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Review article

Performance evaluation of active chilled beam systems for office buildings – A literature review

Haider Latif [a,*], Goran Hultmark [a,b], Samira Rahnama [a], Alessandro Maccarini [a], Alireza Afshari [a]

[a] Department of the Built Environment, Aalborg University, Copenhagen, Denmark
[b] Indoor Climate Solutions, Lindab A/S, Denmark

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ABSTRACT

The applications of Active Chilled Beam (ACB) technology have increased over the two decades and received a lot of attention in research publications due to its ability to provide a suitable indoor climate for building occupants with minimum energy use. In the literature, no comprehensive review on ACB systems has been reported. This study provides a review of the ACB technology by investigating its functions, component and control strategies, design and testing techniques, and its applications for office buildings. Literature shows that ACB systems fulfil sensible cooling demands for office setups and can provide a space-friendly solution by making effective use of ceiling space in buildings. The cooling demands can be met with high induction rates, proper coil circuitry design, and optimum chilled water supply temperature. The high induction rates with more even air-jet patterns inside the terminal unit of ACBs can be achieved by using nozzles of different sizes, cross-sections, and lengths. Studies show that a reduction in energy use up to 30% can be achieved by ACBs as compared to conventional HVAC systems.

Introduction

The rapid growth of world energy use has meant that a critical situation has developed due to the depletion of energy resources and negative environmental impacts [1,2]. The building sector accounts for a significant portion of the world's total electricity usage. The energy demand in residential and commercial buildings has gradually increased, with figures reaching up to 40% in developed countries [3]. According to the International Energy Agency (IEA), the world's total electricity use in buildings is expected to increase by an average of 1.5%/year by 2040 [4]. The new energy-efficient policies for buildings need to be adopted to combat these challenges. In the European Union, continual effort is being made to set out strict building standards and strategies to meet the EUs long-term 2050 goals [5]. Despite these efforts, cooling demand is increasing due to global climate change, affordability of air-conditioning, and increased living standards [6]. A significant fraction of this energy use in buildings comes from Heating, Ventilation and Air Conditioning (HVAC) systems [3,7], as people spend up to 90% of their time indoors [8]. The Global Carbon Capture and Storage (CSS) Institute published projections about the increasing need for cooling equipment in Europe [9]. Hence, sustainable space-cooling technologies are desired. The IEA's future projections regarding the growth of global electricity demand for space cooling show similar stats, as shown in Fig. 1 [10].

History of chilled beams

Technological change has played a critical role in the green transition and sorting out global issues. These challenges have led many researchers to develop different energy-efficient and cutting-edge technologies. Over the past 50 years, many developments have taken place in manufacturing advanced HVAC products to establish high-quality indoor climate conditions on commercial scales [11,12]. A variety of these HVAC products employed in building applications include diffusers, fan coil units, ventilators, chilled beams, and diffused ceilings, etc. These products have been modified over time to provide suitable Indoor Air Quality (IAQ) and thermal comfort for building occupants [13]. Based on the working principle, chilled beams are categorised into two main types: passive and active. Passive Chilled Beams (PCBs) [14] were first developed in Norway in 1975. These PCBs are operated with a cooling coil in an enclosure. They are suspended from the room ceiling, as in Fig. 2. Chilled water is circulated through the coil, and cooling

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* Corresponding author.
E-mail address: hala@sbi.aau.dk (H. Latif).

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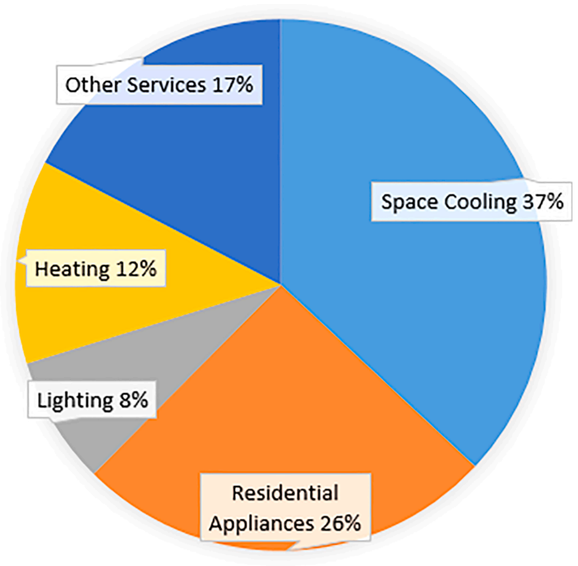


Fig. 1. Share of global electricity demand growth until 2050 [10].

happens in the occupied space through the natural convection of air [15]. Due to low sensible cooling capacity and inability to provide heating and fresh air, PCBs are less applicable for office buildings [16,17]. Therefore, more attention is given to Active Chilled Beams (ACBs) in literature.

