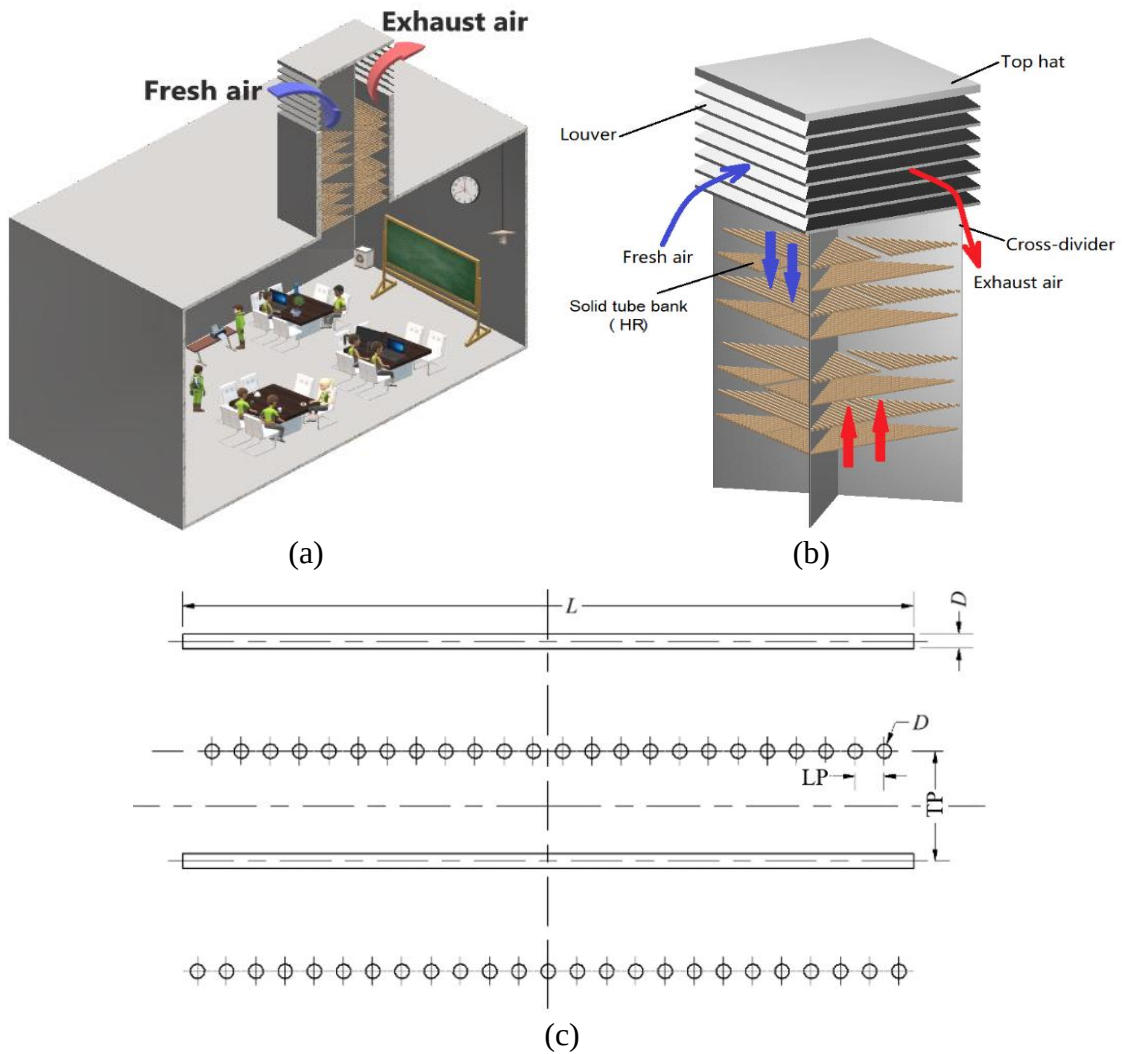


Fig. 9 (a) The schematic of the three-dimensional model of the proposed windcatcher system; (b) the detailed view of the solid THR device; (c) the dimension diagram of the THR device

When optimising and evaluating the ventilation performance of the proposed windcatcher, the outdoor air temperature was fixed at 5 °C, which is a typical temperature during the UK winter [155]. The incoming wind direction was assumed to be perpendicular to the windcatcher's supply quadrant. At a wind angle of 0°, one quadrant serves as a supply quadrant, bringing in fresh outdoor air, while the remaining quadrants facilitate the escape of warm and stale air from the room. As the warm and stale air passes through the solid copper 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.

The introduction of the THR device can potentially reduce ventilation heat loss and recover some of the heat that is exhausted from the windcatcher, which is used to pre-heat the supply air. The present study employed a fluid domain that simulates the wind tunnel experimental set-up in Calautit et al. [138], which allows for a more straightforward validation against the experimental data in [138]. Therefore, the windcatcher ventilation system was located in the middle of the wind tunnel test section (5 m× 5 m ×10 m) with the upstream distance equal to the downstream distance. The dimensions of the geometry are summarised in Table 11.

Table 11 Summary of the geometric dimensions

Parameter	Value
Height, width, and length of the room (fluid domain)	3, 5, 5 m
Height, width, and length of the windcatcher with THR (fluid domain)	2.2, 1, 1 m
Height, width, and length of the wind tunnel (fluid domain)	5, 5, 10 m
Louver angle	45°
Louver height	0.7 m
Louver layers	7

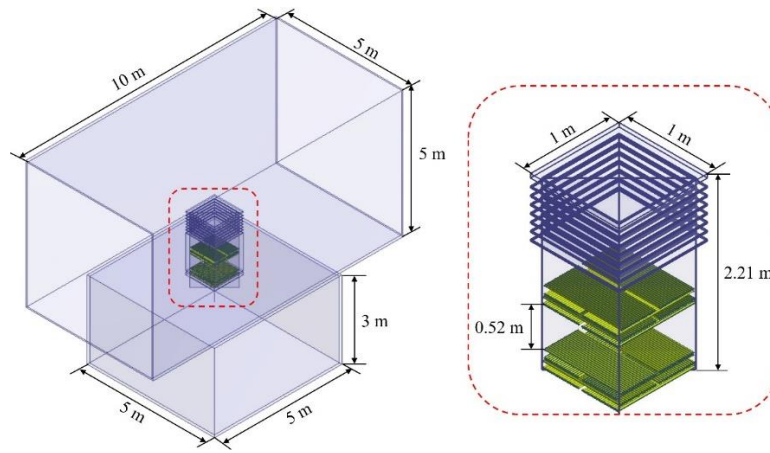
Longitudinal pitch (LP)	25-45 mm
Transverse pitch (TP)	60-180 mm
Tube diameter (D)	20 mm
Tube length (L)	1 m

3.2.2 Computational domain and boundary conditions

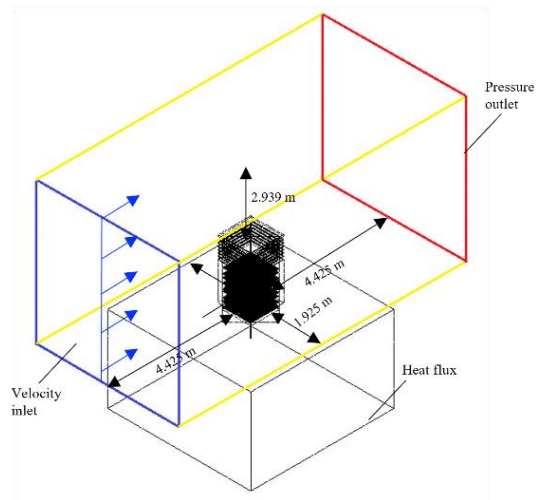
The commercial software ANSYS Fluent (version 18.1) was used to conduct the CFD simulation. Before proceeding with the modelling, several assumptions were made to simplify the simulation [156].

- (1) Flow regimes inside and around the windcatcher system were considered fully turbulent. The wind direction angle was assumed to be constant.
- (2) The fluid domain was considered steady and incompressible. The full buoyancy option was not set for simplification.
- (3) Radiation and infiltration were neglected in this study. The ventilation heat loss was only caused by windcatcher ventilation.

The outdoor airflow with a uniform velocity profile and a constant temperature of 5 °C was set at the inlet of the wind tunnel domain. A pressure outlet was set at the outlet. A heat flux of 30 W/m² was set along the room floor to simulate the effect of the heat gains from occupants, lighting, and equipment in a typical classroom [3]. SIMPLE algorithm was used, and no-slip boundary condition was applied to all walls [138]. The momentum equation adopted the second-order central difference scheme. The equations for turbulent kinetic energy and turbulent energy dissipation rates used the second-order upwind scheme. The RNG k-epsilon model with standard wall function was implemented [157]. Roughness height and roughness constant were 0.001 mm and 0.5, respectively. The computational domain and boundary conditions are shown in Fig. 10. The CFD parameters are summarised in Table 12.



(a)



(b)

Fig. 10 (a) the computational domain and (b) boundary conditions

Table 12 Summary of the CFD parameters [138]

Time	Steady state
Gravity (m/s^2)	-9.81
Turbulence model	RNG k-epsilon
Wall function	Standard
Velocity inlet (m/s)	1-5 (uniform)
Temperature inlet ($^{\circ}\text{C}$)	5
Pressure outlet	Atmospheric
Heat source (W/m^2)	30
Wind direction angle ($^{\circ}$)	0
Wall	no slip
Roughness height	0.001 mm
Roughness constant	0.5

3.2.3 Mesh generation and mesh independence analysis

A 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. Curvature refinement was applied to all surfaces and edges to better capture the airflow characteristics around sharp areas. The mesh growth rate was set to 1.20. The obtained mesh quality was 0.84, with the maximum skewness kept lower than 0.85. The number of mesh elements was 18,642,314. Fig. 11 presents the surface mesh of the louvers and solid tubes.

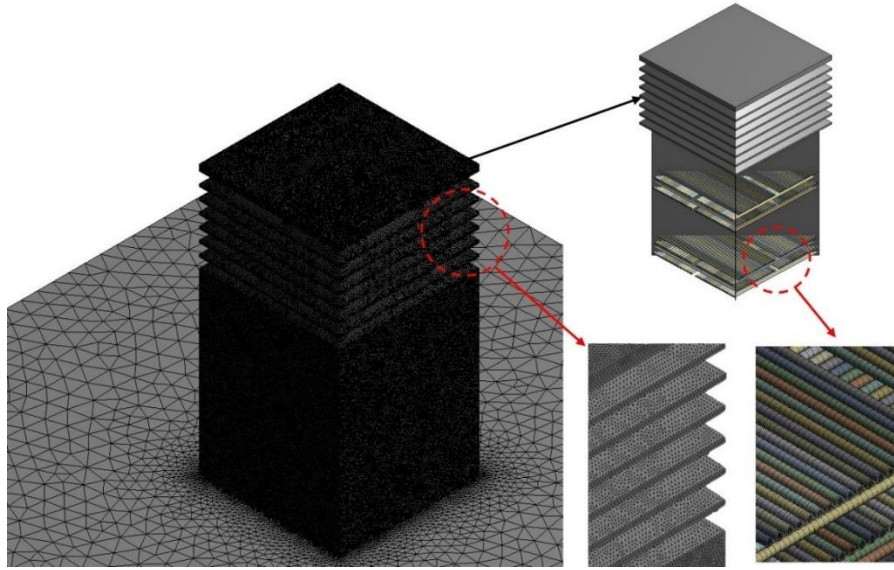
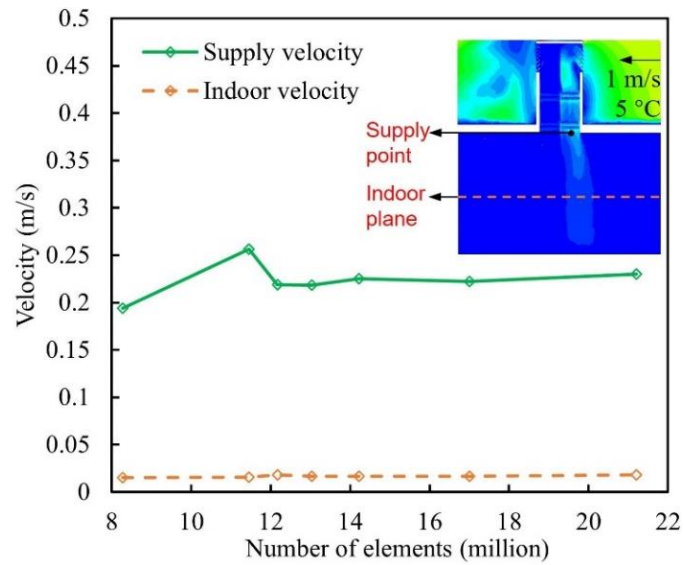
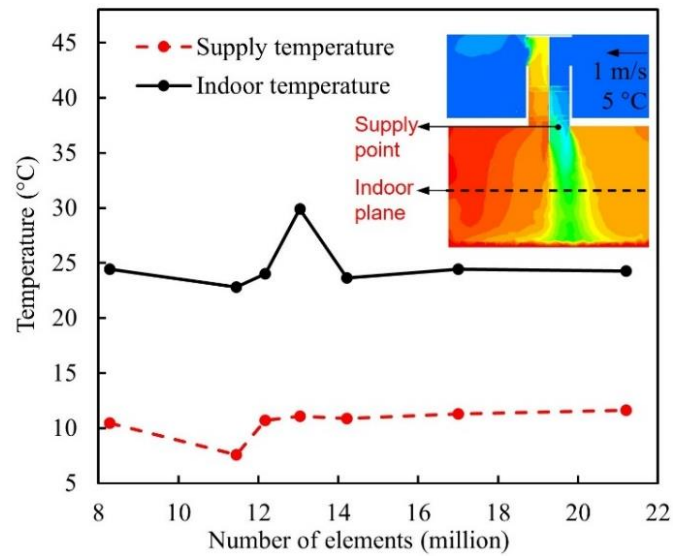


Fig. 11 Surface mesh of the louvers and solid tubes

To minimise the influence of the mesh resolutions on simulation accuracy, mesh independence analysis should be conducted until the difference between the simulation results becomes insignificant. Six different mesh resolutions, ranging from coarse to fine, were tested, and the simulation results are shown in Fig. 12. As can be seen, when the number of elements increased from 14 million to 21 million, the air velocity and air temperature values almost remained unchanged, with a maximum variation of 7%. Hence, the total number of mesh elements used in this study was 17 million. In addition, a y^+ value of 65 was obtained over walls. The log law should be applied to the region corresponding to $30 < y^+ < 300$. The y^+ value in the present work satisfied the requirements [158].



(a)



(b)

Fig. 12 Mesh independence analysis: (a) velocity and (b) temperature

3.3 Summary

This chapter provided the background information on the CFD model applied in this study. It detailed the process and convergence criteria for developing a robust CFD model capable of yielding accurate results. Furthermore, it highlighted the significance of mesh generation and mesh sensitivity analysis while addressing the selection of appropriate solvers and equations for simulation tasks.

Chapter 4 CFD Validation

Before carrying out the modelling work, the CFD model proposed in Chapter 3 should be fully validated to ensure the reliability of the simulation results. The validation proceeded against the experimental work conducted by Calautit et al. [138].

4.1 Validation of the indoor air velocity

Fig. 13 shows the geometry of the standard windcatcher investigated in [138]. As can be seen, the four-sided windcatcher was mounted on the roof of the test room. The windcatcher and room model is then tested in a wind tunnel to explore the airflow patterns.

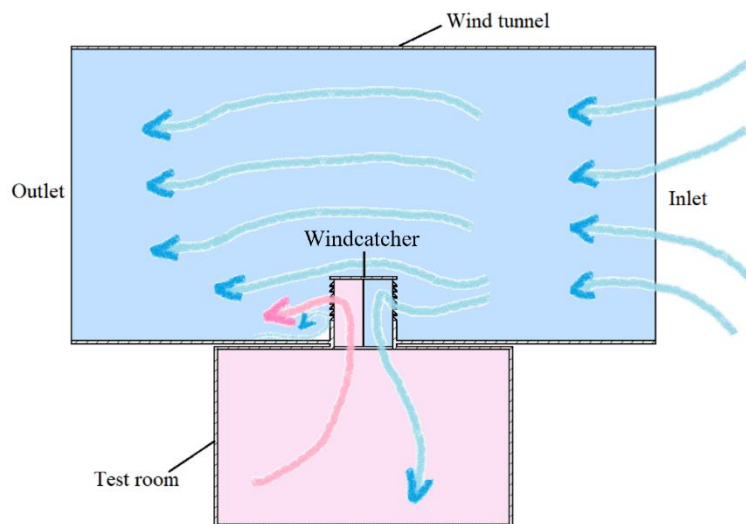


Fig. 13 The geometry configuration of the standard windcatcher [138]

Fig. 14a shows the average indoor air velocity values and contours represented by 9 sample points in the CFD simulation and the experiment conducted by Calautit et al. [138]. A similar overall trend can be observed. The maximum air velocity in the middle of the room was obtained with a value of 1.08 m/s in the simulation and 1.0 m/s in the experiment. Among these sample points, the air velocity at points 4, 5 and 6 in the CFD simulation was consistent with the experimental values. However, CFD slightly underestimated the values of indoor velocity at the remaining six points. Fig. 14b also presented the velocity vectors on the plane of $y=1.55$ m. As can be seen, flow separation mainly occurred around points 1, 2, 3, 7, 8 and 9, resulting in low-speed vortex regions.

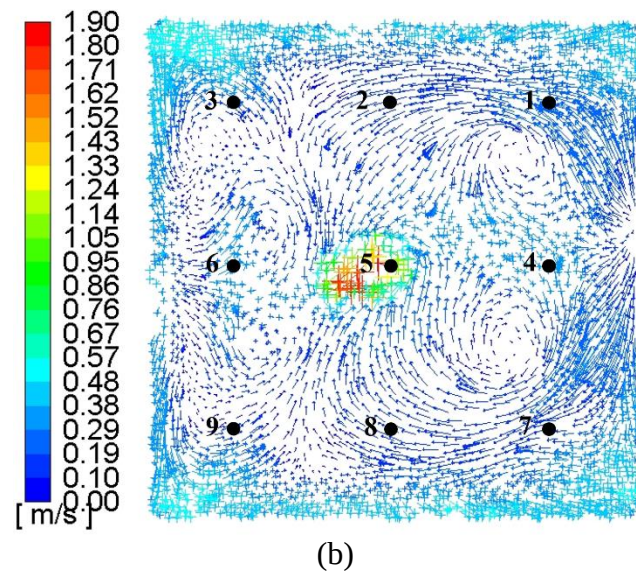
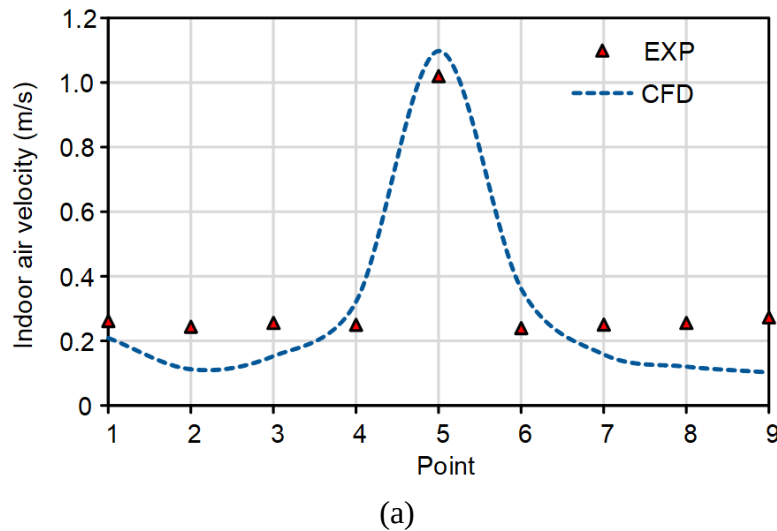


Fig. 14 (a) Indoor air velocity (points 1-9) when the outdoor wind speed was 3 m/s: CFD and experiment [138]; (b) indoor velocity vector ($y=1.55$ m)

Fig. 15a displays the simulated streamline contour in the windcatcher and the ventilated space. Fig. 15b presents the flow pattern observed in the smoke visualisation tests [138]. The overall flow patterns in the CFD simulation and experiment were consistent. As can be seen, the air flowed smoothly around and above the windcatcher. Some of the air entered the windcatcher's supply channel through the louvers and was subsequently directed towards the floor of the room below. As the airflow reached the bottom surface, it slowed down and spread out towards the side walls, creating several regions of low-speed vortices. The discrepancy between the numerical and experimental results can be attributed to the limitations of the RANS model in capturing complex flow phenomena such as jets,

separation, thermal plumes, etc..