ACBs were introduced in 1998 and were suspended from the ceiling to make use of the Coandă effect for horizontal air distribution along the ceiling [16,18]. The ductwork transports fresh air from outside to the pressure box called as primary air plenum. The air inside this plenum is called primary air. The primary plenum is usually set at a pressure that is 30 Pa to 120 Pa above room pressure [19]. These chilled beam designs proved to be more effective than PCBs. 4-Way ACBs were first introduced in 2004 to produce multi-directional or circular air distribution patterns [20]. Both ACBs and PCBs are designed to provide sensible cooling for office buildings. Thus, a Dedicated Outdoor Air System (DOAS) is often required with ACBs to achieve dehumidification. Table 1 shows that the sensible cooling capacities of ACBs are approximately twice that of PCBs [21].

Table 1
Chilled Beams' Sensible Cooling Capacities [19].

Chilled Beam types	Sensible Cooling Capacities* W/m^2
Passive Chilled Beams	60–70
Active Chilled Beams	130–160

*Taking air speed 0.25 m/s into account in the occupied zone, passive chilled beam and ACB will have maximum cooling capacities of 50 W/m^2 and 100 W/m^2, respectively.

Today, ACB systems are considered to be one of the significant energy-saving systems in the countries which use them around the world. Being listed as one of the most promising HVAC-related technologies by the American Council for Energy-Efficient Economy (ACEEE) in 2009 [22], use of ACBs is considered a standard practice in Europe, the USA and Australia as an alternative to conventional Fan Coil and VAV systems.

Working principle of active chilled beams

ACBs (also known as induction diffusers) consist of a heat exchanger to pass chilled or hot water depending on their function. Chilled water temperature, usually between 14 °C and 18 °C, is maintained above the dew point to avoid condensation on the cooling coil [19,23]. ACB systems can be used for heating. Despite their multiple functions, ACB studies relating to the primary heating mode are limited in the literature. In heating mode, water between 30 °C and 45 °C is cycled through the coils. The flow rate of the water determines the room temperature [24]. Processed air from the Air Handling Unit (AHU) is forced into the set of nozzles as primary air. The purpose of the nozzles is to provide high speed primary air and consequently create high dynamic pressure and low static pressure to facilitate induction i.e., pressure differences between mixing chamber and room. The ductwork takes this outside air to the primary air plenum. The primary air plenum is usually set at a pressure that is 30 Pa to 120 Pa above room pressure [19]. The primary air is mixed with the induced air (or secondary air) in the mixing chamber and supplied into the occupied zone as a mixture called supply air [25]. ACBs are mostly fixed in the ceiling to make use of the Coandă effect for proper air distribution. This Coandă effect can be increased with a higher pressure drop or if there is a smaller temperature difference between the discharged air and the air in the room [17]. The ~~warm~~ room air (secondary air) goes up and is induced to the mixing chamber. This secondary air cools (is chilled) down after passing through the

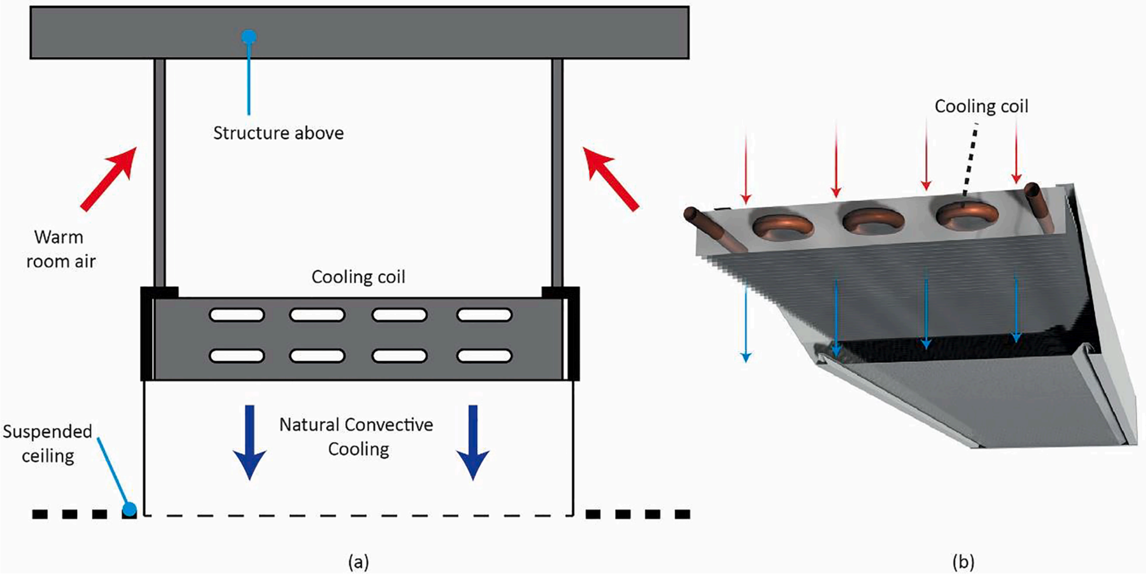


Fig. 2. (a) Passive Chilled Beam working principle (b) Actual passive chilled beam [15].

cooling coils. The heat in the room is taken away by the chilled water inside the cooling coils. The heat transfer between the secondary air and the cooling coil is made forced convection – the operating principle as shown in Fig. 3.

ACBs usually require less ceiling space (up to 0.3 m) and ductwork, classifying it into distinct architecture for office setups [16].

Indoor climate by ACBs

ACBs are a complete indoor climate solution for cooling, heating and ventilation for commercial buildings, hospitals, laboratories, and schools. ACBs can provide satisfactory indoor climate including thermal comfort and Indoor Air Quality (IAQ) [26]. The thermal comfort is provided by the tempered supply air, and the cooling and heating of the air in the room by heating and cooling coil respectively. The Indoor Air Quality (IAQ) is provided first by filtration of the primary air. The room air quality can also be improved by filtration of the recirculated room air before it reaches the cooling coil [27].

Comparison with different HVAC systems

Conventionally, HVAC systems are classified as centralized and decentralized systems according to the functions they provide to the whole building [28]. Centralized HVAC systems are designed to provide air conditioning to the whole building, whereas decentralized or local systems provide separate air conditioning to specific zones of the building. Table 2 shows a detailed comparative overview of centralized HVAC systems for the office buildings.

Most of the studies indicate that ACB systems used in buildings for cooling are more efficient than conventional VAVs in terms of energy use [30]. This is because primary air mostly fulfils the ventilation needs, while chilled water treats the most sensible cooling loads [21]. The comparative analysis between ACBs and conventional VAV systems shows that systems' performance is mainly dependent on the specific building and climate of the locality. The American Council for an Energy-Efficiency Economy reports that energy savings of about 30% can be estimated when comparing ACB systems with traditional VAV systems [22]. However, some still argue that these conventional VAV systems are more energy-efficient than ACBs [31].

In terms of costs, the smaller ductwork and reduced space requirements required in ACB installations lead to the smaller building volume as compared to conventional VAV systems, and consequently to reduce installation and construction costs [21]. Although the initial product cost of ACB was found more than conventional diffusers by some manufacturers [32], this additional cost can be offset by long-term energy savings and low life-cycle maintenance costs. However, the product cost of the ACB units in comparison to different HVAC system was dependent more on manufacturer and market penetration. The low maintenance cost of ACBs is due to no fans or fewer electric connections required to run the system as compared to traditional VAV systems [16]. Different scientific research carried out over the past 20 years to design ACB systems for office setups is explained through the literature below.

Review objective

With the growing market for ACB systems, a lot of research and analytical studies have been carried out to find out about the performance of ACBs under real office conditions [25]. These studies show that a significant reduction in energy use can be achieved through ACBs due to their high chilled water temperature, optimal nozzle and outlet designs, and their prominent induction feature. Despite its advantages, there is a lack of compiled framework on ACBs in literature for the HVAC research community and field engineers to identify the gaps between research and practice. The objective of this paper is to have a detailed study of the characteristics of ACB systems, the design techniques associated with ACBs and research methods adopted, with a review on the applied experience of their usage for office setups.

Methodology

The terms signifying chilled beams and their impact on thermal comfort and building energy performance were searched through several scientific databases and search engines, including Science Direct, Web of International Patents, Taylor and Francis Online, and Google Scholar. A list of keywords was developed by methodically entering each keyword and combinations of keywords into the search engines, including: ACBs, induction diffusers, air–water systems, ventilation, heating, cooling in combination with thermal comfort and energy performance.