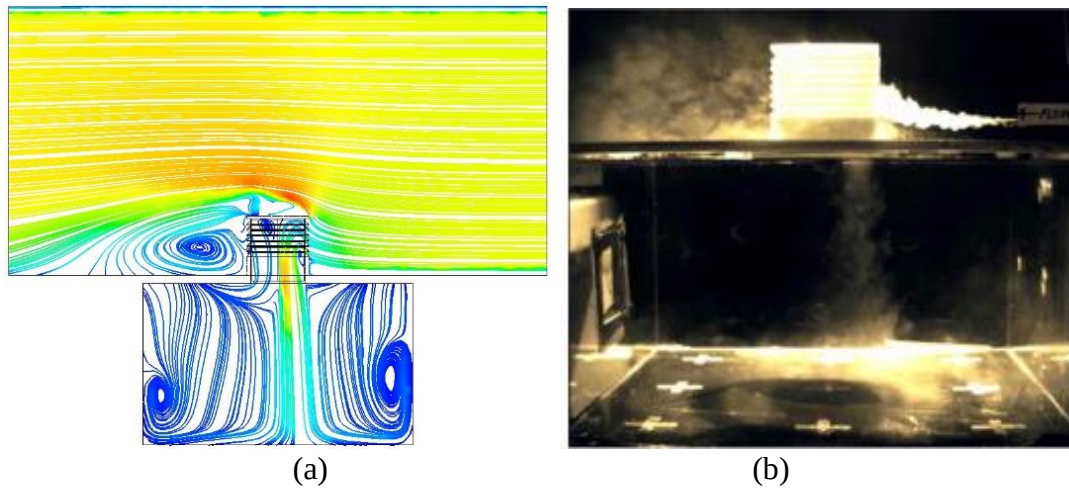
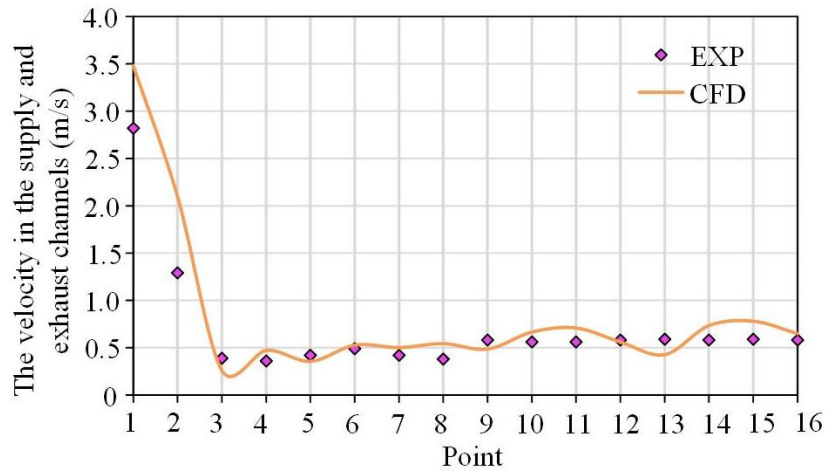


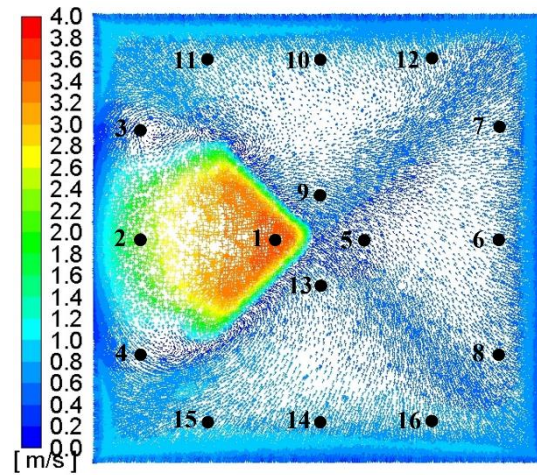
Fig. 15 (a) The CFD streamlines of a cross-sectional plane when the outdoor wind speed was 3 m/s; (b) flow pattern in the smoke visualisation tests [138]

4.2 Validation of the supply and exhaust air velocity

Fig. 16a compares the CFD-predicted supply and exhaust air velocity values with the experimental data measured by Calautit et al. [138]. Fig. 16b shows the velocity vectors in the supply and exhaust quadrants at the plane of $y=3.05$ m. Points 1, 2, 3 and 4 were located in the supply quadrant, while the other three quadrants represented exhaust outlets. The average supply velocity was 1.58 m/s, which was higher than the average exhaust air velocity of 0.58 m/s, at a wind direction angle of 0° and a wind speed of 3 m/s. The airflow patterns presented here were consistent with the findings from the experimental study by Calautit et al. [138]. Overall, the supply and exhaust air velocities in the CFD simulation fluctuated around the experimental results, with an average error of 25%, which is considered acceptable for this type of study [159].



(a)



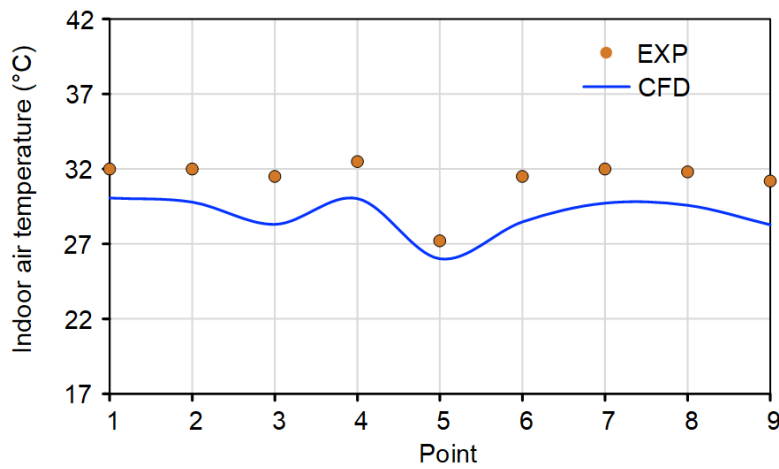
(b)

Fig. 16 The velocity in the supply and exhaust channels when the outdoor wind speed was 3 m/s: CFD and experiment [138]; (b) velocity vector at the supply and exhaust channels ($y=3.05$ m)

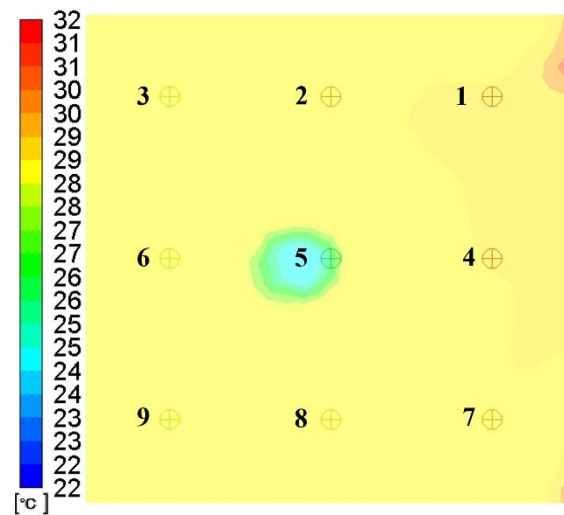
4.3 Validation of the indoor air temperature

Fig. 17a compares the predicted indoor temperature results with the experimental measurements [51]. The indoor temperature results were obtained from the 9 sample points in the plane at $y=1.55$ m, as shown in Fig. 17b. A similar trend was observed between the CFD simulation and experimental results. However, the CFD results slightly underpredicted the experimental results across the 9 sample points, with the temperature difference ranging from 1.2 °C to 3.2 °C. The lowest air temperature difference was observed in point 5, about 26.0 °C in the CFD model and 27.2 °C in the experiment. The differences could be caused by the turbulence model employed, simulation simplification, and the accuracy of the measurement tools in [51]. The environmental conditions in the wind tunnel, such as temperatures and heat sources,

may also be challenging to reproduce. The differences were higher in locations with complex flows or recirculation, which is also similar to the velocity results.



(a)



(b)

Fig. 17 (a) Indoor air temperature (points 1-9) when the outdoor wind speed was 2 m/s: CFD and experiment [51]; (b) indoor temperature contour (y=1.55 m)

4.4 Validation of the full buoyancy effect

Windcatcher ventilation is driven by both wind pressure and buoyancy effect. As described in the simplification, the full buoyancy option was disabled in the present work. This section evaluates the impact of this simplification on the accuracy of the results. Fig. 18 compares the CFD-predicted indoor air temperatures with full buoyancy on and off. From the comparison, it can be found that the full buoyancy option had a slight effect on indoor temperatures, with differences of up to 0.05 °C. Fig. 19 shows the effect of the full buoyancy option on the indoor air velocity values. The effect was also minimal, with differences of up to 0.09 m/s. The findings

indicate that enabling or disabling the full buoyancy effect option does not affect the simulation results for this model setup, which is also consistent with the results from previous works [82,110,160,161]. For example, Hughes and Cheuk-Ming [160] highlighted that the external wind accounted for 76% of the driving force for windcatcher ventilation, while the buoyancy effect was considered a secondary driving force. They also demonstrated that the buoyancy effect was minimal where there was no additional airflow passage other than the windcatcher itself.

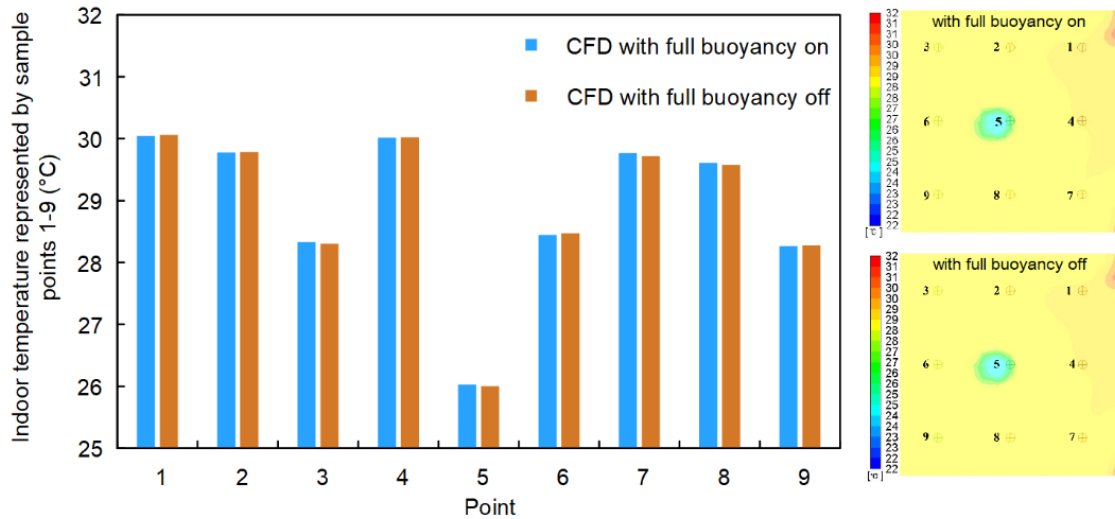


Fig. 18 The effect of enabling the full buoyancy option in ANSYS Fluent on the indoor air temperature (outdoor wind speed was 2 m/s)

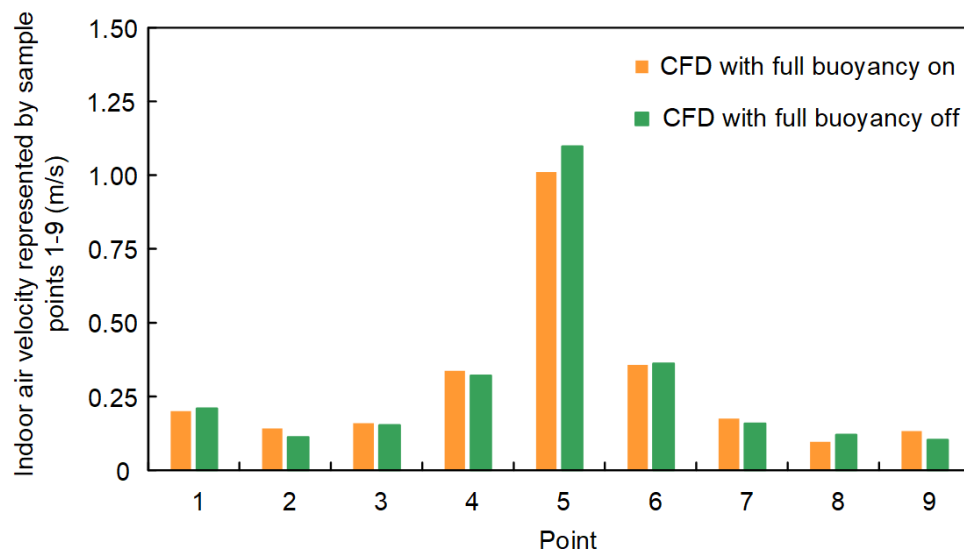


Fig. 19 The effect of enabling the full buoyancy option in ANSYS Fluent on the indoor air velocity (outdoor wind speed was 3 m/s)

4.5 Summary

Validation is necessary to ensure a reliable and accurate CFD model. In this study, the CFD model was validated against the experimental data obtained in [51] and [138]. By comparing the overall airflow velocities and temperatures, it is found that the adopted CFD model can provide accurate simulation results. Furthermore, a detailed analysis was conducted on the impact of enabling and disabling the full buoyancy option. The effect of enabling or disabling the full buoyancy option on the indoor airflow velocities and temperatures is minimal.

Chapter 5 Results and Discussions

The following chapter details the results of the numerical modelling. First, the tube arrangements will be optimised according to the windcatcher ventilation rates and tube thermal performance. Second, the thermal comfort achieved by the optimised windcatcher with THR will be evaluated using the average year-round climatic data in the UK from 1990-2021. The overheating risk during summertime and ventilation heat loss during wintertime will also be discussed. Finally, the IAQ performance in the ventilated space, which is indicated by CO₂ levels, will be analysed. The CO₂ transport from the local environment and released by the human manikins will be investigated.

5.1 Overall airflow distribution

This section compares the airflow velocity, pressure, and temperature distribution between the windcatcher with and without THR. Several sample points were created to measure the airflow velocity and temperature in the supply and indoor measurement points. Table 13 provides the locations of supply sample points.

Table 13 Locations of the supply sample points

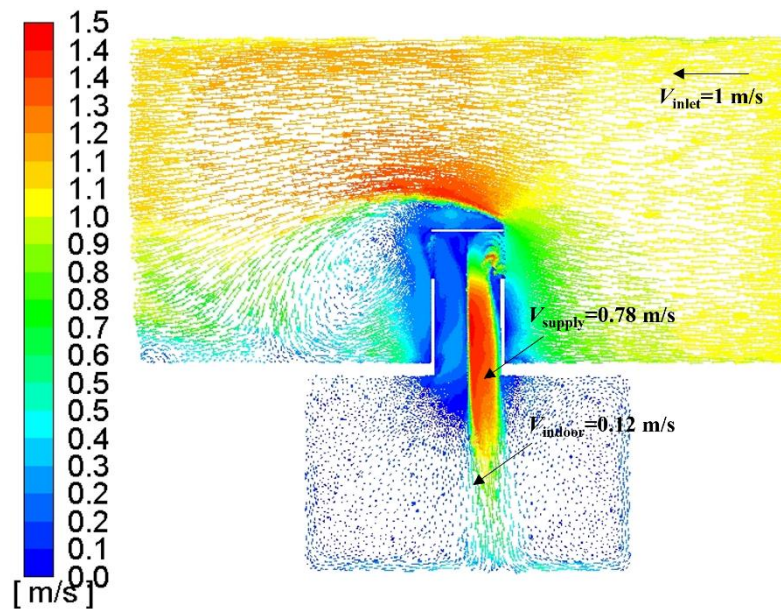
Supply sample points	Coordinates x, y, z (m)
1	(-0.25, 3.085, -0.375)
2	(0, 3.085, -0.375)
3	(0.25, 3.085, -0.375)
4	(-0.125, 3.085, -0.25)
5	(0, 3.085, -0.25)
6	(0.125, 3.085, -0.25)
7	(0, 3.085, -0.125)

5.1.1 Air velocity

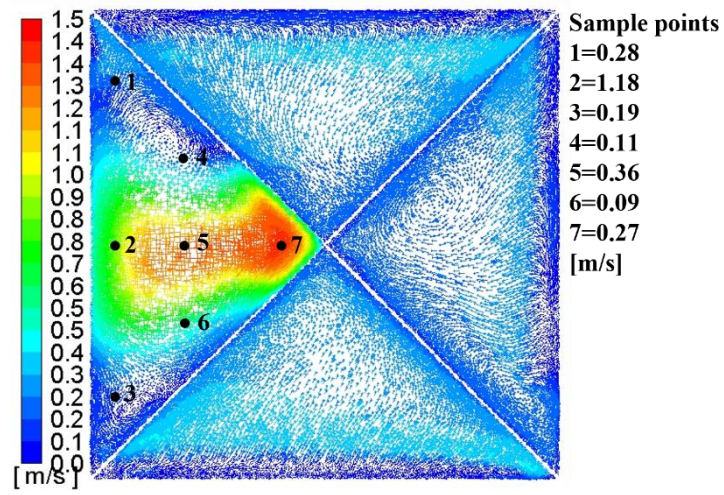
Figs. 20 and 21 show the velocity vectors on the cross-sectional plane ($x=0$) at the middle of the ventilated room, as well as at the supply and exhaust quadrants, for the windcatcher with and without THR at a wind speed of 1 m/s. As shown in Fig. 20a, part of the inlet air flows over the top of the windcatcher, generating a low-speed

vortex zone on the windward side. Some of the air flows into the windcatcher through the openings with louvers. The airflow gains speed along the windcatcher's shaft, reaching up to 1.2 m/s. Upon entry into the room below, however, its velocity gradually diminishes, leading to an average indoor air velocity of 0.12 m/s. Overall, the wind speed in the middle of the room is the highest, whereas it significantly decreases near the walls due to flow separation.

As shown in Fig. 20b, one quadrant in the windcatcher supplies fresh air, while the other three quadrants discharge exhausted air. The average supply air velocity is 0.78 m/s, indicating that the ventilation rates may not reach the required value. This highlights one of the limitations of windcatcher ventilation during windless days. A similar overall velocity distribution can also be found in the windcatcher with THR (Fig. 21), but it is clear that the supply and indoor air velocity are reduced to 0.22 m/s and 0.02 m/s, respectively. This is because the addition of the THR device leads to an increase in airflow resistance. It underscores the importance of conducting detailed site investigations and evaluating average/prevaling wind speed levels to minimise the limitations when employing the proposed windcatcher.