The articles were reviewed, and the compilation process was denoted by a list of relevant articles, patents and reports; and this list was double-checked for any sign of duplication. The screening process for the

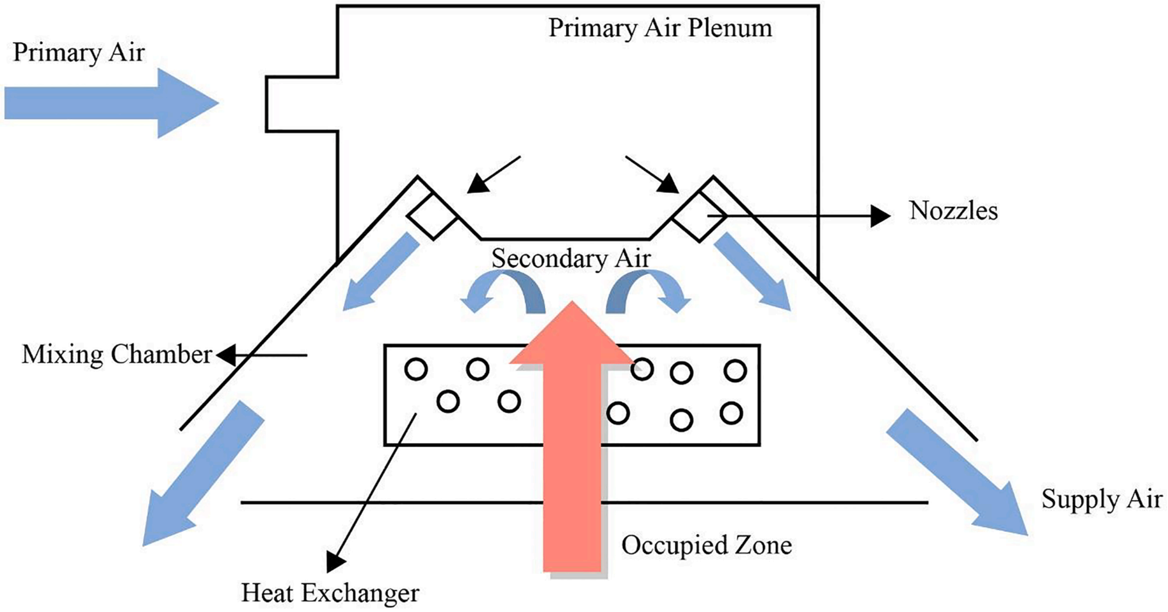


Fig. 3. Working principle of an Active Chilled Beam [23].

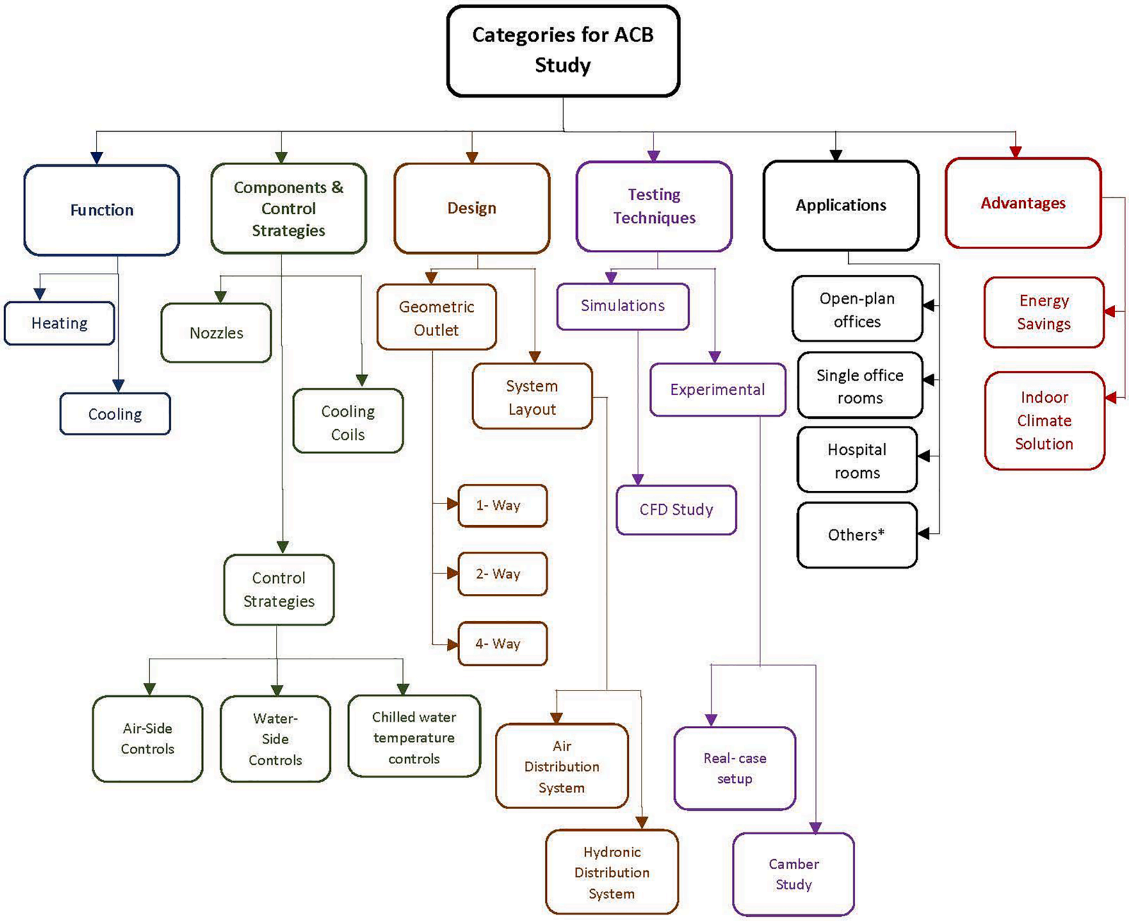
Table 2
Comparisons of different HVAC Systems.