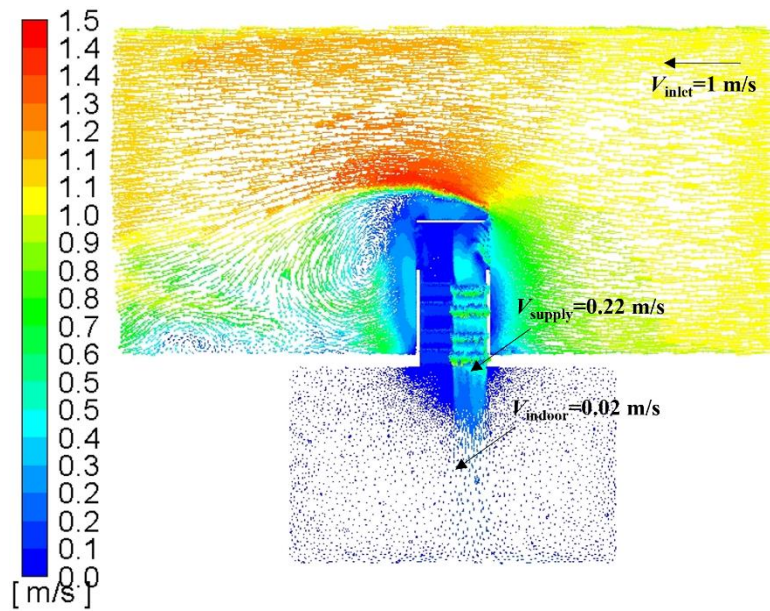


(a)

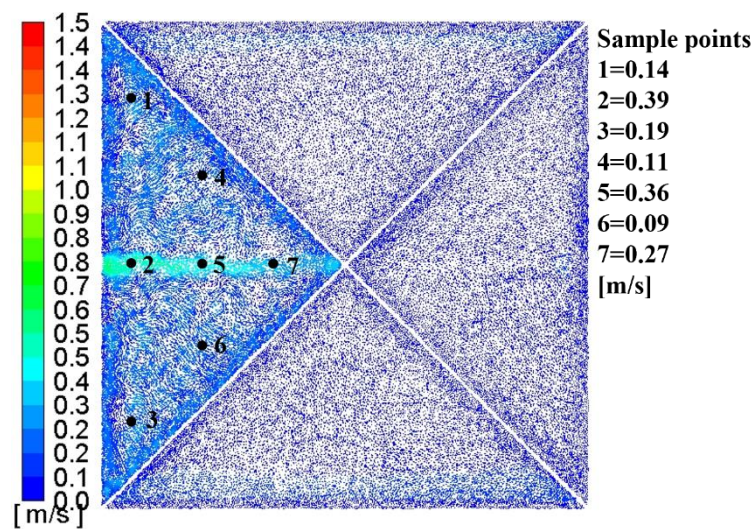


(b)

Fig. 20 Velocity vectors in the windcatcher without THR at an inlet velocity of 1 m/s: (a) the cross-sectional plane ($x=0$) and (b) the supply channel



(a)



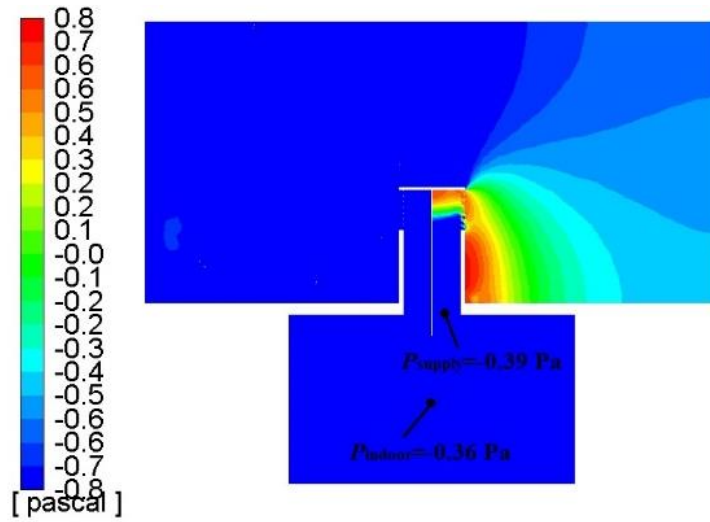
(b)

Fig. 21 Velocity vectors in the windcatcher with THR at an inlet velocity of 1 m/s:

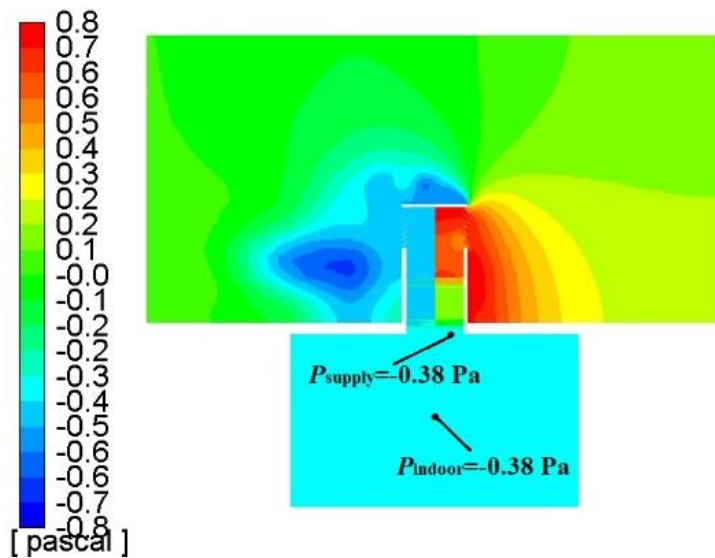
(a) the cross-sectional plane ($x=0$) and (b) the supply channel

5.2.2 Air pressure

Fig. 22 shows the pressure contour of a cross-sectional plane ($x=0$) along the wind direction. It can be seen that the room is under negative pressure, about -0.36 Pa in Fig. 22a and -0.38 Pa in Fig. 22b. This negative pressure condition indicates that the exhaust rate within the room is higher than the supply rate, which means more air is being removed from the room than is being supplied.



(a)



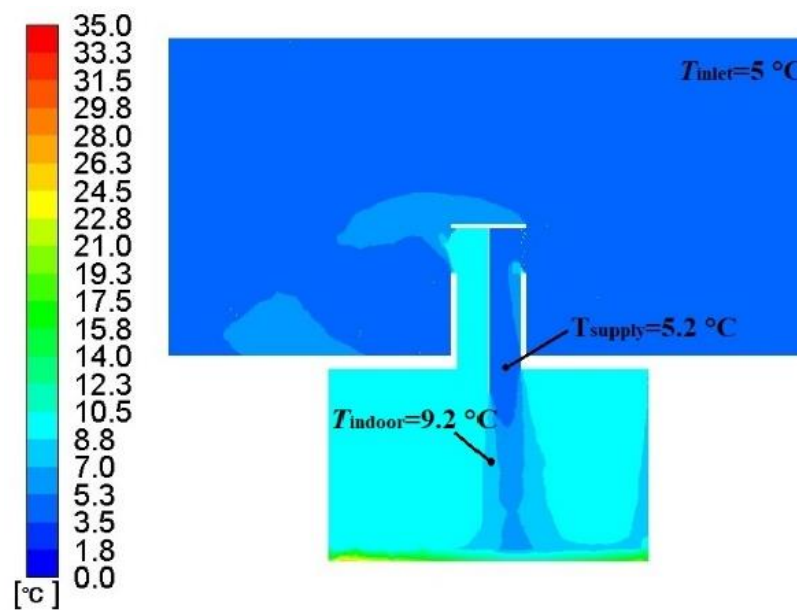
(b)

Fig. 22 Pressure contours of a cross-sectional plane with an inlet velocity of 1 m/s:

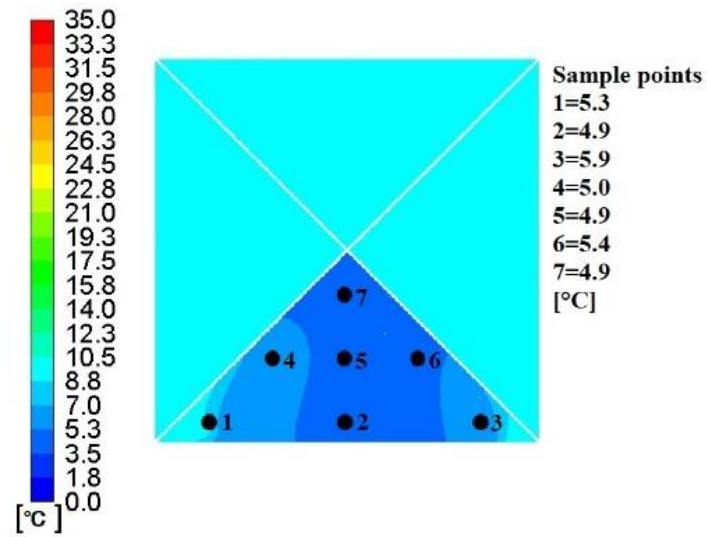
(a) the windcatcher without THR and (b) the windcatcher with THR

5.2.3 Air temperature

Figs. 23 and 24 compare the air temperature contours in the cross-sectional plane in the middle of the room ventilated by the windcatcher without and with THR at an inlet velocity of 1 m/s. From Fig. 23, it can be seen that due to the effect of indoor heat gains and natural ventilation, the average indoor temperature in the windcatcher without THR is 9.2 °C, which falls outside of the thermal comfort range. However, after integrating the heat recovery device into the windcatcher, the indoor temperature increased to 24.5 °C, showing an increment of up to 15.3 °C, as shown in Fig. 24. The temperature increase indicates that tube heat recovery can potentially minimise indoor heat waste and reuse some of the energy exhausted by the windcatcher to preheat supply fresh air. However, it should be noted that the improved indoor thermal comfort is achieved by the combined effect of the tube heat recovery and reduced ventilation heat loss. In addition, the simulation results do not account for heat loss from walls, roofs, etc., as the room is fully insulated and closed. From the observed flow patterns in Fig. 23, the jet stream in the middle has the lowest air temperature in the room, which may lead to thermal discomfort in this location. However, in the windcatcher equipped with THR, the temperature distribution has been improved to be more even.

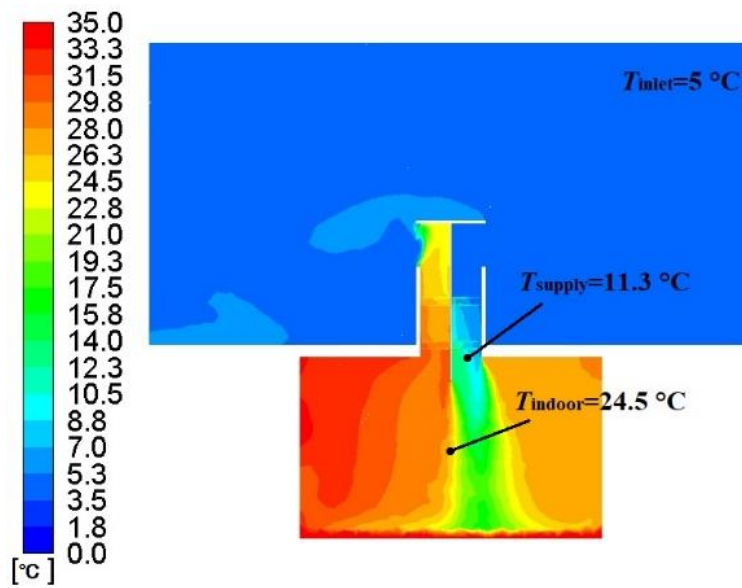


(a)

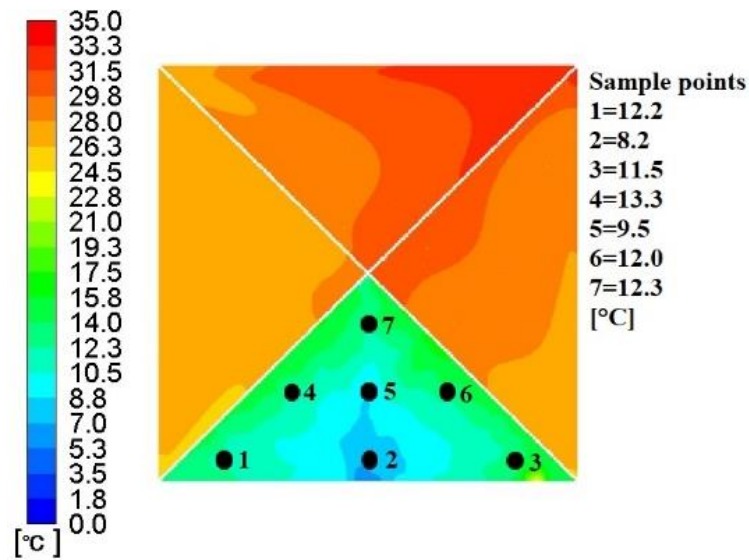


(b)

Fig. 23 Temperature contours in the windcatcher without THR at an inlet velocity of 1 m/s: (a) the cross-sectional plane ($x=0$) and (b) the supply channel



(a)



(b)

Fig. 24 Temperature contours in the windcatcher with THR at an inlet velocity of 1 m/s: (a) the cross-sectional plane ($x=0$) and (b) the supply channel

5.2 Ventilation performance

5.2.1 Effect of longitudinal pitch LP and transverse pitch TP on ventilation and thermal performance

Longitudinal pitch (LP) and transverse pitch (TP), as shown in Fig. 25, are the dominant factors influencing ventilation and tube thermal performance. This section discusses the effect of the staggered arrangement of solid tubes with varying LP and TP on fresh air rates and supply/indoor temperatures.

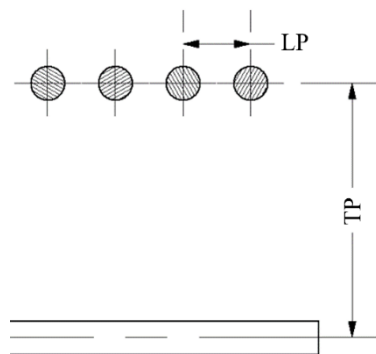


Fig. 25 Schematic of longitudinal pitch LP and transverse pitch TP

Fig. 26 shows the supply temperature, indoor temperature and fresh air rate with various LP values ranging from 25 mm to 45 mm. It can be seen that the supply temperature increases by reducing LP, with the maximum supply temperature

reaching up to 10.9 °C at the smallest LP of 25 mm. However, the ventilation rate can only achieve a minimum of 4.35 L/s/person at the smallest LP of 25 mm. Based on these results, it is suggested to reduce the LP as long as the system can provide a sufficient fresh air rate.

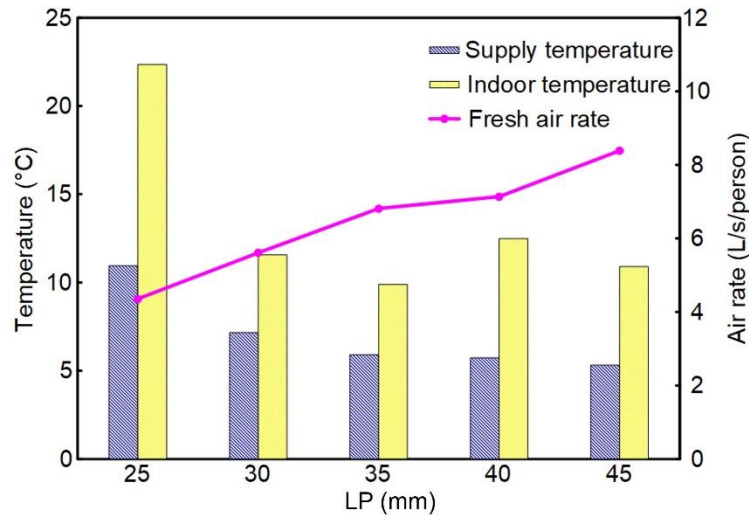


Fig. 26 Effect of varying LP on supply air temperature and fresh air rate

Fig. 27 shows the effects of different TP values, from 60 mm to 180 mm, on the supply temperature and fresh air rate. The results indicate that, as TP increases from 60 mm to 180 mm, a gradual decrease in supply temperatures from 6.4 °C to 5.6 °C and a slight increase in fresh air rates from 3.71 L/s/person to 3.94 L/s/person can be observed. Despite no noticeable difference in supply temperature and fresh air rate, it is recommended to use a smaller TP to achieve maximum heat recovery while keeping the structure more compact.

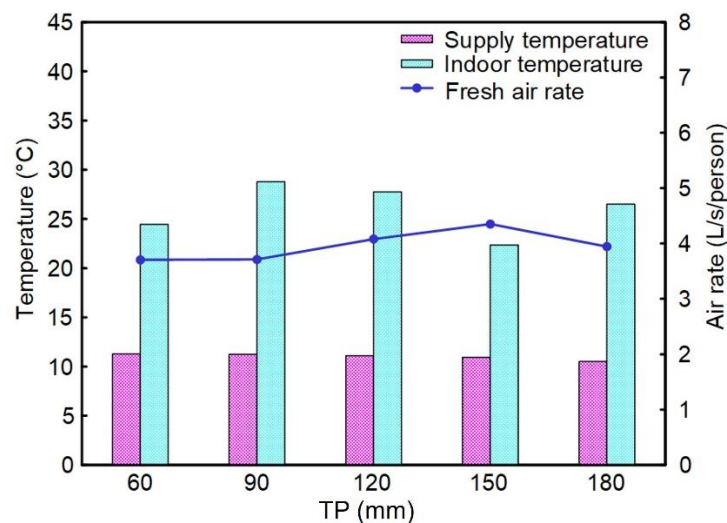


Fig. 27 Effect of varying TP on supply air temperature and fresh air rate

5.2.2 Effect of outdoor wind speeds

Fig. 28 shows the effect of outdoor wind speeds on the ventilation rate and heat recovery performance achieved by windcatcher with THR. It is clear that outdoor wind speeds can significantly affect the supply fresh air rate. Integrating the THR device into the windcatcher leads to a decrease in the fresh air rate, with reductions of up to 52 L/s/person at a wind speed of 5 m/s and 9 L/s/person at 1 m/s.

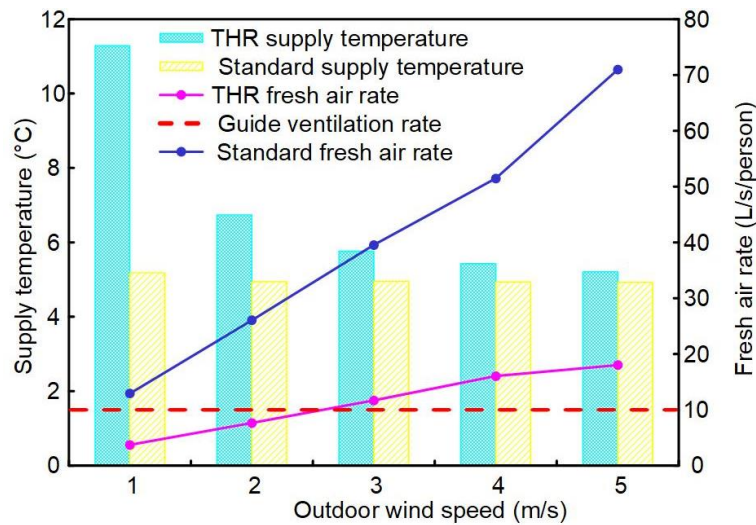


Fig. 28 Effect of varying external wind speeds on supply air temperature and fresh air rates

In addition, higher outdoor wind speeds result in lower supply air temperatures. Under simulated conditions (5 °C, 30 W/m²), the supply air temperature in the windcatcher with THR ranges from 5.21 °C to 11.3 °C, while in the standard windcatcher (without THR), the maximum supply air temperature is 5.17 °C. Furthermore, the capacity to pre-heating supply fresh air in the windcatcher with THR is comparable to that of a windcatcher equipped with a passive heat recovery wheel, raising the supply air temperature by up to 2.8°C [3], and is also competitive with a windcatcher incorporating heat pipe heat recovery, capable of increasing the supply temperature by 4.5 K [51]. According to the building regulations, the occupants' minimum air supply rate is 10 L/s/person for a 15 people classroom. For a wind speed of 1 m/s and below, the windcatcher does not comply with this recommendation; however, when the external wind speed increases to 3 m/s and above, satisfying ventilation rates can be provided.

Fig. 29 shows the effect of varying outdoor wind speeds (1-5 m/s) on the indoor air velocity and temperature for the windcatcher with THR and the standard windcatcher (without THR). It can be observed that after introducing the tube heat recovery device into the windcatcher, the average indoor air temperature increased while the average indoor velocity decreased. This could be a combined effect of reduced ventilation heat loss and heat transfer between the heat recovery device and airflow. As outdoor wind speeds increase, the indoor air temperature is reduced, as shown in Fig. 30b. This is because winds at higher speeds have larger momentum to overcome the pressure drops caused by the THR, resulting in higher ventilation heat losses as they enter the room. It is recommended that windcatchers be equipped with control devices, such as a damper at their bases, to adjust the air intake into the windcatchers during periods of high wind speeds. Compared with the heat pipe-assisted windcatcher in Ref. [51], which achieved a 5.3 °C increase in indoor air temperatures, the proposed windcatcher also demonstrated its potential for heat recovery and preheating, achieving a temperature increase of up to 7.9°C.

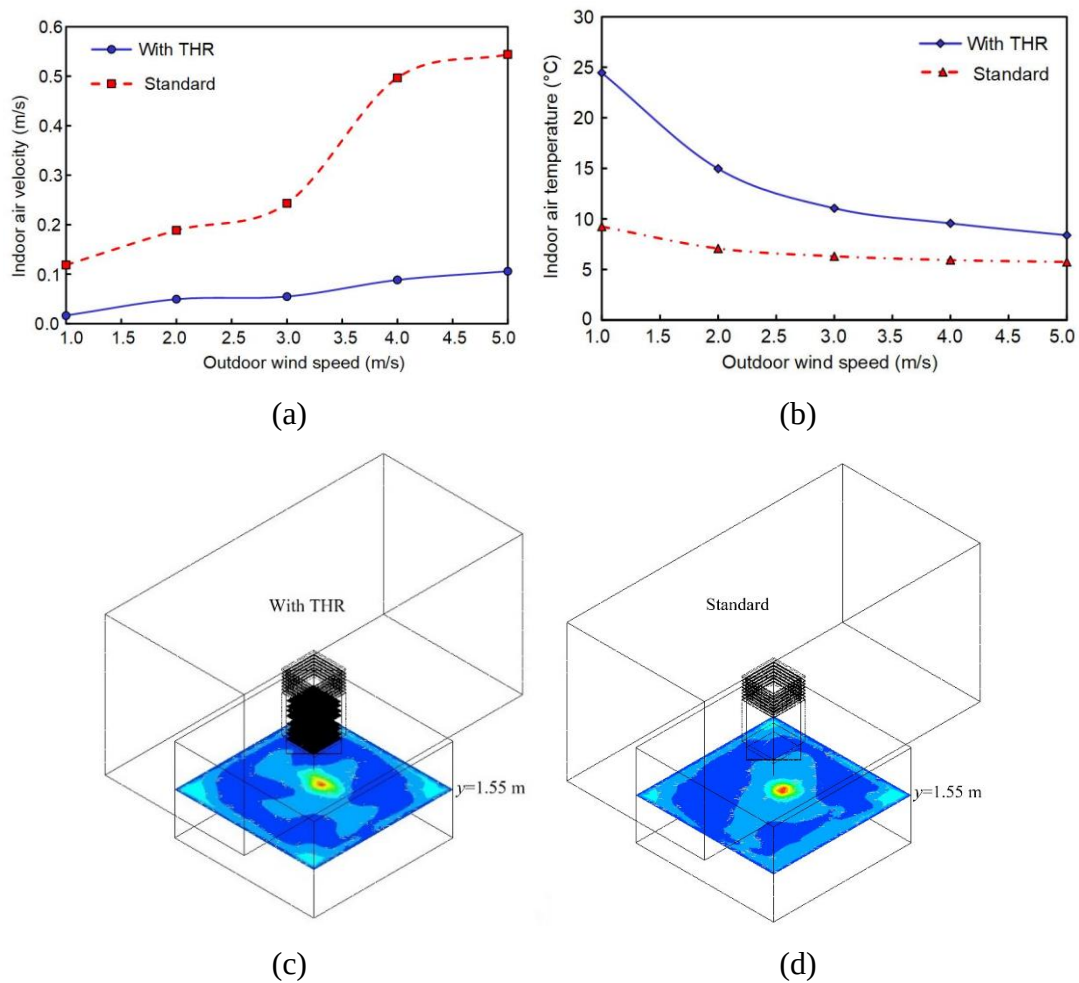


Fig. 29 Effect of varying external wind speeds on (a) indoor air velocity and (b) indoor air temperature; the characteristic plane ($y=1.55$ m) in (c) the standard

windcatcher (without THR) and (d) the windcatcher with THR

To evaluate the THR's heat recovery performance, Fig. 30 estimates the heating energy demand over a 5-hour period for rooms equipped with the standard windcatcher and the proposed windcatcher. The ventilated room has a width, length, and height of 5 m, 5 m, and 3 m, respectively. The U values of the roof, walls and floor are assumed to be 0.18 W/m²K, 0.26 W/m²K, and 0.22 W/m²K, respectively [3]. The indoor temperature is expected to be maintained at 21 °C. The building heating loss Q is calculated as Eq. (7):

$$Q = (\sum (A \times U) + 0.33 \times N \times V) \times (T_i - T_o) \quad (7)$$

Where, A is the building component area, U is the U value, N is the air change rate, V is the volume of the building, T_i is the indoor temperature, and T_o is the outdoor temperature.

Substituting Eq. (7) into Eq. (8) can yield the required supply air temperature T_{se}.

$$Q = m \times c_p \times (T_i - T_{se}) \quad (8)$$

Where, c_p is the specific heat capacity of air and m is the mass flow rate of air.

The estimated heating energy demand (W) over a time period of 5 hours is calculated by Eq. (9):

$$W = t \times m \times c_p \times (T_{se} - T_{sr}) \quad (9)$$

Where, T_{sr} is the supply air temperature after the THR device.

During a 5-hour period, as the outdoor speed increases from 1 m/s to 5 m/s, the heating energy demand for the room with the standard windcatcher (without THR) increases from 17.3 kWh to 103.9 kWh. However, after adding the heat recovery device, the heating energy demand is reduced, ranging from 0.2 kWh to 24.6 kWh. The heating load is significantly reduced due to the addition of the heat recovery device and the reduced ventilation heat loss.

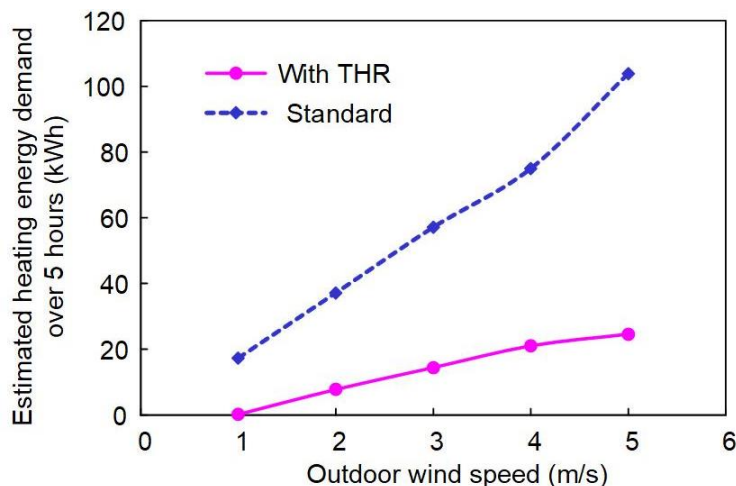


Fig. 30 Estimated ventilation heating energy: standard windcatcher vs with THR (5 °C outdoor temperature)

5.2.3 Summary

In Section 5.2, a four-sided windcatcher system integrated with THR is proposed, which aims to provide satisfying ventilation rates while achieving good thermal comfort. The proposed windcatcher is expected to function throughout a year, especially in temperate climates with cool to cold winters. A three-dimensional CFD model is developed to simulate the airflow characteristics and heat recovery performance achieved by the windcatcher with solid tubes in a staggered arrangement. The results demonstrate that installing solid tubes can improve the heat transfer effect and may enable the windcatcher to function during UK winter conditions while reducing heat loss. As LP and TP are reduced to 25 mm and 60 mm, respectively, the supply temperature reaches its maximum value of 11.28 °C. It is recommended to adopt smaller LP and TP if the required ventilation rate can be met. This section also compared the influence of varying outdoor wind speeds on the airflow and temperature distribution. When the external wind speed increases from 1 m/s to 5 m/s, the supply temperature is reduced from 11.28 °C to 5.21 °C, while the average supply velocity is increased from 0.22 m/s to 1.08 m/s.

5.3 Thermal performance and overheating risk

As discussed in Section 5.2, introducing THR can reduce ventilation heat loss and improve the supply air temperature. With a LP of 25 mm and a TP of 60 mm, a ventilation rate of 10 L/s/person can be met at wind speeds of 3 m/s or higher. However, it is obvious that THR can block the airflow channel and reduce the

ventilation rate. With decreased ventilation rates, the windcatcher's capacity to passively cool the space will also be reduced during warmer weather conditions. Hence, an overheating risk must be evaluated to ensure the windcatcher can effectively operate under such circumstances.

Section 5.3 will analyse the year-round thermal environments achieved by the proposed windcatcher under average UK annual climatic conditions. The evaluation will focus on buildings with high occupancies, such as schools, that must create a healthy and productive work environment. Using the validated CFD model, the natural ventilation potential of the proposed windcatcher will be assessed during summer, winter, and mild-cold months. The airflow velocity and temperature in the windcatcher with THR have been compared against one without THR in Section 5.2. The ability of the windcatcher to provide a satisfactory fresh air rate and thermal environment indoors will be one of the most important considerations. Potential issues, such as overheating risk during summertime, will be assessed. The ventilation heat loss and heat recovery performance during the wintertime will be quantified.

5.3.1 Climatic data of the UK

By modelling the average monthly wind speed and temperature in the UK, the annual ventilation performance and pre-heating/cooling potential of the windcatcher can be obtained. Variations in wind directions are not considered because the windcatcher is multi-directional and can capture air from all directions; instead, the focus was on the influence of adding the THR on the airflow behaviours across different months. The monthly weather data for the UK from 1990-2021 was obtained from the Met Office [162], as shown in Fig. 31. 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.

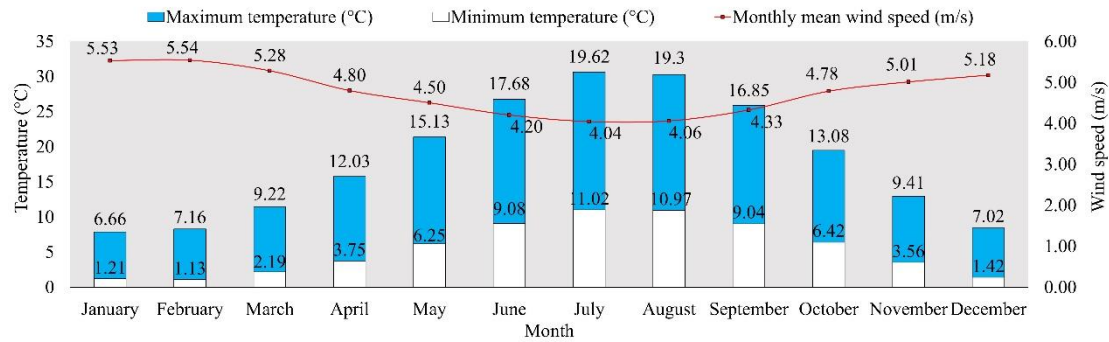


Fig. 31 Velocity and temperature data of UK from 1990 to 2021. Figure created by the data from Met Office [162]

5.3.2 Indoor thermal performance

The air temperature is one of the most important factors for ensuring indoor comfort and can, therefore, serve as an indicator for evaluating thermal comfort [163]. The UK government considers a pleasant living room temperature of 21 °C; for other areas of a dwelling, the acceptable temperature is 18 °C [164].

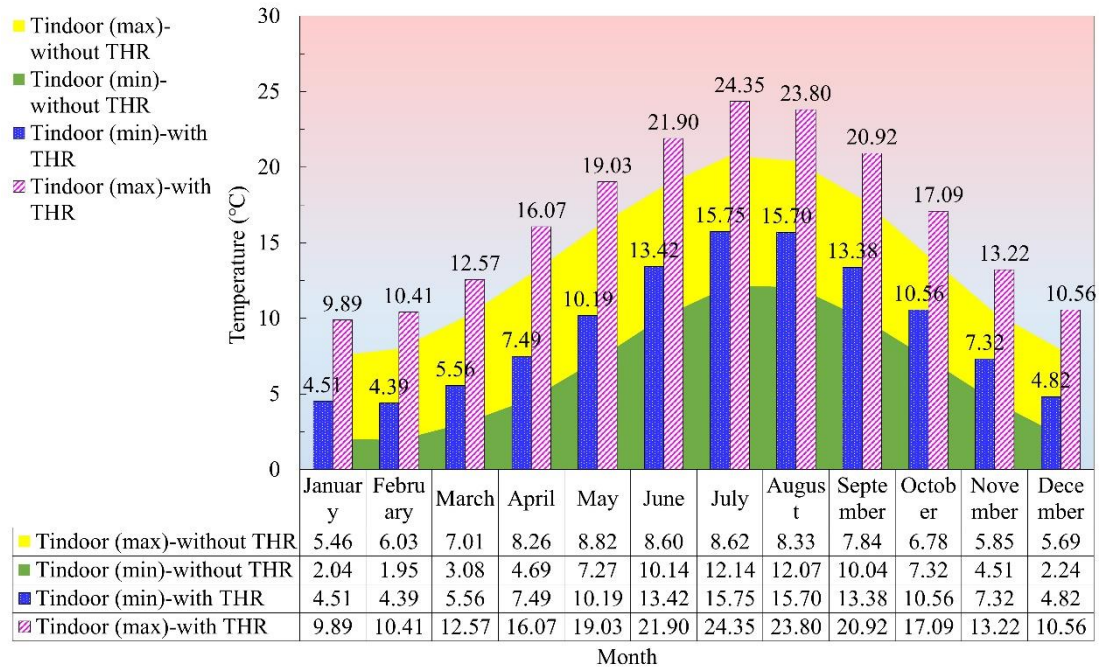
Fig. 32a shows the influence of the weather conditions on indoor temperatures for the windcatcher with and without THR throughout the year. Overall, the annual indoor temperature of the windcatcher with THR was higher than that without THR. During the months when the maximum outdoor temperature did not exceed 10 °C (i.e., November-December, January-March), the indoor temperature with THR ranged between 4.39 °C and 13.22 °C, increased by an average of 2.56 °C compared to without THR. Although the temperature does not meet the criteria for indoor thermal comfort in the winter, the inclusion of THR is beneficial for reducing ventilation energy loss and extra heating demand.

During the mild-cold months (i.e., April-May and September-October), the average indoor temperature in the windcatcher with THR varied between 11.78 °C and 17.15 °C, while that in the windcatcher without THR was 8.82-13.96 °C, an average of 3.1 °C lower. The introduction of THR could extend the windcatcher'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 temperate climates. In the warmer summer months, June to August, the maximum indoor temperature fluctuated between 21.90 °C and 23.80 °C for the windcatcher with THR and from

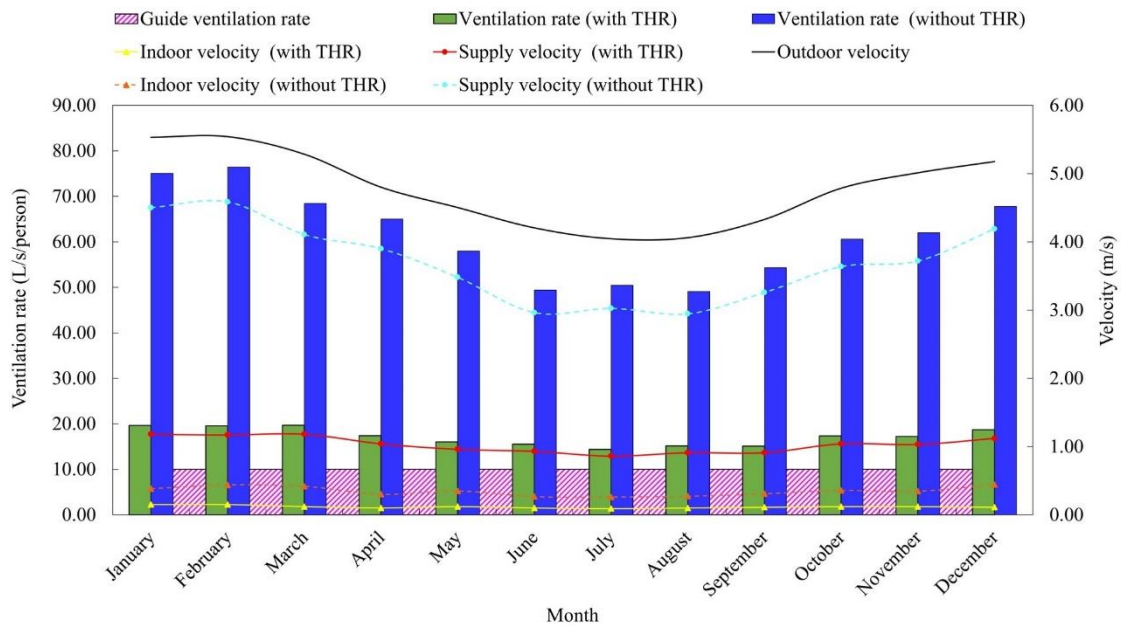
18.74 °C to 20.75 °C for that without THR. According to the static overheating criteria (CIBSE Guide A [73], CIBSE Guide J [75], TM36 [74], TM59 [165]), the temperature in the space ventilated by the windcatcher with THR was within the upper threshold. However, it is suggested that additional ventilation methods be used in the summertime, such as opening windows and vents, to increase ventilation and cooling capacity.

5.3.3 The effect of adding THR on the year-round ventilation performance of the windcatcher

Fig. 32b shows the effect of climatic data for different months on the ventilation rate and airflow velocity for the windcatcher with and without THR throughout the year. Overall, the ventilation rate was lower in the summer than in the winter, mainly due to the lower outdoor wind speed during the summertime. For the windcatcher 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 (4.20 m/s). 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. The supply air velocity throughout the year ranged from 0.86 m/s to 1.18 m/s, while the indoor air velocity remained essentially constant at 0.12 m/s. For the windcatcher without THR, the overall trends in supply velocity and ventilation rate were similar, but the values were much higher, ranging from 2.95 to 4.58 m/s for the supply velocity and from 49.09 to 76.41 L/s/person for the ventilation rate. The windcatcher with THR can provide a ventilation rate of 14.35-19.69 L/s/person throughout the year, which is 44%-97% higher than that the suggested value of 10 L/s/person [163]. In addition, the windcatcher with THR can achieve much higher annual ventilation rates of 49.38-76.41 L/s/person. As can be seen, in the UK's year-round climatic conditions, the windcatcher system with THR has the potential to function effectively. It should be acknowledged that wind speeds at the roof level in real life may be lower than the data used here. Wind speeds may be affected by surrounding buildings, vegetation, and the local environment.



(a)



(b)

Fig. 32 (a)The year-round indoor temperature for the windcatcher with and without THR and (b) the annual ventilation rate in the windcatcher with and without THR

5.3.4 Summertime overheating analysis

As mentioned earlier, while the inclusion of THR may enhance occupant thermal comfort during wintertime, it also reduces the airflow rate. Consequently, a potential drawback of employing the proposed windcatcher is the reduced ventilation and cooling capacity during summer, which may lead to indoor overheating. Inadequate

thermal conditions can affect occupants' health and cognitive performance and also increase cooling demand. Table 14 details the commonly used static overheating criteria.

Table 14 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	[74]
	School	28 °C	Temperatures above 28 °C should be less than 5% of the occupied time of the year	
	Sleeping areas	21 °C (nighttime)	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.	[73]
		28 °C	Operative temperature above 28 °C should be limited to 1% of occupied time.	
TM59	Bedroom	26 °C (10pm-7am)	Operative temperature exceeding 26 °C should be less than 1% of the year.	[165]
CIBSE Guide J	School	28 °C	Temperature above 28 °C should be less than 80 hours of occupied time in a year.	[75]

Fig. 33a shows the indoor overheating evaluation in the windcatcher with and without THR during the summertime (June-August). For the windcatcher 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, corresponding to a maximum indoor temperature of 24.35 °C. As can be observed, the indoor temperatures over summertime remained within the static overheating thresholds specified in TM36 [74], CIBSE Guide A [73], TM59 [165] and CIBSE

Guide J [75]. This indicates that the windcatcher with THR meets the thermal comfort criteria for summer conditions, and when combined with other passive ventilation methods, the indoor thermal environment can be further enhanced. 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.

5.3.5 Wintertime heat recovery and ventilation heat loss prediction for the windcatcher with and without THR

Fig. 33b shows the reduction in ventilation heat loss during the wintertime (November-December and January-March) for the windcatcher with THR and without THR. Building ventilation heat loss can be estimated using Eq. (6). The heat loss from the windcatcher 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 windcatcher with THR was 1089.57 W, compared to 1256.72 W in the windcatcher without THR, a reduction of 15.3%. Similarly, when the external temperature dropped to a minimum of 3.56 °C, the ventilation heat loss in the windcatcher with THR was 1109.18 W, compared to 1273.51 W in the windcatcher without THR, indicating a reduction of 14.8%. In December, when the outside temperature was at a minimum of 1.42 °C, the THR had little effect on reducing ventilation heat loss, which was almost the same as without THR, while when the outside temperature was at a maximum of 7.02 °C, ventilation heat loss can be reduced by 4.2% in the windcatcher with THR. 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 is mainly reflected in the increase in the supply air temperature. As seen from Fig. 33b, THR can preheat the incoming outside air by 0.28-0.33 °C compared to that without THR. However, adding THR in the windcatcher still cannot provide occupants with good thermal comfort in cold/mild-cold months.