	Types	Function	Classifications	Characteristics	
Central HVAC System	All-Air systems* [29]	The thermal heat transfer medium through the building duct system is air.	- Constant Air Volume (CAV) system - Variable Air Volume (VAV) system	**CAV** - Provides constant airflow at variable temperature - Designed for peak load conditions. - CAV systems are less expensive (in terms of initial costs) and simpler to design as compared to VAV systems.	**VAV*** - Provides variable airflow at a constant air temperature - Designed for instantaneous load conditions. - VAV provide energy savings due to less fan power and less heating or cooling of the primary air.
	Air-water Systems [28]	This hybrid system involves both water and air as medium to transfer thermal load in building.	- Fan Coil Unit (FCU) - Active Chilled Beams or Induction Units	**Fan Coil Unit** - Circulation of the room is done by a fan.	**Active Chilled Beams** - The circulation of the room air is done by induction.
	All-water systems [28]	The heat transfer takes place between the cooling/heating coil and room air without dependency on ventilation system.	- Fan Coil Units - Passive Chilled Beams	**Fan Coil Unit** Circulation of the room is done by a fan	**Passive Chilled Beams** The circulation of the room air is done by natural convection.

*VAV systems studied in this paper focus on cooling room air with the chilled air. The heating system can be of radiators, floor heating, ceiling panels.

shortlisting initially constituted a list of 216 peer-reviewed articles, 38 conferences and 26 patents and reports on ACBs and their performance on commercial scales. These were published mainly between 1998 and 2020. Based on the unique design types and several technologies that are essential in improving efficiency and performance of ACBs, these articles and reports were further categorised. A final list of 150 works of literature was attained after a complete and thorough process. These articles were classified into six categories: ACB functions, components and control strategies, design, testing techniques, applications, and advantages. These categories were divided to sub-categories to further investigate and give a detailed overview of each main category, as shown in Fig. 4.

Systematically, the review outcomes were then summarised. Subsequently, the summary was checked to determine whether there was detailed information that needed to be included in the review paper.



*Include commercial buildings, laboratories and schools etc.

Fig. 4. Categories for making ACB review.

Categories of research investigation for active chilled beams

Based on literature studies, various design strategies for ACB systems have been formulated to give forward-looking guidance to HVAC engineers, consultants, and researchers with regard to choosing suitable design criteria for the office buildings. An overview of ACB performance is given in detail below by exploring each fundamental component of the system and its design and functions.

Geometric shape and design

The shape and design of ACB systems have a crucial role in the HVAC industry. It is sometimes challenging for engineers to establish a suitable work environment for building occupants, as ACB systems cannot meet high sensible cooling requirements for large spaces [33]. Some spaces are considered suitable for chilled beams, but for other spaces, this technology may not be appropriate. Studies show that open-plan offices with high heat loads can have abnormal air circulation patterns due to asymmetrically placed chilled beams, and these may cause a draught risk [34,35].

The geometry of ACBs is one area where researchers are improving efficiency through design modifications. An ACB unit comprises a heat exchanger, primary air plenum, mixing chamber and nozzles, as shown in Fig. 3. Studies have shown that the arrangement of ACBs installed in open-plan offices may result in a draught sensation due to the asymmetrical layout of terminal units concerning room geometry and heat sources [36]. One type of ACB design applied to a given space may not fulfil high load requirements for other spaces. Upadhyay et al. [37] evaluated the performance of ACB systems for an actual office setup under steady-state conditions and concluded that the design of ACBs requires further research and investigation in a controlled environment. The geometry of ACB systems is mainly designed multiway according to the office space requirements. Based on supply direction, ACBs can be divided into 1-Way, 2-Way and 4-Way (or 360° air distribution) to have the airflow distribution patterns for the required room geometry, see Figs. 5 and 6. Cehlin et al. [26] carried out a comparative analysis by experimentally measuring air change effectiveness (ACE) and air exchange effectiveness (AEE) of 4-Way and 1-Way ACBs in an office setup. Results indicated that 4-Way ACB design provides efficient mixing with the room air and results in a higher mean age of air uniformity throughout the room than with the 1-Way ACB setup. At the same time, local air-change effectiveness (ACE_p) of the unidirectional flow 1-Way ACB design shows improvement in the local air quality and local thermal condition for the single office setups. These 1-Way ACBs are often used for customised applications like patient rooms in hospitals, where there is a need to maintain local IAQ and thermal comfort [38].

Most of the climate chamber studies for ACB systems have been carried out using 2-Way ACBs as terminal units, see Table 3. The 2-Way ACB units have been used in experimental and simulation studies to provide design guidelines and explore turbulent velocity behaviours in the occupied zones [39]. Cai et al. declared the terminal part of ACB systems as an essential component for assessing the overall system's performance and highlighted heat exchangers issues experimentally using a 2-Way discharge ACB terminal unit [40]. Designing existing building systems, including ACBs, often has several accuracy issues and lacks realism. Fred et al. highlighted differences in existing energy models for 2-Way ACBs (versus the actual 2-Way ACB designs) and, based on this, formulated one guided approach for the modelling community to use to evaluate ACB systems [41].

ACB system layout

An ACB system comprises two parts: the air distribution system and the water distribution system, as described below.

Air distribution system

The air distribution system consists of ACBs, air handling unit (AHU), and ductwork [33]. The AHU mainly has filters, chilled water coil, hot water coil, and fans. This system design often has a heat recovery feature, including a heat exchanger between the exhaust air and the outside air, and humidification/dehumidification components. This air distribution setup provides the primary air to the ACBs and return air to the exhaust through the duct network, as shown in Fig. 7. Some ventilation systems, referred to as Dedicated Outside Air System (DOAS), use 100% outside air (with no recirculation) and dehumidify it before it enters the building space [32]. The system with air recirculation can save energy compared to using DOAS without recirculation [42].

Hydronic distribution system

The hydronic distribution system of ACBs consists of three major parts: generation, distribution, and consumer loads. This water distribution is typically arranged in a two-pipe or four-pipe configuration [43], as shown in Fig. 8. A two-pipe configuration includes one supply pipe and one return pipe. This means that building spaces can only be either heated or cooled at any given time. On the other hand, a four pipe configuration enables simultaneous heating and cooling in the building, as it consists of two supply pipes and two return pipes [44].

Maccarini et al. [45] developed a novel ACB water distribution system that can simultaneously heat and cool building spaces using a two-pipe configuration. The work was supported by simulations in Dymola and later implementation in an office building [46]. Traditionally, two-pipe systems circulate supply water at temperatures of about 30–45 °C and 14–18 °C respectively for heating and cooling operations. The innovative two-pipe system operates with a supply water temperature of

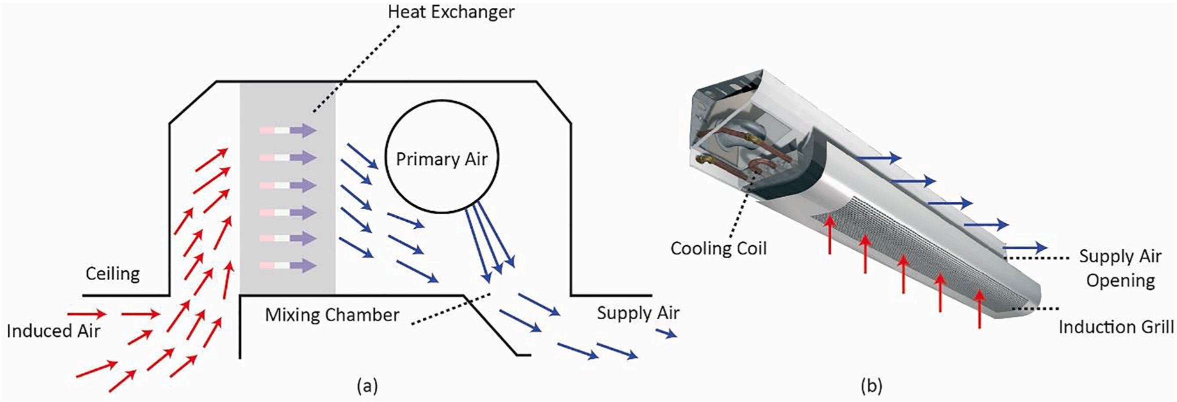


Fig. 5. (a) Working principle of 1-Way ACB (b) Actual 1-Way ACB Unit with one supply-air opening [26].