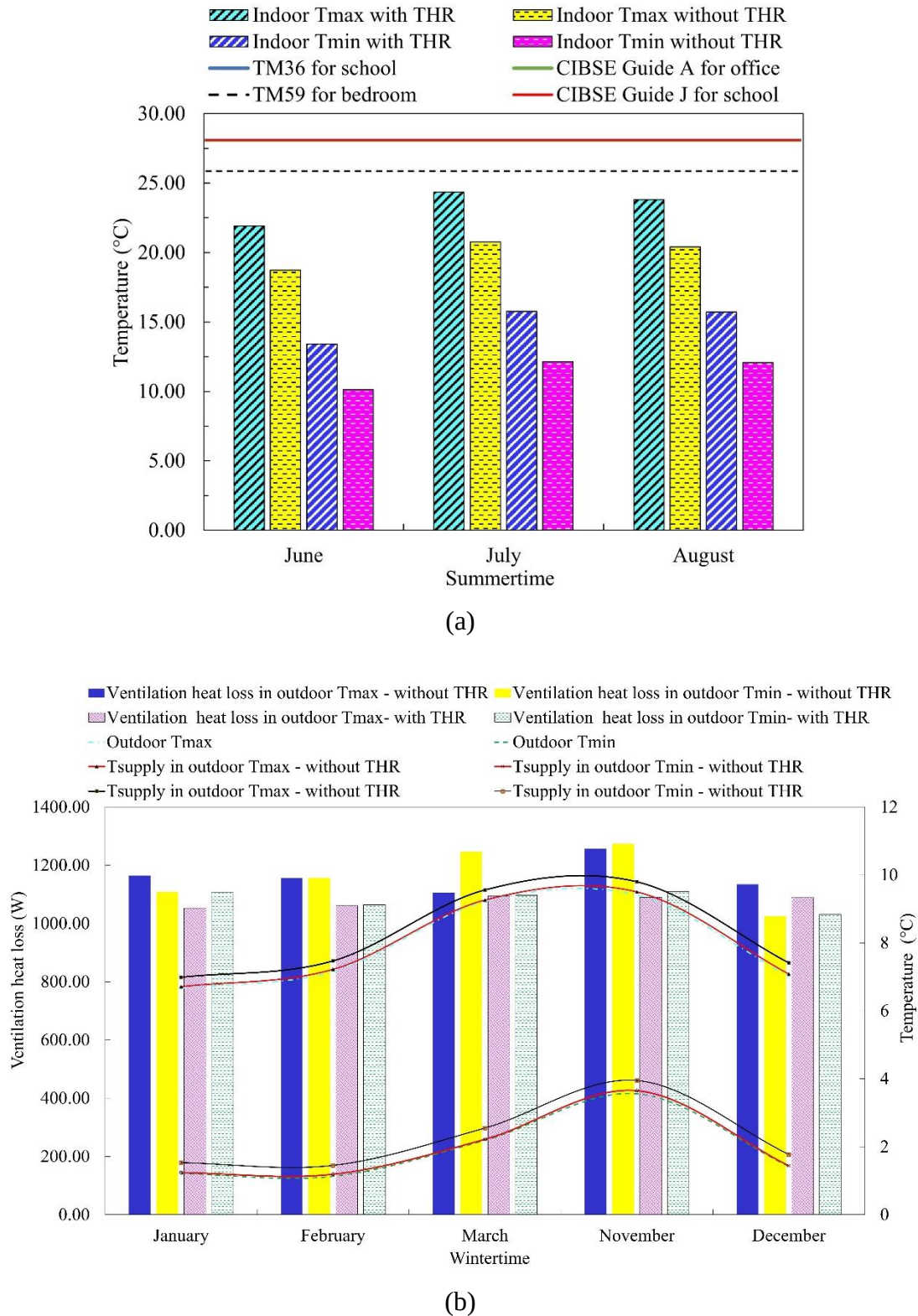
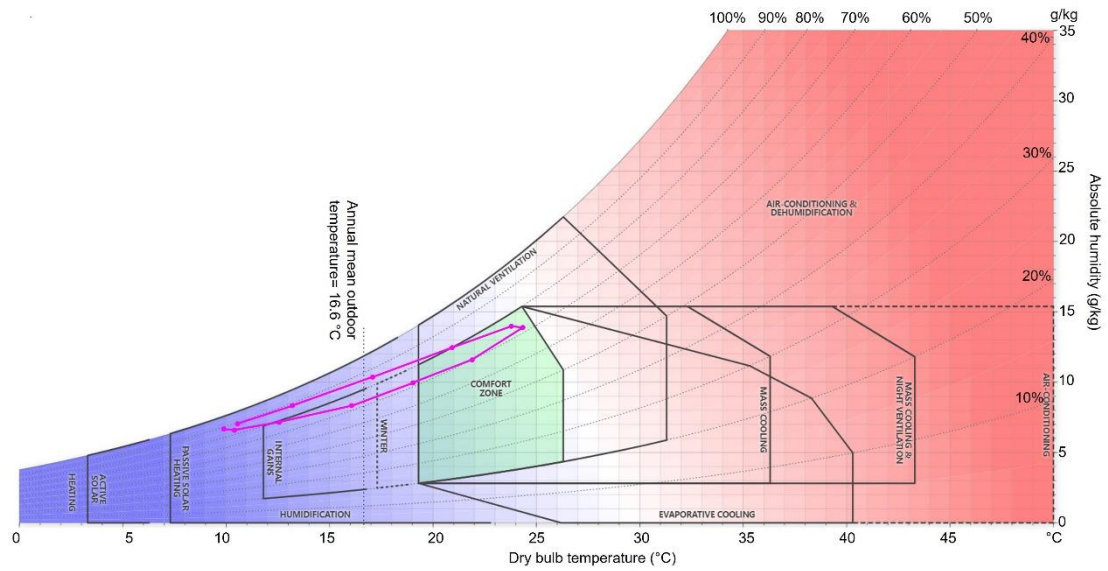


Fig. 33 (a) Indoor overheating evaluation in the windcatcher with and without THR during the summertime (June-August) and (b) ventilation heat loss prediction in the windcatcher with and without THR during the wintertime

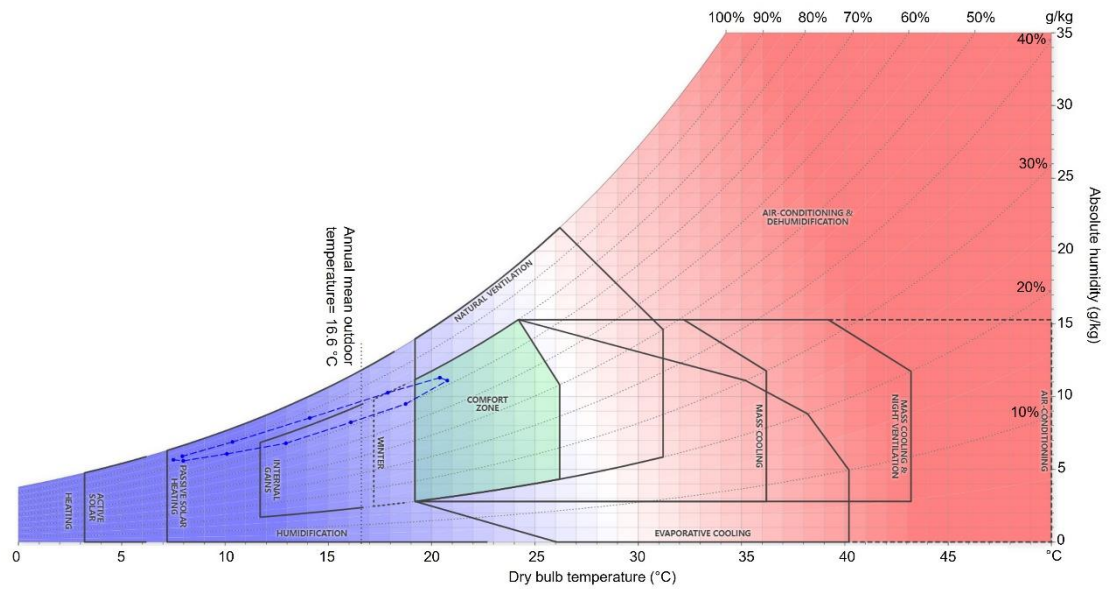
Fig. 34 shows the psychrometric chart (represented by the Givoni bioclimatic chart) for the windcatcher with and without THR throughout the year in the UK. The Givoni bioclimatic chart was proposed by Baruch Givoni in 1963 based on expected

indoor temperatures, which is mainly applicable to residential scale buildings [166,167]. It can present the boundaries of comfort zones and heating/cooling or dehumidification/humidification strategies required for different zones [168]. In addition, I plotted the average of the occupants' votes on a seven-point heat-sensitivity scale, i.e., PMV. The background colour changes from blue to red from left to right to represent votes from cold, cool, slightly cool, neutral to slightly warm, warm, and hot [169]. 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 [76]. 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) [170].

In the windcatcher with and without THR, the predicted indoor air velocity in the CFD model was 0.12 m/s and 0.35 m/s, respectively. From the comparison of Fig. 34a,b, the inclusion of THR expanded the comfort zone achieved by the windcatcher (mainly from June to September), whereas the comfort ranges in the windcatcher 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 during the cold months such as January, February and December, additional heating inputs may still be required in the windcatcher with THR to provide satisfactory thermal comfort; during some extreme weather conditions in the summertime, THR may cause the indoor thermal environment to reach warm. Fig. 35 also presents the year-round adaptive thermal comfort for the windcatcher with THR and without THR in the UK. As can be seen, when the mean outdoor temperatures reach 10.69-16.32 °C, the windcatcher with THR has the potential to offer good thermal comfort, while, for most of the temperature values, the windcatcher without THR still struggles to maintain a favourable thermal condition. Although the inclusion of THR can enhance the indoor thermal environment, neither the windcatcher with nor without THR can provide satisfactory thermal comfort when the mean outdoor temperatures are at 9.75 °C or lower.



(a)



(b)

Fig. 34 Psychrometric chart (represented by the Givoni bioclimatic chart) for (a) the windcatcher with THR and (b) without THR throughout the year in the UK

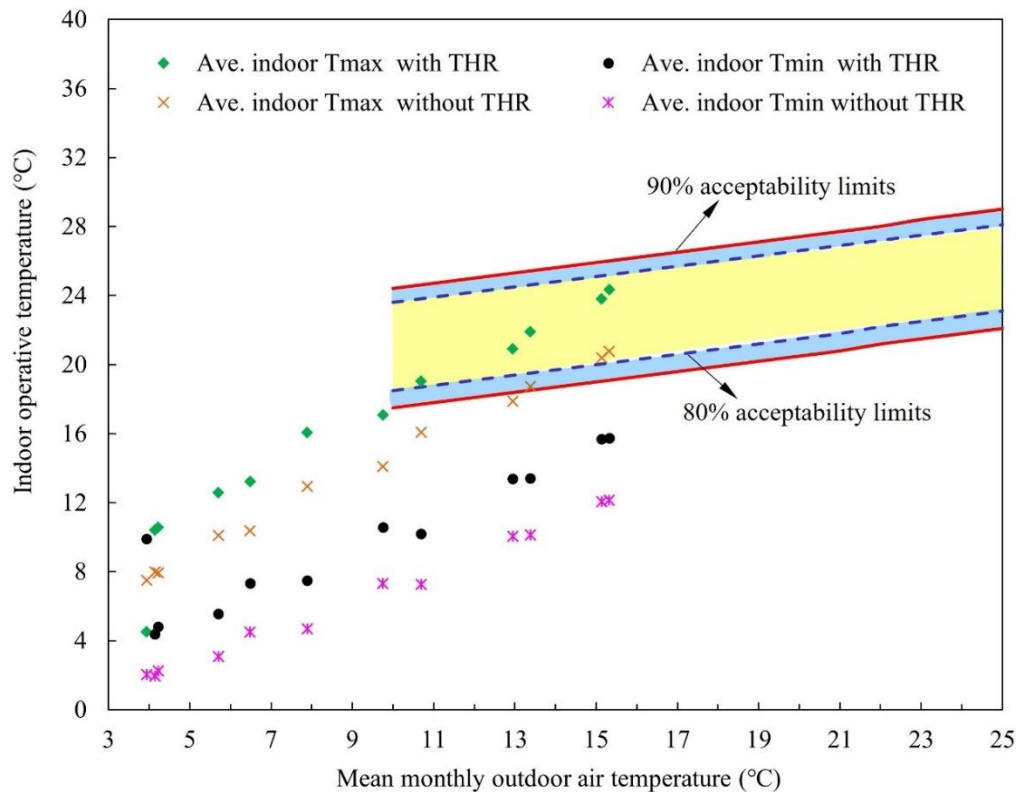


Fig. 35 The year-round adaptive thermal comfort for the windcatcher with THR and without THR in the UK

5.3.7 Comparison with the previous studies

To evaluate the comparability of the windcatcher with THR in terms of thermal performance, this section compares the present results with the previous related studies [2–4,48]. To obtain more data for comparison, the studies [2,4,48] 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 to be more comparable. A larger difference represents the potential of the heat recovery's capability to increase the indoor temperature in cold/mild-cold conditions. It was found that the present tube heat recovery performance was competitive compared to the heat pipes [51] and the rotary thermal wheel [3]. For example, at a wind speed of 4 m/s, the indoor temperature increase in the current study can reach 4.73 °C, compared to a 5 °C indoor temperature improvement obtained from the rotary thermal wheel in [3] and a 3 °C increase from the heat pipes in [51]. In addition, the tube heat recovery is considered fully 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.

5.3.6 Summary

Following Section 5.2, which discussed the ventilation performance of the proposed windcatcher, Section 5.3 further explored the thermal comfort level in the occupied space. The ability of THR to ventilate, cool during summertime and preheat during wintertime was evaluated. It was found that 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, and increased by 7.64 °C and 4.77 °C, respectively, compared to the windcatcher without THR. According to the static overheating criteria, during the summertime (June-August), the overheating risk 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 windcatcher with THR reduced the ventilation heat loss by an average of 7.3%-8.1% and increased the supply temperature by 3.7%-18.2%, compared to that without THR. Furthermore, throughout the year, the windcatcher 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 chapter shows that the previously proposed windcatcher 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 windcatchers 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 the 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 windcatcher assisted by THR during the cold months, such as January, February and December, may still require additional heating inputs to provide satisfactory thermal comfort; during some extreme weather conditions in the summertime, THR may cause the indoor thermal environment to reach warm.

5.4 Indoor air quality (IAQ)

Indoor environments under natural ventilation are vulnerable to outdoor conditions, such as temperature, wind speed and humidity, which can vary greatly and lead to discomfort indoors. Natural ventilation can also be limited if the area is exposed to high levels of pollution or noise. Windcatchers, as an effective way of natural ventilation, can promote indoor ventilation and reduce building energy consumption, which should be encouraged when the outdoor weather conditions are favourable. There have been many studies that investigated the ventilation performance and thermal performance of windcatchers, but limited research has been done on the effect of windcatcher ventilation on the levels and spatial distributions of indoor CO₂. As discussed in Section 5.1, the windcatcher with THR can pre-heat supply air in mild-cold climates while providing a satisfactory ventilation rate. The air in the room is warmer due to the heat gains from occupants, computers, and heating devices. As the indoor air passes through the exhaust quadrants, the heat is recovered by the THR inside the windcatcher. After the low-temperature external air enters the windcatcher through the louvers, the air temperature increases after the two-stage THR. Therefore, it can reduce heat loss caused by windcatcher ventilation in low-temperature conditions and reduce the extra heating demand.

However, the previous work did not investigate the effect of introducing THR on the CO₂ concentration and distribution in the ventilated space. In addition, previous studies that explored the CO₂ distribution in the space ventilated by windcatchers have not considered the impact of factors such as occupant age, density, and activity level. Furthermore, no previous work has discussed the effect of heating and non-heating seasons on the CO₂ level in the space ventilated by windcatchers. Few studies on windcatchers have quantitatively studied the effect of outdoor CO₂ levels on indoor CO₂ concentration.

This chapter aims to evaluate the influence of integrating THR into the windcatcher on the CO₂ levels in the ventilated space. The effects of the occupant activity level and density on the CO₂ distribution were investigated. The influences of the external wind speeds and heating/non-heating seasons were explored. The limitations of the windcatcher ventilation with THR were also discussed in terms of the external CO₂ levels. This work aims to strike a balance between heat recovery, ventilation rate,

and low CO₂ level in the indoor environment.

5.4.1 CO₂ modelling

5.4.1.1 CO₂ guideline and critical parameters

Table 15 lists the CO₂ guideline in EN 16798-1:2019 for schools. Categories I, II and III generally represent high-level expectations for vulnerable people, normal-level expectations for new or renovated buildings, and medium-level expectations for existing buildings, respectively. Category IV denotes expectations that are not included in those categories and should only be accepted for a limited period of time. As suggested in EN16798-1 (2019), the indoor CO₂ level can be classified as Category I when its value above the outdoor level is within 550 ppm. In the more recent CO₂ standard, REHVA COVID-19 Guidance, the alarm CO₂ level is 1000 ppm, and the warning level is 800 ppm, considering the outdoor CO₂ level of 400 ppm. In this work, the regulations in EN 16798-1:2019 for CO₂ concentrations are adopted, as shown in Table 15.

Table 15 The CO₂ guideline in EN 16798-1:2019 for schools

Category	CO ₂ level above the outdoors
Category I	550 ppm
Category II	800 ppm
Category III	1350 ppm
Category IV	1350 ppm

Critical parameters affecting indoor CO₂ levels include occupants-influenced variables (i.e., occupant activity level and density) and external environment-influenced variables (i.e., external wind speed, CO₂ level and heating/non-heating seasons).

(1) Occupants-influenced variables

Since occupants are the primary indoor CO₂ sources, the CO₂ release rate per occupant (G_{CO_2}) is a crucial parameter, which is expressed by Eq. (8) [171,172].

$$G_{CO_2} = \frac{0.00276A_D MRQ}{(0.23RQ + 0.77)} \quad (8)$$

Where, A_D is Dubois surface area (m²) which is given as Eq. (9).

$$A_D = 0.202w^{0.425}h^{0.725} \quad (9)$$

Where, w is per occupant's weight, h is per occupant's height. Children aged 9-11

years had an average height of 1.38 m, a weight of 32 kg, and an A_D of 1.1 m^2 [173]. According to [171], an average-sized adult's A_D was 1.8 m^2 . M is the metabolic rate, which represents a person's physical activity [174]. Table 16 summarises M values of various activity levels for children aged 9-11 years and an average-sized adult.

Table 16 M values for children and a teacher at different activity levels [174–177]

	Sedentary	Light working	Medium working
	M (met)	M (met)	M (met)
Children	1.0	1.3	1.7
Teacher	1.2	1.6	2.0

RQ is a dimensionless variable that stands for respiratory quotient and is mainly affected by diet [172]. In this work, RQ was fixed at 0.85, as suggested by Persily and de Jonge [172]. The indoor CO_2 level is also related to occupant density, i.e., average floor area or volume occupied per person [178,179]. The occupant density for a UK primary school classroom was suggested to be $1.6\text{--}2.7 \text{ m}^2/\text{p}$ [180] or $1.8\text{--}2.4 \text{ m}^2/\text{p}$ [181]. In order to gain more simulation data to explore the influence of the number of occupants on the CO_2 level, the occupancy density employed in this research was $1.6\text{--}2.7 \text{ m}^2/\text{p}$ ($5.0\text{--}8.3 \text{ m}^3/\text{p}$), corresponding to 9-15 people.

(2) External environment-influenced variables

Indoor CO_2 levels under natural ventilation can be influenced by external wind speed, temperature, CO_2 level, solar radiation, etc. [21,81,105,130,182]. The effects of outdoor wind speeds, CO_2 levels and heating/non-heating seasons (representing external temperature) were mainly studied in this work; however, the influences of wind direction and solar radiation were not investigated and should be explored in future studies. Indoor CO_2 levels can also be affected by building-related factors such as the window's open area [183], the window's location [184] and orientation [185]. However, these factors were not considered in the present work because the occupied space was assumed to be fully ventilated by the windcatcher with THR.

5.4.1.2 Geometry model of the windcatcher ventilation system with human manikins

The width, length, and height of the windcatcher were 1 m, 1 m, and 2.21 m, respectively. The dimensions of the below room were 5 m, 5 m, and 3 m [139], in which a number of students and a teacher were equally distributed. LP and TP

between the tubes were set at 25 mm and 60 mm, respectively. Two 1500 W radiators with dimensions of 0.6 m×0.6 m×0.1 m were mounted on the side walls inside the ventilated space. The windcatcher and the ventilated room were assumed to be put in a wind tunnel domain with dimensions of 10 m, 5 m, and 5 m, in order to maintain consistency with the previous Sections and also to allow a more straightforward validation of the CFD methodology [139].

As mentioned before, the children's height was 1.38 m [173], and the thickness and width were 0.13 m and 0.25 m (the body surface area was 1.1 m²), respectively [186]. The average height of a European adult male was 1.75 m [187], and the thickness and chest breadth were 0.19 m and 0.3 m, respectively [188]. The dimensions of the mouth were 0.013 m and 0.01 m [189]. The mouth-to-floor heights for children and adults were 1.24 m and 1.57 m, respectively [188]. The diagram of the geometry is shown in Fig. 36. The geometry model was imported into ANSYS DesignModeler to extract the computational fluid domain.

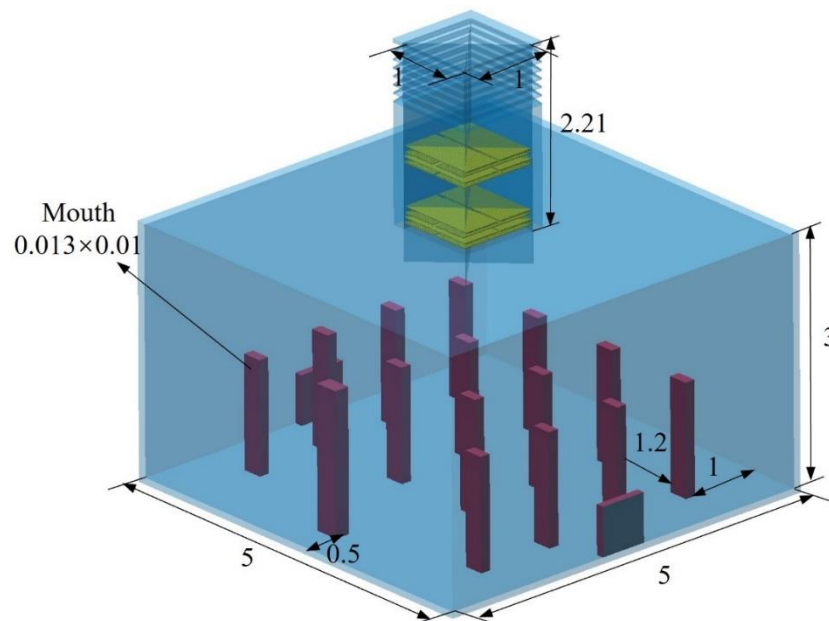


Fig. 36 The diagram and dimension of the geometry of the CFD model (units: m)

5.4.1.3 Boundary conditions

The simulation work was based on the following assumptions and simplifications.

- (1) The occupants were simplified into manikins represented by rectangular cuboids and evenly distributed throughout the ventilated space.
- (2) Disregarding the heterogeneity of the occupants' activities, it was considered that the physical activity of each person remained constant.

- (3) The wind direction was perpendicular to the windcatcher's supply quadrant.
- (4) The effects of infiltration, radiation, etc. were not considered.

The variables affecting indoor CO₂ levels in this study include occupants- and external environment-influenced variables. The atmospheric CO₂ level is typically around 382 ppm [190,191]. However, if the occupied space is located near the roadside or in a high-polluted area, the outdoor CO₂ level can reach about 800 ppm [192]. Therefore, outdoor CO₂ levels of 382-782 ppm were selected for the parametric study. The inlet was set as velocity inlet, and the outlet was considered atmospheric pressure outlet. According to Met Office [162], the average monthly wind speed in the UK from 1990-2020 was generally more than 4 m/s.

The average external temperatures in heating and non-heating seasons were 5 °C and 15 °C, respectively. However, the wind speed in real life could be lower because buildings are usually not single-isolated, and there could be obstacles around, such as vegetation. A range of inlet velocity values (1-5 m/s) were simulated to quantify the effects of wind speeds on the indoor CO₂ levels. The radiators were assumed to operate at full power in heating seasons, i.e., the heat flux was 2500 W/m², and were switched off during non-heating seasons. Although human breathing is an irregular process, the occupants' breathing was considered to be steady, and the exhalation velocity was 0.77 m/s [193–195]. In addition, the metabolic rates for the children and the teacher, both performing sedentary activities, were 58 W/m² and 70 W/m², respectively [175–177]. It should be noted that these values slightly vary across the literature, as indicated by Persily and de Jonge [172], and should be taken into account when evaluating the results presented in this study.

The amount of exhaled CO₂ by the occupants was related to various factors, such as age, activity level and sex. Calculated by Eq. (8), the CO₂ release rates from children when performing sedentary, light, and medium work were 2.67, 3.47, and 4.54 cm³/s, respectively, with an average value of 3.56 cm³/s. The average CO₂ release rate per child aged 9-11 years mentioned in Coley and Beisteiner [196] was 3.8-4 cm³/s, similarly, 2.9 cm³/s in Andamon et al. [197] and 4.3 cm³/s in Deng and Lau [198]. Kabirikopaei and Lau [199] clarified that the CO₂ generation rate for 8-11-year-old children was 3.47-4.10 cm³/s. Accordingly, in this study, the teacher's CO₂ release rates were 5.25, 6.70 and 8.75 cm³/s, respectively, with an average value of 6.99 cm³/s. Similar values of 7.36-8.33 cm³/s [200] and 5.8 cm³/s [201] were also

reported. Table 17 shows the range of parameters chosen in this study.

Table 17 The range of parameters chosen in this study

Parameters		Values
Occupant [171–179]	Children's CO ₂ release rate	2.67 (sedentary), 3.47 (light working), and 4.54 (medium working) cm ³ /s
	Teacher's CO ₂ release rate	5.25 (sedentary), 6.70 (light working), and 8.75 (medium working) cm ³ /s
	Density	1.6-2.7 m ² /p (9-15 people)
External-environment [162,192]	Temperature	5 °C in heating seasons; 15 °C in non-heating seasons
	Wind speed	1-5 m/s
	CO ₂ level	382-782 ppm

5.4.1.4 Mesh generation and sensitivity analysis

After extracting the fluid domain, the computational zone was discretised using the meshing tool in ANSYS Workbench. As demonstrated in the previous sections, a face sizing size of 10 mm of the windcatcher met the mesh-sensitivity requirement. In this section, since the occupant's CO₂ release rates greatly influenced the indoor CO₂ concentration, it was necessary to refine the mesh near the mouth and perform mesh sensitivity analysis. Three different mesh configurations were generated, i.e., coarse (28,319,680), medium (33,654,919), and fine (40,352,272). Fig. 37 shows the supply air velocity and indoor CO₂ levels for the three mesh configurations. As the mesh changed from coarse to medium, the average supply velocity increased from 0.36 m/s to 0.75 m/s, and the average CO₂ level reduced from 727 ppm to 658 ppm. However, as the mesh changed from medium to fine, the difference among the simulation values was minimal (less than 5%). The medium mesh was thus chosen as more appropriate, in terms of the computer resources consumed and the accuracy of the results.

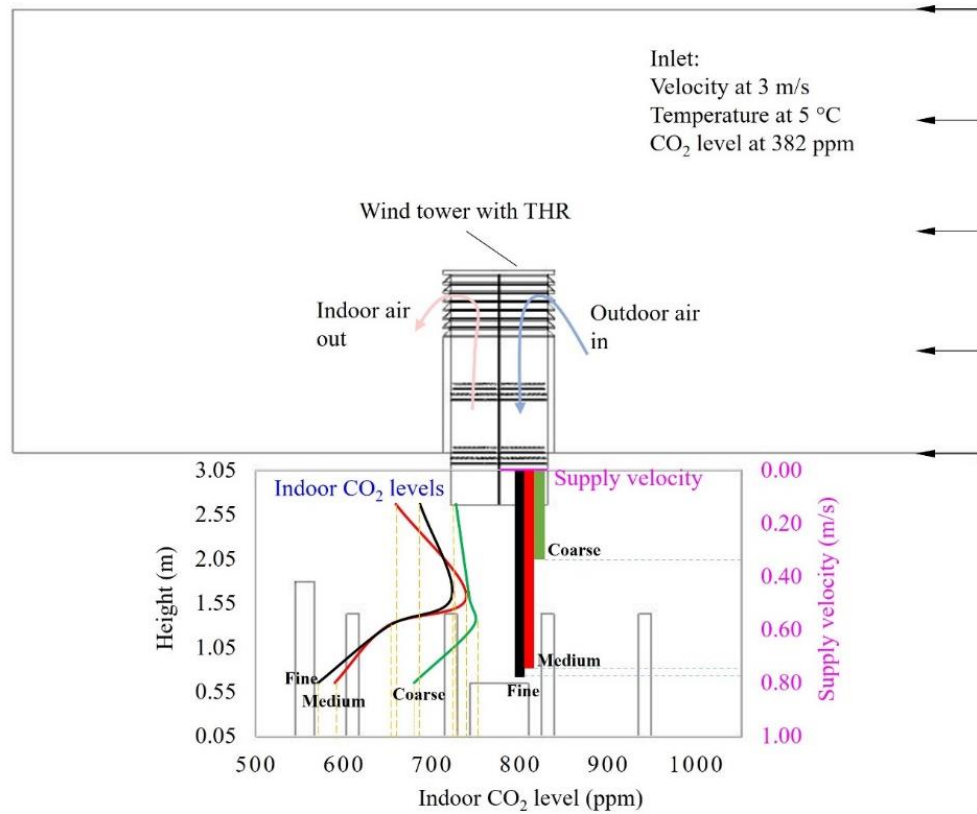


Fig. 37 Mesh sensitivity analysis for the coarse, medium and fine mesh

5.4.1.5 Measurement planes

To evaluate the indoor CO₂ levels in more detail, four indoor measurement planes were selected, i.e., the children's breathing height (CBH, $y=1.29$ m), the teacher's breathing height (TBH, $y=1.62$ m), the bottom plane (BP, $y=0.65$ m) and the plane near the ceiling (CP, $y=2.665$ m). The cross-sectional plane $x=0$ was also chosen. The locations of the selected planes are shown in Fig. 38.

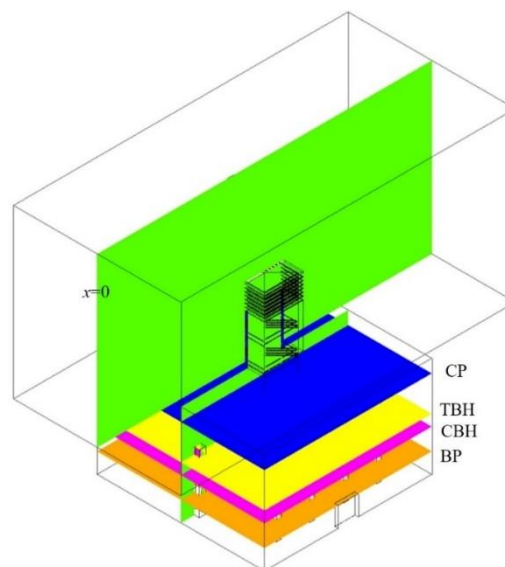


Fig. 38 The locations of the selected measurement planes in the CFD model (BP=

bottom plane, CBH=children's breathing height, TBH= the teacher's breathing height, CP=plane near the ceiling)

5.4.1.6 Convergence of the simulation results

As shown in Fig. 39, as the iteration proceeded, the CO₂ levels in the selected planes showed a regular oscillation in the monitored residuals, and the amplitudes cannot be ignored. This may be due to the constant exhalation of CO₂ from the occupants promoting the formation of secondary flows and vortex zones, and, thus a greater perturbation of the flow field [202]. Wang et al. [203] demonstrated a similar pattern in the indoor air velocity following the addition of an indoor pollutant release source. A similar tendency was also observed in Ramponi and Blocken [153] and Castillo et al. [204]. In the following research, I adopted the solution from Ramponi and Blocken [153], in which the results were averaged to reduce errors.

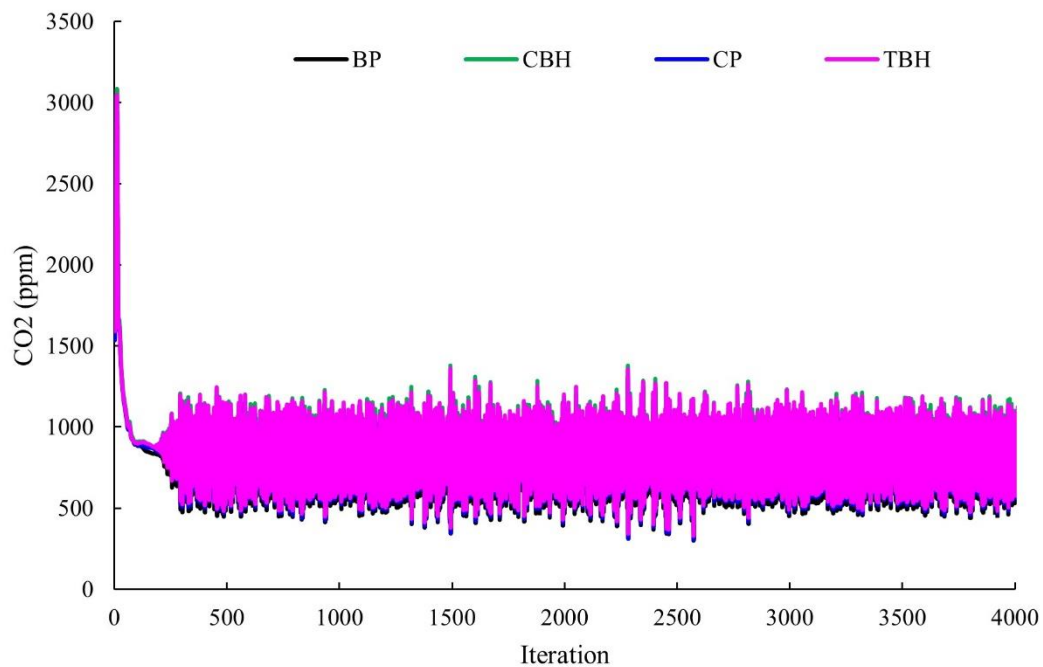


Fig. 39 Variations of the CO₂ levels in the selected planes versus iterations (BP= bottom plane, CBH=children's breathing height, CP=plane near the ceiling, TBH= the teacher's breathing height)

5.4.2 CO₂ model validation

A validation against Calautit et al. [139] was carried out to justify the present CFD model. Calautit et al. [139] explored the ventilation performance of different arrangements of windcatchers. As shown in Fig. 40, two in-line arranged windcatchers were used to ventilate a room with an even distribution of 15 people

and an empty room (both rooms were $5 \times 5 \times 3 \text{ m}^3$), respectively. The external air with a CO_2 level of 382 ppm entered from windcatcher 1 and diluted the CO_2 concentration inside room 1. Due to the recirculation effect, some of the exhaust air from windcatcher 1 re-entered room 2 and thus the inlet CO_2 concentration for windcatcher 2 was higher than 382 ppm.

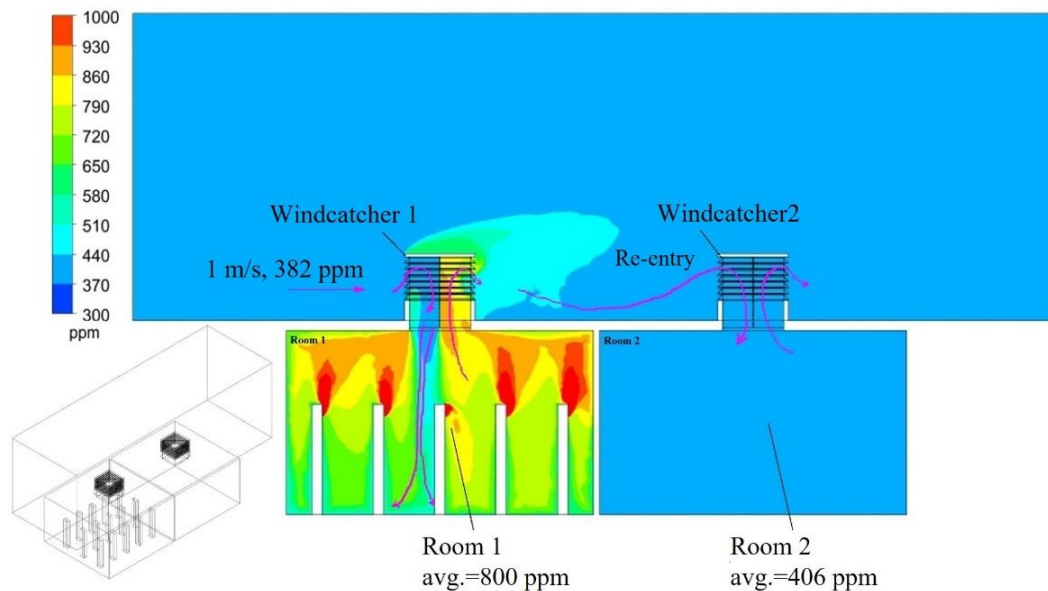


Fig. 40 Diagram of the airflow pathway in the validated model [139]

Fig. 41 and Table 18 show the average CO_2 level in rooms 1 and 2 at different wind speeds in the present CFD model compared to that in Calautit et al. [139]. It can be seen that the CFD simulations showed a good agreement. The average CO_2 level in room 1 was higher than that in empty room 2, due to the CO_2 release in room 1. The inlet CO_2 concentration in windcatcher 2 was higher than 382 ppm due to the recirculation effect from windcatcher 1. The CO_2 levels in both rooms showed a decreasing trend, as the external wind speed increased. The errors between the present study and Calautit et al. [139] were within 10% for most of the wind speeds, except for an error of 13% (indicated by orange) in the average CO_2 level in room 1 at a wind speed of 3 m/s. The smallest error of 0.8% (indicated by green) occurred in the average CO_2 level in room 2 at a wind speed of 5 m/s. It can be shown that the errors of this validation were within acceptable limits and that the present CFD settings were reasonable.

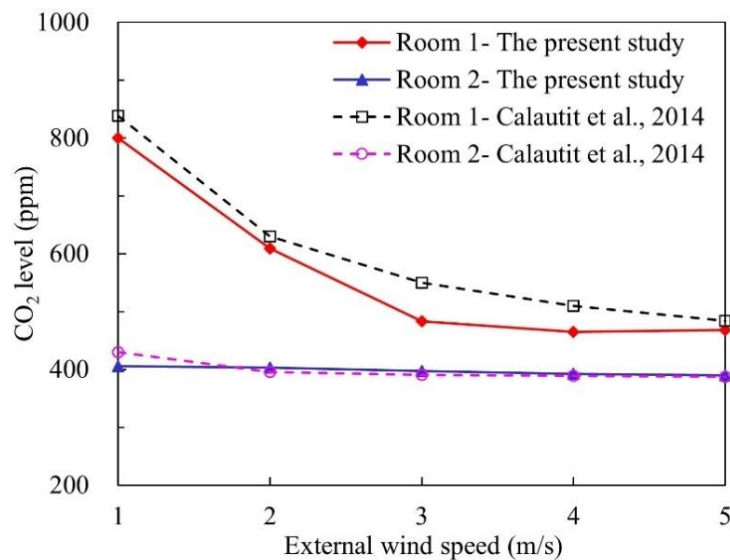


Fig. 41 Average CO₂ levels in rooms 1 and 2 at different external wind speeds in the present study and Calautit et al., 2014 [139]

Table 18 The present CFD model validation with Calautit et al. (2014) [139]

External wind speed (m/s)	Room 1 average CO ₂ level (ppm)		Error (±%)	Room 2 average CO ₂ level (ppm)		Error (±%)
	The present study	Calautit et al., 2014 [139]		The present study	Calautit et al., 2014 [139]	
1	800	838	4.8	406	430	5.9
2	609	630	3.4	403	396	1.8
3	483	550	13.8	397	391	1.5
4	465	510	9.8	392	389	0.9
5	468	484	3.4	390	387	0.8

5.4.3 Effect of occupant-influenced variables on the CO₂ levels in the occupied space ventilated by the windcatcher with THR

(1) CO₂ level and occupant activity levels

Many studies have confirmed that occupant activity levels can affect indoor CO₂ levels [172,205–207]. Although occupant activity was heterogeneous and dynamic, it was assumed that the activities of the teacher and children remained constant in this study.

Fig. 42 shows the effect of different occupant activity levels on the CO₂ level in the

selected planes. As can be seen, the CO₂ levels were higher at the occupants' breathing heights (CBH and TBH), followed by CP, and lowest at BP. This pattern was related to the air trajectory, as can be seen from Figs. 20-24 in Section 5.1. The external air entered the room through the windcatcher supply zone and continued to move downwards along the room's height until it reached the floor, where it dispersed in all directions. In addition, the CO₂ exhaled by the occupants tended to move upwards and escaped through the windcatcher exhaust quadrants.

It can also be observed that the more intense the occupant activity level, the higher the indoor CO₂ level. Compared to the sedentary scenario, the indoor average CO₂ levels increased by 28.6% for occupants in light work and by 46.2% for those in medium work. As demonstrated by Korsavi et al. [177], who monitored the CO₂ level in a primary school (naturally ventilated by windows and doors) in Coventry, UK, the occupant activity levels also had a significant impact on the indoor CO₂ levels. The change from sedentary activity to standing and walking resulted in a 29.3% increase in the average indoor CO₂ level. This was similar to the trend observed in this simulation work. The maximum CO₂ levels among the measurement planes when the occupants were performing sedentary and light working were 754 ppm and 940 ppm, respectively. However, the CO₂ level can reach 1089 ppm at TBH when all occupants are engaged in medium working.

Based on the results, it was clear that CO₂ levels at the breathing heights were significantly higher than those at other heights. As a result, more attention should be paid to the CO₂ levels in the breathing heights when using the windcatcher with THR. Furthermore, for buildings with different functions, designers should thoroughly consider the impact of occupant activity levels on indoor CO₂ concentration. For example, spaces like sports halls or playrooms should have a correctly sized windcatcher to provide a higher ventilation rate than offices. Overall, at a wind speed of 3 m/s and a CO₂ level of 382 ppm, the indoor CO₂ levels above the outdoors were within 550 ppm. The corresponding ventilation rate provided by the windcatcher with THR was 12.4 L/s/person. The CO₂ level from sedentary to light working can be classified as Category I, according to EN 16798-1 :2019. If the 15 occupants were performing medium work, the CO₂ level above the CBH was within Category II.