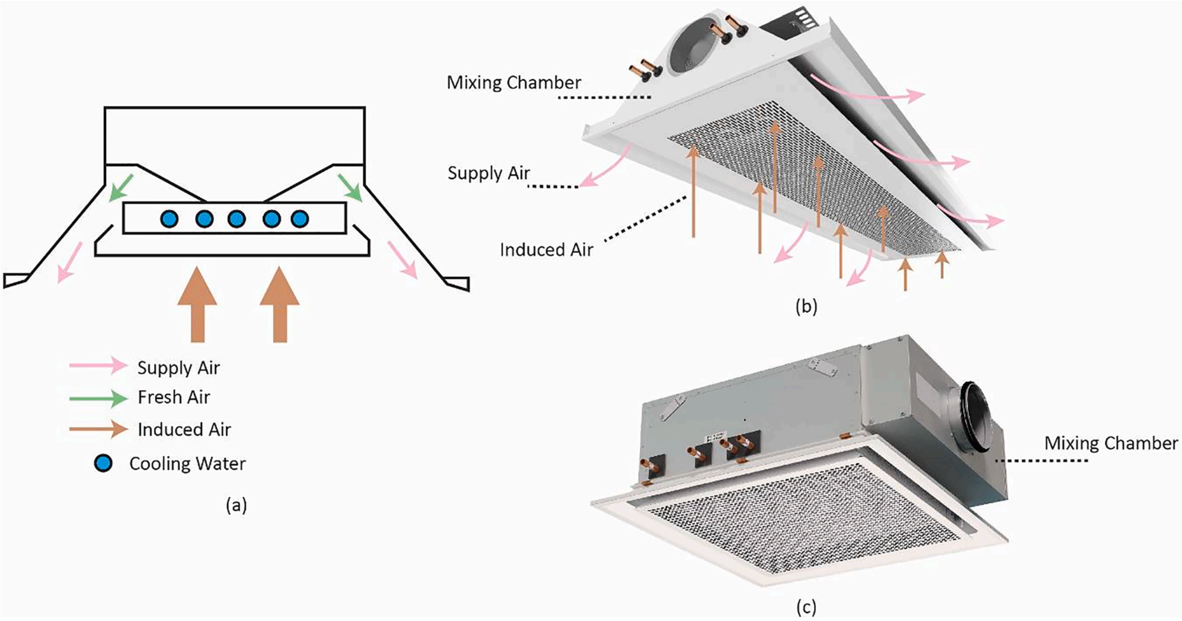


Fig. 6. (a) 2/4-Way ACB principle (b) Actual 2-Way ACB with two supply-air openings (c) Actual 4-Way ACB with four supply-air openings [26].

Table 3
ACB studies according to its design and applications.

Ref.	Design and Geometry					Layout		Operating mode**	
	1-Way	2-Way	4-Way	9 mm round/cylindrical-shaped	Other nozzle shape	Open-plan office	Other setups*	Heating	Cooling
[24,37]		✓				✓		✓	
[17,34]		✓		✓		✓			✓
[40,58–60,77,78]		✓		✓			✓		✓
[68,79]		✓				✓			✓
[80]		✓			✓	✓			✓
[81,82]		✓				✓		✓	✓
[26]	✓		✓			✓			✓
[36,83–85]		✓				✓	✓		✓
[86]		✓					✓		✓
[64]		✓		✓	✓		✓		✓

*other setups include independent ACB studies or single rooms with no activity.
**operating mode in most of the studies is either heating or cooling. Only one case for simultaneously heating and cooling through ACBs is reported in literature.