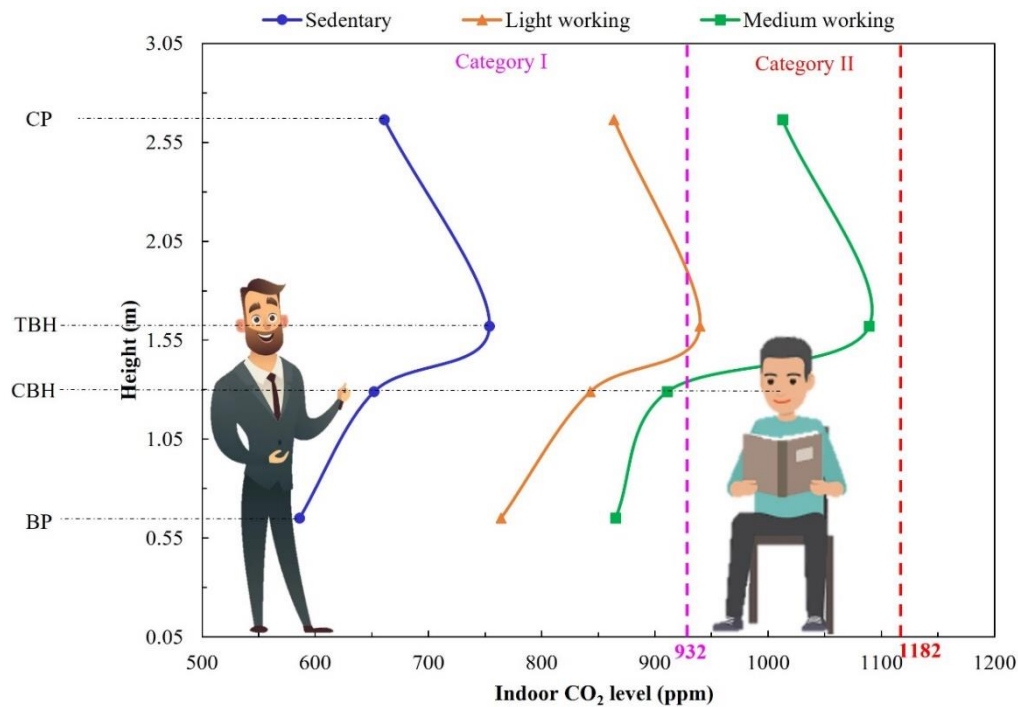


Fig. 42 The effect of occupant activity levels on the indoor CO₂ levels at the selected planes (external wind speed and CO₂ level at 3 m/s and 382 ppm; BP=bottom plane, CBH=children's breathing height, TBH=the teacher's breathing height, CP=plane near the ceiling)

(2) CO₂ level and occupant density (OD)

The following analysis will discuss the influence of occupancy density on indoor CO₂ levels. It was assumed that all the occupants were sedentary, as this could be the most common scenario in classrooms. Fig. 43 shows the effect of different occupant densities on the CO₂ level at the measurement planes. An overall trend of increasing CO₂ levels was observed as the OD increased, and the CO₂ accumulation rate was faster at TBH. In the sedentary scenario, as the number of occupants increased from 9 to 15 (OD from 2.6 to 1.7 m²/p), the CO₂ levels at BP, CBH, TBH and CP increased from 533, 559, 562, 557 ppm to 586 (10%), 652 (17%), 754 (34%), 661 (19%) ppm, respectively.

As recommended by Building Bulletin 99: Briefing Framework for Primary School Projects, the normal size for 30 students in primary or secondary schools was 70 m², i.e., the occupancy density was 2.3 m²/p, which means the windcatcher with THR can provide effective ventilation and lead to low indoor CO₂ levels. Fig. 44 also shows the correlation between the average indoor CO₂ level and the number of occupants based on the simulation results. It was predicted that the average indoor CO₂ level could reach 800 ppm as the number of occupants increased to 21 (1.19

m²/p).

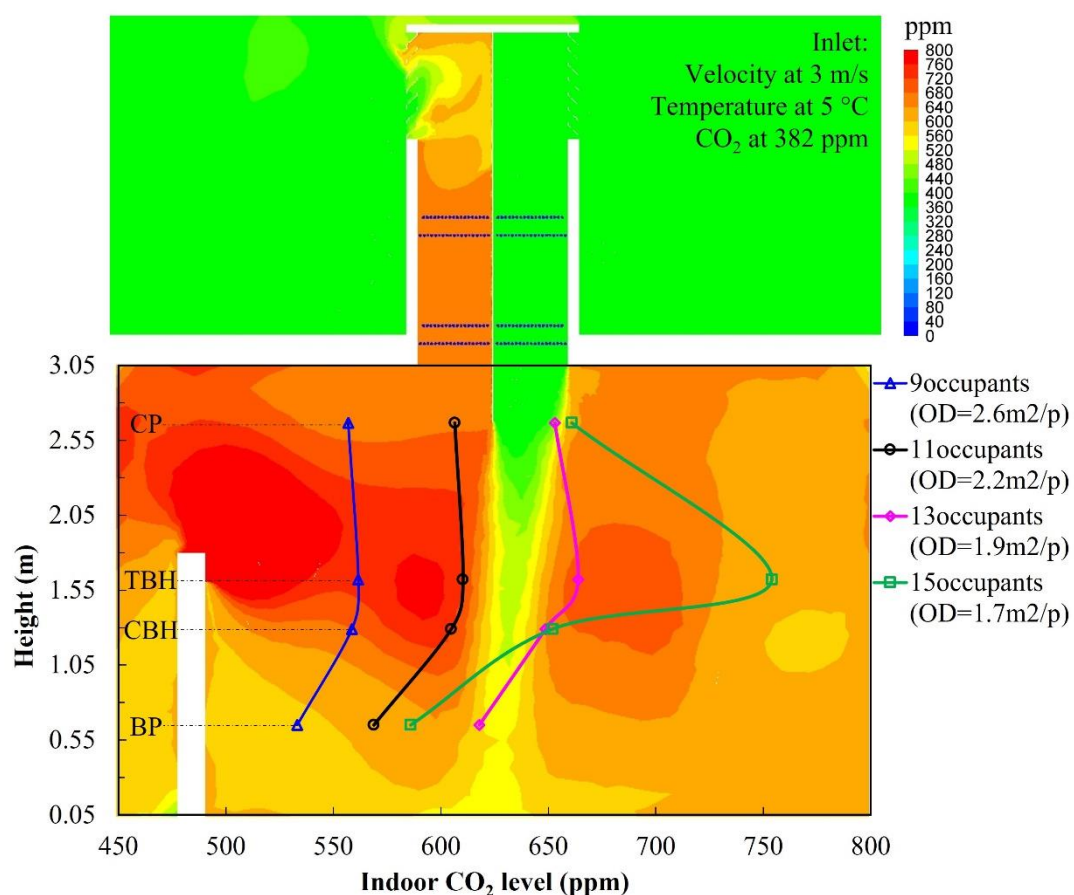


Fig. 43 The effect of occupant density (OD) on the indoor CO₂ levels at the measurement planes when occupants are performing sedentary activity (external wind speed and CO₂ level at 3 m/s and 382 ppm; BP= bottom plane, CBH=children's breathing height, TBH=the teacher's breathing height, CP=plane near the ceiling)

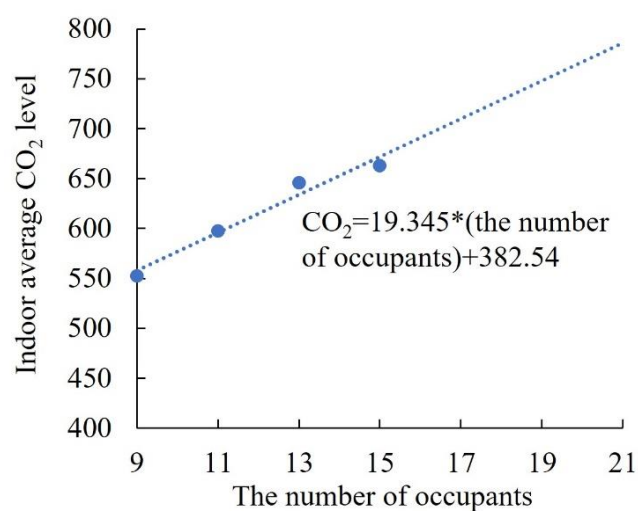


Fig. 44 The number of occupants vs indoor average CO₂ levels when occupants are

performing sedentary activity (external wind speed and CO₂ level at 3 m/s and 382 ppm)

5.4.4 Effect of external environment-influenced variables on the CO₂ levels in the occupied space ventilated by the windcatcher with THR

As mentioned in many studies, natural ventilation can be limited by external conditions, such as weather [83,185], pollution levels [208], and noise levels [209]. This section explored the effects of external wind speeds, CO₂ levels and heating/non-heating seasons (mainly characterising the external temperature difference) on indoor CO₂ levels.

(1) CO₂ level and wind speed

Wind speeds have a significant influence on windcatcher ventilation effectiveness. Fig. 45 shows the relationship between wind speed and the indoor CO₂ levels in the measurement planes. As the wind speed increased from 2 m/s to 3 m/s, the average CO₂ levels dropped from 747 ppm to 663 ppm. It should also be noted that the reduction in the CO₂ levels slowed down at the external wind speed of 3 m/s and above. For example, by increasing the wind speed to 5 m/s, the CO₂ level decreased to only 573 ppm. This provides a guide for implementing the windcatcher with THR in terms of striking a balance between ventilation and indoor CO₂ concentration, particularly in low-temperature and high-wind speed periods. A similar trend was also found in Calautit et al. [21], specifying the external CO₂ of 382 ppm and investigating the effect of the windcatcher with heat pipe heat recovery on indoor CO₂ level, as shown in Fig. 46. The comparison shows that although the trend is similar, the CO₂ levels in the windcatcher with THR are higher, which indicates that the proposed windcatcher is less capable of removing polluted air out of the space. This is because the windcatcher with THR has a two-stage passive heat recovery design, which provides a slightly lower ventilation rate and is, therefore, less effective in diluting indoor CO₂.

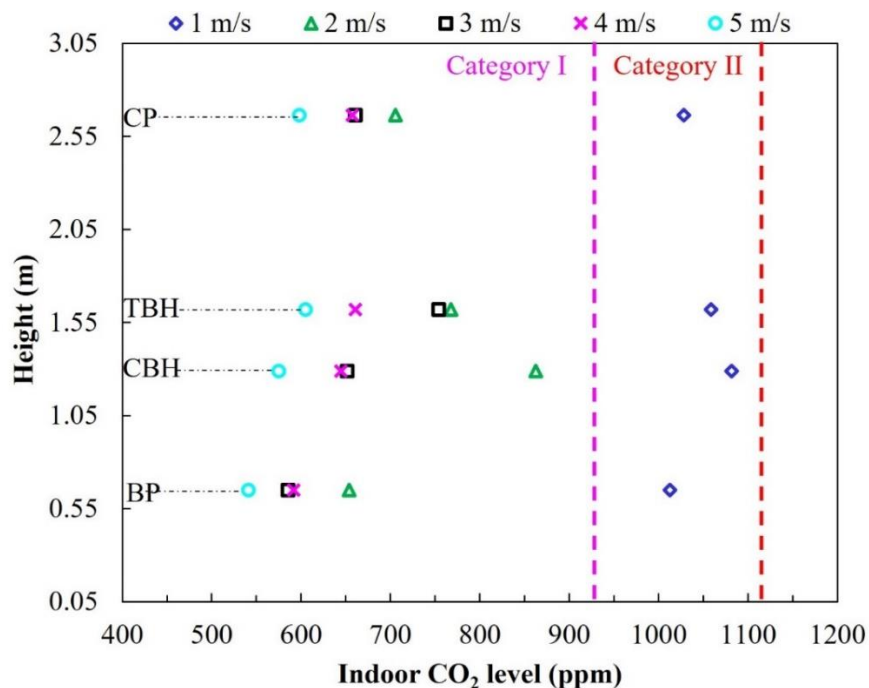


Fig. 45 The effect of external wind speed on the indoor CO₂ levels at different measurement planes (external CO₂ level at 382 ppm; BP=bottom plane, CBH=children's breathing height, TBH=the teacher's breathing height, CP=plane near the ceiling)

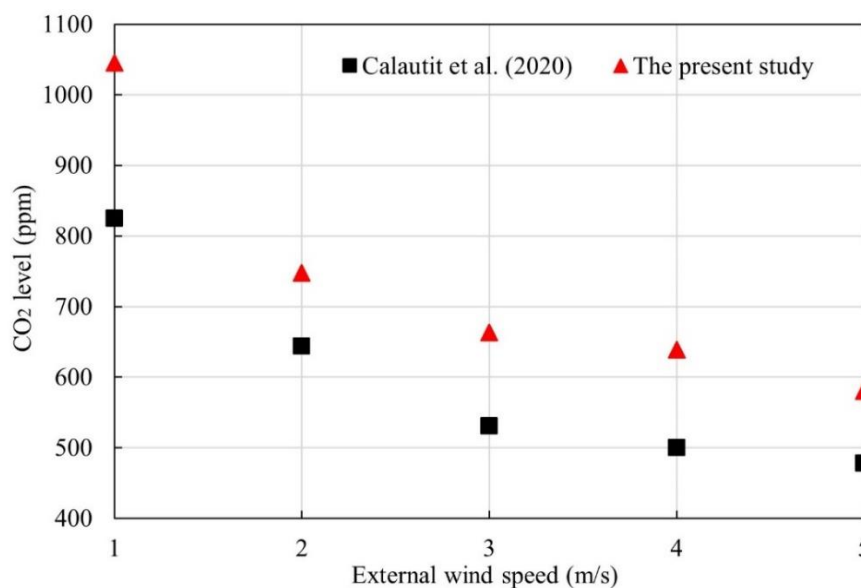


Fig. 46 The indoor average CO₂ levels in the present study versus in Calautit et al., 2020 [21]

The monthly average velocity for the UK from 1990 to 2020 was 4-6 m/s [162], which indicates that the indoor CO₂ concentration could be kept at a low level when using this windcatcher with THR for ventilation and heat recovery. However, in reality, buildings are generally not isolated, and there should be some

vegetation/buildings around, which means the wind speed could be lower than 4-6 m/s. Hence, to reduce the potential risk of inadequate ventilation when using the windcatcher with THR, it can be combined with windows/doors/skylights and a solar or low-powered fan to enhance ventilation.

(2) CO₂ level and external CO₂ level

Many studies have found a correlation between atmospheric CO₂ levels and population density, and heavy traffic [210,211]. For instance, George et al. [212] monitored the CO₂ levels in rural and urban areas of Maryland, USA, over a period of 5 years and found that CO₂ levels varied from 395-439 ppm in rural areas to 448-537 ppm in urban areas. Similarly, during a 1-year CO₂ field monitoring in Phoenix, USA, the daily maximum outdoor CO₂ level can reach 619 ppm, with a minimum of 390 ppm [213]. In addition, ongoing industrialisation and global warming also lead to an increasing trend in greenhouse gas emissions. Global CO₂ emissions have been increasing at an annual rate of 3.1% since 2000 [214]. Therefore, it is important to evaluate the effect of different external CO₂ levels on the indoor CO₂ levels in the space ventilated by the windcatcher with THR.

Fig. 47 shows the relationship between external and indoor CO₂ levels. The higher the level of external CO₂, the higher the level of indoor CO₂. At low outdoor CO₂ levels, such as 382 ppm, the maximum CO₂ level among the measurement planes was 784 ppm, and the average indoor CO₂ level was 663 ppm, at which point the CO₂ level was expected to reach Category I (EN 16798-1:2019). However, as the outdoor CO₂ level increased to 482 ppm (moderate) and further up to 782 ppm (high), the average indoor CO₂ level increased from 833 ppm to 1159 ppm. The CO₂ levels at the occupants breathing heights were generally higher than the average. Higher indoor CO₂ levels may also lead to more unpleasant indoor odours. Therefore, additional consideration should be given to the impacts of external CO₂ levels and other contaminants when employing this windcatcher ventilation approach in a more polluted or densely populated location, as the supply air may not be fresh.

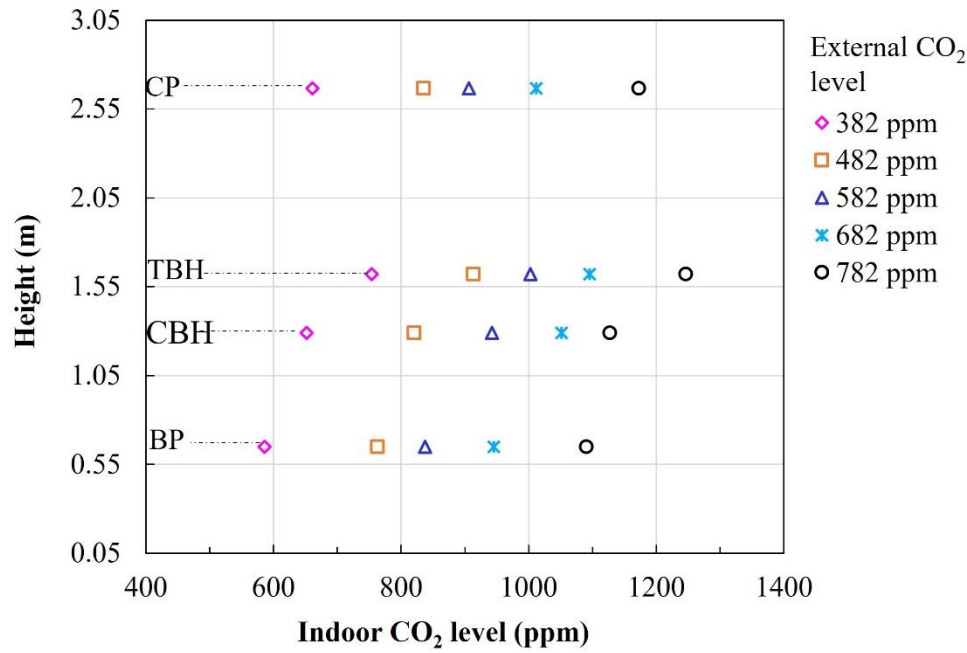


Fig. 47 The relationship between external and indoor CO₂ levels (external wind speed at 3 m/s; BP=bottom plane, CBH=children's breathing height, TBH=the teacher's breathing height, CP=plane near the ceiling)

(3) CO₂ level and heating/non-heating seasons

In the UK, heating seasons are mainly in November-December and January-March when the average external temperature is 5 °C; the typical non-heating seasons are from June to August, with an average external temperature of 15 °C from 1990 to 2020 [162]. It was assumed that the radiators operated at full power during the heating seasons and were switched off during the non-heating seasons.

Fig. 48 shows the relationship between the average indoor CO₂ level, supply velocity, exhaust velocity and heating/non-heating seasons. Compared to the heating seasons, the average indoor CO₂ level increased slightly during the non-heating season, i.e., from 663 ppm to 675 ppm, which is an increase of 1.8%. Correspondingly, the supply and exhaust velocity during the heating seasons were 0.75 m/s and 0.24 m/s, respectively, which were reduced to 0.70 m/s and 0.19 m/s during the non-heating seasons, respectively. The corresponding ventilation rate reduced from 12.4 L/s/person to 11.6 L/s/person from the heating to non-heating seasons. This is because a larger temperature difference between indoors and outdoors is achieved during heating seasons, creating a greater buoyancy effect which contributes to a larger ventilation rate.

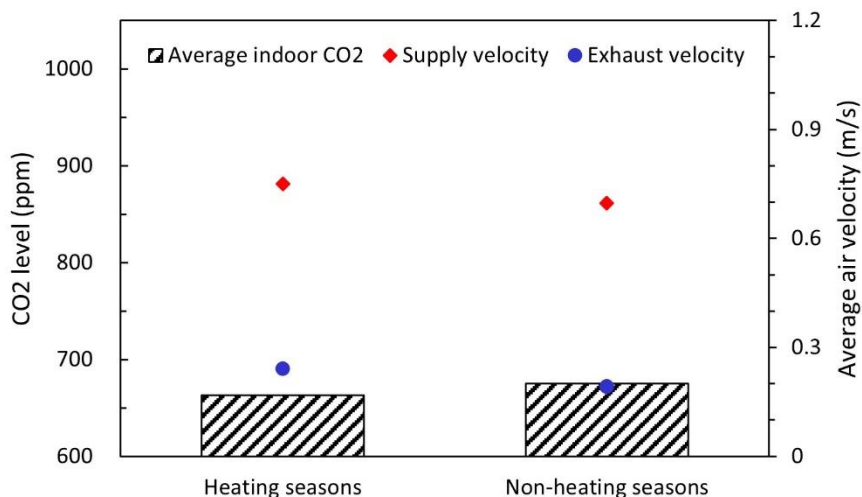


Fig. 48 The effect of heating and non-heating seasons on average indoor CO₂ level, supply velocity and exhaust velocity (external wind speed and CO₂ level at 3 m/s and 382 ppm)

Based on the set conditions, the windcatcher with THR ($W \times L \times H = 1 \times 1 \times 2.21 \text{ m}^3$) can provide adequate ventilation and maintain low indoor CO₂ levels during the heating and non-heating seasons. In addition, the ventilated space was assumed to be completely enclosed and only ventilated by the windcatcher. That means if the space is also equipped with other ventilation options, the indoor CO₂ concentration could be further reduced. In general, the external wind speed was the dominant factor in windcatcher ventilation, as compared to the buoyancy effect, which means the changes in CO₂ levels from heating seasons to non-heating seasons were not significant compared to the influence of wind speed. Therefore, in locations where wind speeds are adequately high throughout the year, heating or non-heating seasons should not be a significant factor for indoor CO₂ concentration.

However, under lower wind speed conditions, the buoyancy effect caused by a larger internal-external temperature difference may not be ignored [215], which means more attention should be paid to the operation of the system during heating and non-heating seasons and its impact on indoor CO₂ levels. As shown in Fig. 48, both the supply and exhaust air velocity decreased from heating to non-heating seasons, with a reduction of 7.6% and 24%, respectively. A slight increase of 1.8% in the indoor CO₂ concentration was also observed. This shows that inadequate ventilation and an unsatisfying indoor environment may be more likely to occur in non-heating seasons compared to heating seasons under the given conditions. However, it should be noted that in real life, occupants' adaptive behaviour may

influence indoor CO₂ concentration. For example, occupants should be more likely to open windows during non-heating seasons compared to during heating seasons.

5.4.5 Overall performance of the windcatcher with THR against a benchmark windcatcher based on CO₂ levels

To provide an overall view of the effect of adding passive THR on indoor CO₂ levels, this section compared the airflow characteristics with those in a benchmark windcatcher. Fig. 49 shows the CO₂ contribution at plane $x=0$ for the benchmark windcatcher (without THR) (a) and the windcatcher with THR (b). It can be seen that the CO₂ distribution was related to the characteristics of the velocity distribution (see Fig. 21). After being introduced into the below space via the windcatcher, the external air continued to move down until it reached the floor and dispersed in all directions. Comparing Fig. 49a,b, it can be seen that the addition of THR resulted in a higher overall CO₂ level, indicating that the introduction of THR caused a reduction in the CO₂ removal capacity of the windcatcher.

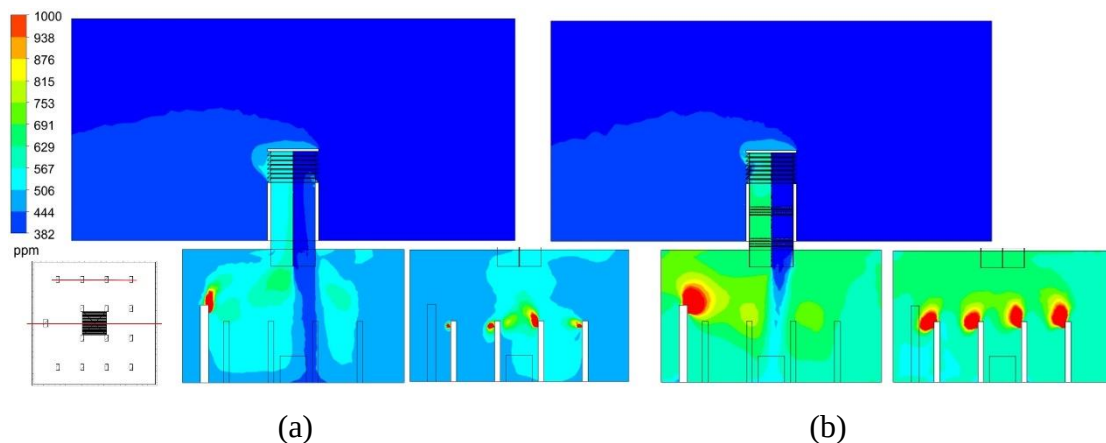


Fig. 49 The CO₂ distribution at plane $x=0$ in the benchmark windcatcher (a) and the windcatcher with THR (b) (external wind speed, temperature and CO₂ level at 3 m/s, 5 °C and 382 ppm)

Fig. 50 shows the CO₂ levels at the measurement planes for the windcatcher with THR and the benchmark windcatcher. The CO₂ levels in the space ventilated by the windcatcher with THR were higher than by the benchmark windcatcher. The CO₂ levels in CP, CBH, TBH and BP increased from 506, 551, 529 and 504 ppm to 586, 652, 754 and 661 ppm, respectively. The indoor average CO₂ level increased from 522 ppm to 663 ppm, an increase of 27%. Incorporating THR decreased the overall airflow velocity and increased the airflow pressure drop. The drop in supply velocity

can also partially explain the higher indoor CO₂ levels in the windcatcher with THR. Furthermore, the addition of THR reduced the size and intensity of the vortex zones on the leeward side, which also contributes to the decreasing ability to dilute indoor CO₂.

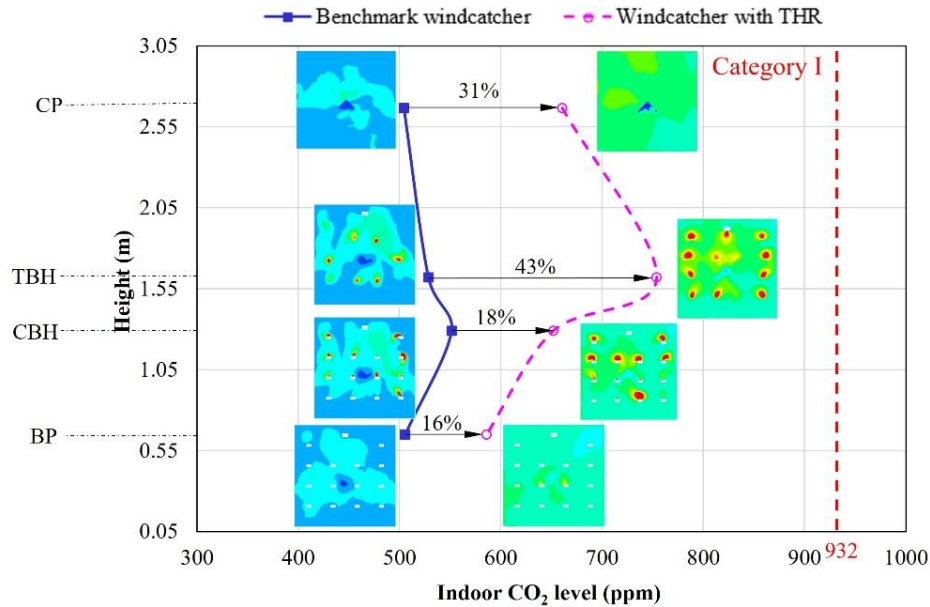


Fig. 50 The indoor CO₂ levels for the benchmark windcatcher and the windcatcher with THR (external wind speed, temperature and CO₂ level at 3 m/s, 5 °C and 382 ppm; BP=bottom plane, CBH=children's breathing height, TBH=the teacher's breathing height, CP=plane near the ceiling)

At an external wind speed, temperature and CO₂ level of 3 m/s, 5 °C and 382 ppm, respectively, the windcatcher ($W \times L \times H = 1 \times 1 \times 2.21 \text{ m}^3$) with THR can potentially increase the supply air temperature to 13 °C, which can improve occupants' thermal comfort and reduce heating energy consumption during cold/mild-cold climates. A ventilation rate of 10 L/s/person for a 15-people classroom ($W \times L \times H = 5 \times 5 \times 3 \text{ m}^3$) at the UK year-round wind speed can be provided. According to EN 16798-1:2019, the CO₂ level in the space ventilated by the windcatcher with THR can be classified as Category I (high-level expectations for vulnerable people) under the set conditions.

5.4.6 Summary

Chapter 5 investigated the impact of the windcatcher with THR on the indoor CO₂ concentration and spatial distribution. This chapter highlighted the influence of occupants (i.e., occupant activity level, occupant density) and the external environmental conditions (wind speed, CO₂ level and heating/non-heating seasons).

The main findings are presented below:

(1) Occupants-influenced variables: the indoor CO₂ level was higher at the occupants' breathing heights than at other heights. At an external CO₂ level of 382 ppm and a wind speed of 3 m/s, ventilation rates higher than 10 L/s/person can be achieved, and the average indoor CO₂ levels from sedentary to medium working increased from 663 ppm to 929 ppm (a 40% increase). The CO₂ level in the space ventilated by the windcatcher with THR was classified as Category I or II, according to EN 16798-1:2019. Designers should optimise windcatcher design and integration into buildings' design according to different uses, e.g., office, playroom, etc. Depending on the use of different spaces, more effective demand-controlled ventilation strategies could be developed. Higher occupant density increases the risk of occupants being exposed to high CO₂ levels. The windcatcher ($W \times L \times H = 1 \times 1 \times 2.21 \text{ m}^3$) with THR was expected to effectively ventilate the primary classrooms ($W \times L \times H = 5 \times 5 \times 3 \text{ m}^3$) with a normal density of 1.7-2.6 m²/p.

(2) External environment-influenced variables: high wind speeds contributed to reducing indoor CO₂ levels in the ventilated space. As the wind speed increased from 1 to 5 m/s, the average indoor CO₂ levels decreased from 1045 ppm to 580 ppm (an 80% reduction). The average monthly wind speed in the UK from 1990 to 2020 was between 4-6 m/s, so using the windcatcher with THR had a high probability of maintaining a low CO₂ level indoors. At low external wind speeds, it was recommended to open windows/doors/skylights to increase ventilation rate; or add other passive ventilation methods, such as solar chimneys, when designing/renovating buildings with windcatcher ventilation. The limitations of the windcatcher ventilation with THR should be considered when the building is in a densely populated or highly polluted area. The results showed that the effect of the heating and non-heating seasons may not be significant where the wind speeds are at adequately high levels such as 3 m/s. Inadequate ventilation and high indoor CO₂ levels may be more likely to occur in non-heating seasons compared to heating seasons based on the set conditions. It should be noted that occupants' adaptive behaviour should be considered in real life.

(3) Compared to the benchmark windcatcher, the airflow velocity was lower, and the average indoor CO₂ level was 27% higher in the windcatcher with THR. Nonetheless, both configurations can provide a ventilation rate of more than 10

L/s/person at an external wind speed of 3 m/s, at which point the CO₂ level was expected to reach Category I, according to EN 16798-1:2019.

However, it should be noted that this study did not intend to model a real-life classroom model. The classroom model was simplified and assumed to be fully enclosed and isolated. In addition, this study did not consider the effects of outdoor microenvironment and different school building stocks on indoor airflow patterns. In practical applications, the design and integration of windcatchers into classrooms must be treated as problem-specific, and more factors, such as buildings' operations/designs, should be considered. However, the approach proposed in this thesis, and the factors influencing CO₂ distribution can be used as a reference for future studies on the effect of windcatchers on indoor CO₂ levels.

Chapter 6 Conclusions and Future Work

6.1 Conclusions

This research conceptualised a windcatcher device with passive tube heat recovery (THR) for mild-cold or cold climates, such as the UK. ANSYS Fluent 18.1 was employed for steady-state RANS simulations, and the RNG k-epsilon model was adopted to simulate turbulent properties. The CFD model was validated against the experimental work in the existing literature. The proposed windcatcher's performance in ventilation rate, thermal comfort, and IAQ was evaluated through a validated CFD model. The optimal thermal performance of THR was achieved with a smaller LP, while the influence of TP was minimal. This optimal tube configuration can provide a ventilation rate exceeding 10 L/s/person at a wind speed of 3 m/s or higher, resulting in a supply and indoor temperature increase of 0.8 °C and 4.75 °C, respectively. Incorporating THR can improve thermal comfort and potentially extend the function time of windcatchers throughout the year in the UK or in similar temperate climates with cool to cold winters. The IAQ in a typical-sized UK primary classroom equipped with the proposed windcatcher may reach Category I or II when the wind speed is 3 m/s or higher. The detailed findings are summarised as follows.

(1) THR can collect and store some of the indoor heat gains that have always been wasted. Instead, the collected heat can be transferred to the cold supply air, thereby improving the incoming air's temperature. As LP and TP are reduced to 25 mm and 60 mm, respectively, the supply temperature reaches the maximum value of 11.28 °C. It is recommended to adopt smaller LP and TP if the required ventilation rate can be provided. It should be noted the improvement of the air temperature in the occupied space is a result of the joint action of heat recovery from the THR device and the reduction in ventilation heat loss due to lower airflow velocity. When the wind speed increases from 1 m/s to 5 m/s, the supply temperature is reduced from 11.28 °C to 5.21 °C, while the average supply velocity increases from 0.22 m/s to 1.08 m/s. The optimal windcatcher's design can provide sufficient ventilation for a classroom occupied by 15 people (10 L/s/person) at external wind speeds of 3 m/s and higher.

(2) Following the optimisation of the heat recovery performance and ventilation rate, this research also looks into the ability of the proposed windcatcher to ventilate, cool during summertime and preheat during wintertime. The year-round thermal comfort was evaluated by simulating monthly wind speeds and temperatures in the UK for the years 1990-2021. The results show that the highest indoor temperature (24.35 °C) and supply temperature (20.19 °C) are 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) occur 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 quadrant and the below room are 23.35 °C and 19.40 °C, respectively, an improvement of 7.64 °C and 4.77 °C compared to the windcatcher without THR. In addition, according to the static overheating criteria, during the summertime (June-August), the risk of overheating in the room is low but additional ventilation strategies are recommended to improve thermal comfort during the summer months. During the wintertime (November-December and January-March), the windcatcher with THR reduces the ventilation heat loss by an average of 7.3%-8.1% and increases the supply temperature by 3.7%-18.2% compared to that without THR. Furthermore, throughout the year, the windcatcher 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 is 43.5%-96.9% above the recommended value of 10 L/s/person.

(3) Moreover, the effects of the proposed windcatcher ventilation on the levels and spatial distribution of indoor CO₂ are investigated at various environmental and occupancy conditions. The indoor CO₂ levels are higher at the occupants' breathing heights than at other heights. At an external CO₂ level of 382 ppm and a wind speed of 3 m/s, a ventilation rate of more than 10 L/s/person can be achieved, and the average indoor CO₂ levels from sedentary to medium working increase from 663 ppm to 929 ppm (a 40% increase). The CO₂ level in the space ventilated by the windcatcher with THR is classified as Category I or II, according to EN 16798-1:2019. Designers should optimise windcatcher designs and integrations into buildings according to different uses, e.g., office, playroom, etc. More effective demand-controlled ventilation strategies can be developed. Higher occupant density increases the risk of occupants being exposed to high CO₂ levels. In this study, the windcatcher ($W \times L \times H = 1 \times 1 \times 2.21 \text{ m}^3$) with THR is expected to effectively ventilate the room ($W \times L \times H = 5 \times 5 \times 3 \text{ m}^3$) with a normal density of 1.7-2.6 m²/p. High wind

speeds contribute to reducing indoor CO₂ levels in the occupied space. As the wind speed increases from 1 to 5 m/s, the average indoor CO₂ levels decrease from 1045 ppm to 580 ppm (an 80% reduction). The average monthly wind speed in the UK from 1990 to 2020 is between 4-6 m/s, so using the windcatcher with THR has a high probability of maintaining a low CO₂ level indoors. At low external wind speeds, it is recommended to open windows/doors/skylights to increase ventilation rate; or add other passive ventilation methods, such as solar chimneys, when designing/renovating buildings with windcatcher ventilation. The limitations of the windcatcher ventilation with THR should be considered when the building is in a densely populated or highly polluted area. The results show that the effects of the heating and non-heating seasons may not be significant where the wind speeds are at adequately high levels, such as 3 m/s. Inadequate ventilation and high indoor CO₂ levels are more likely to occur in non-heating seasons compared to heating seasons based on the set conditions. It should be noted that occupants' adaptive behaviour should be considered in real life. At an external wind speed of 3 m/s, at which point the CO₂ level was expected to reach Category I, according to EN 16798-1:2019.

6.2 Recommendations for future work

Windcatchers have been proposed to combine with various heating or cooling technologies to improve their applicability across different climates. However, windcatchers' cooling or heating efficiency, and their long-term cost-effectiveness remain unclear. The dehumidification function of windcatchers has been underdeveloped. Regarding the tube heat exchanger integration proposed in this research, modifying the shapes of the tubes could reduce airflow resistance and enhance the system efficiency. The heat conduction efficiency across the tube heat exchanger should also be discussed to evaluate the heat transfer efficiency. Effective heat conduction ensures rapid heat transfer, reducing the time required to reach the desired temperature or heating effect. Factors such as infiltration and solar radiation should be further considered to fully evaluate the windcatcher's performance in real-world settings. Further research on windcatcher materials with varying thermal properties may be of interest.

An increasing number of studies focused on the effects of windcatcher ventilation on indoor thermal environments. However, very few studies have discussed the potential overheating risk caused by windcatcher ventilation, especially for the

modifications that could increase the airflow resistance. Further in-depth research is required to look into whether windcatcher ventilation can effectively cope with the challenges posed by global warming trends and to explore strategies for reducing failed ventilation during extreme weather conditions. The resilience of windcatchers in heat waves needs more investigation. Moreover, many studies on windcatchers' IAQ performance employed indoor CO₂ concentration as an indicator, while future research could look into the effects of indoor air pollutants, such as VOCs. It also should be noted that although CO₂ can be used as an IAQ indicator, the limitations cannot be ignored. High CO₂ concentrations are more likely to indicate inadequate ventilation, potentially higher levels of other indoor air pollutants and unpleasant occupants' odours.

Lastly, very few studies have quantitatively measured the energy savings achieved by retrofitting buildings with windcatchers. There is also a lack of scenario-based field experiments regarding the energy performance between windcatcher ventilation and other ventilation methods. Few studies have conducted the economic cost analysis or LCA of windcatcher ventilation, which is important to understand the long-term cost-effectiveness. Most previous studies have mainly used numerical modelling and wind tunnel experiments, with building models that are always hypothesised or simplified. Limited factors have been considered when investigating windcatcher performance, while the effects of occupants, surrounding context, and building design/operation have not been reported.

In addition to these discussions, there are other factors that should be taken into consideration, which are summarised below.

- (1) Acoustic/sound pollution evaluation: few studies have investigated the structural vibration and noise levels of windcatchers, factors that can impact their structural integrity, cost analysis, maintenance, and indoor environmental comfort.
- (2) Moisture/condensation evaluation: more studies should be conducted to address the issue of moisture or condensation in windcatchers, especially for those coupled with water evaporation cooling technology. Prolonged high humidity levels in warm conditions can lead to mould growth, which is harmful to occupants' health. Moreover, research has shown that moisture levels can impact the airborne transmission of respiratory viruses. Although the correlation between air moisture levels and airborne transmission remains unclear, it is important to evaluate moisture/condensation in windcatcher ventilation, especially in tropical or near-

coastal areas. In such cases, windcatchers can be equipped with dehumidification techniques as necessary.

(3) Controllability/control strategy: modern windcatchers require more effort in integrating intelligent control systems. For example, at high outdoor wind speeds, the airflow volume induced by windcatchers should be regulated by adjusting the dampers to reduce excessive ventilation. While at low outdoor wind speeds, the dampers should be fully opened to improve the ventilation rate. In terms of introducing different cooling/heating devices into windcatchers, future efforts could be dedicated to maintaining a low pressure drop.

(4) Cross transmission of pollution from outside or other buildings: external wind plays a significant role in windcatcher ventilation. This highlights the potential impact of wind on the transmission of pollution. Under specific wind conditions, pollution from external sources or neighbouring buildings can be transmitted indoors. The utilisation of windcatcher ventilation in highly polluted or densely populated areas may be limited, and it is necessary to adopt air purification methods before outdoor air enters the occupied spaces. The possibility of air cross-contamination caused by windcatcher ventilation, especially in multi-storey buildings, should also be considered. Research on dust entry through windcatchers has also been limited.

In the UK, the windcatcher commercial market has not witnessed significant growth and may even be experiencing a decline, particularly after the COVID-19 pandemic. While the analysis of the commercial market and case studies primarily focuses on the UK, the findings, such as the challenges and potential opportunities, can be applied to other regions with temperate climates that can benefit from such technology. The stagnation of the market can be attributed to various factors, including low awareness and lack of regulatory incentives, cost considerations, aesthetic preferences, and misconceptions or concerns regarding the effectiveness of windcatchers. Currently, the increasing emphasis on renewable energy and the demand for healthier indoor environments, as advocated by the global climate action and the pandemic, may favour the promotion of windcatcher technology. However, these considerations must be addressed before large-scale commercial deployment can take place.

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