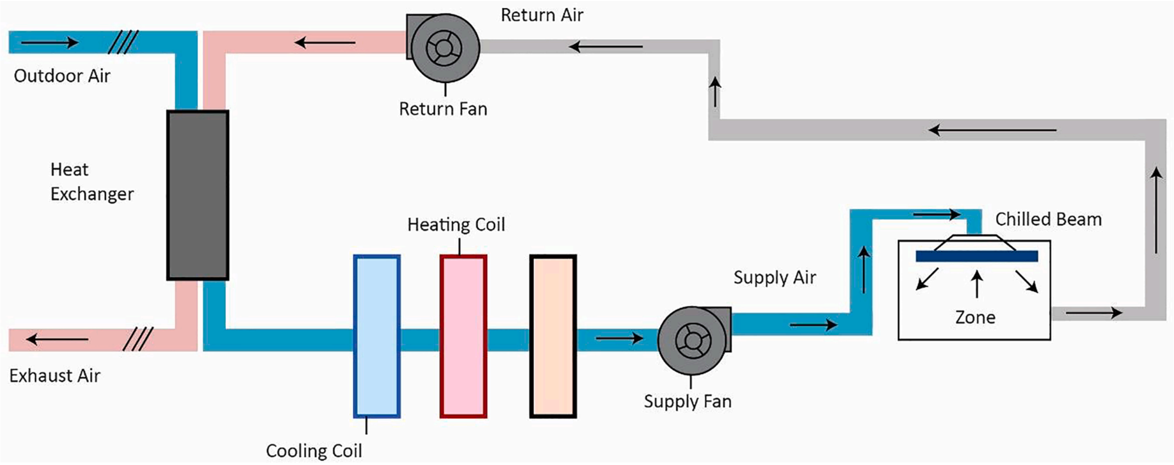


Fig. 7. Air distribution layout of ACBs consisting of ACBs, air handling unit (AHU) and duct work [42].

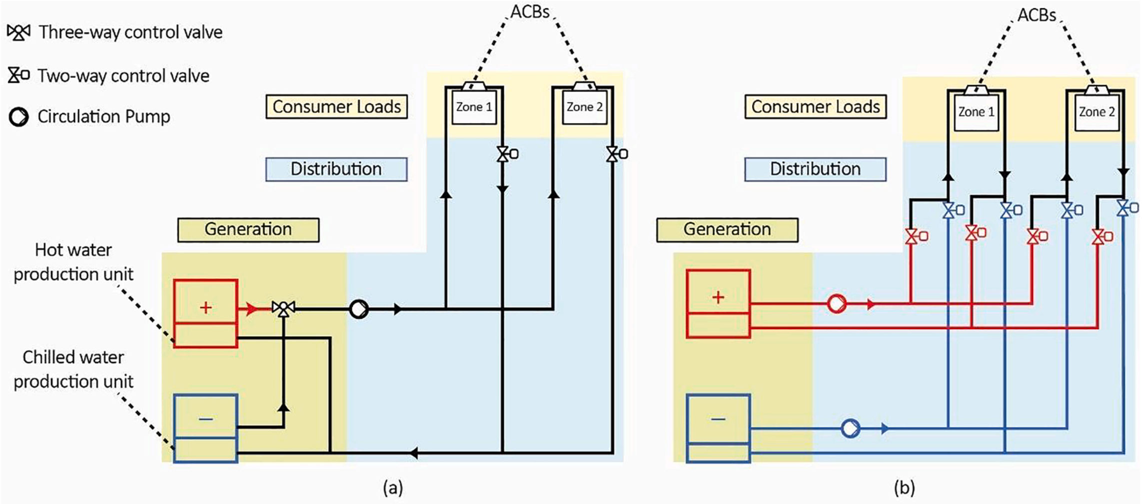


Fig. 8. (a) Two-pipe configuration with one supply pipe and one return pipe (b) Four pipe configuration with two supply pipes and two return pipes [43].

about 22 °C all year round. Results from simulations show that the innovative two-pipe system can save approximately 12–18% of total annual primary energy compared to traditional four-pipe systems, mainly due to useful heat transfer from warm to cold zones and higher potential to provide free cooling [47].

Active Chilled Beam controls

An ACB system consists of water and air distribution systems, as described in the section above. These systems require control strategies to maintain zone temperatures and control chilled water temperature to avoid condensation and maximise the cooling output of the beams [23,48].

Air-side and water-side controls

In ACB systems, the primary airflow rate, water flow rate and zone temperature are control variables for developing any control strategy to minimise energy use and improve thermal comfort [49]. The primary air temperature and chilled water temperature are kept constant, as they are not control variables. The desired room air temperatures are usually achieved by varying the water flow rate in the water distribution system. Water-side control is a closed loop which controls the room temperature by varying the water flow rate while primary air temperature and airflow rate remain constant. The purpose of air-side controls [40] in ACBs is to meet zone ventilation requirements and minimise draughts by properly maintaining air distribution patterns through variable primary airflow rate. Demand-controlled ventilation (DCV) is also applied, where the primary airflow rate is varied in response to zone occupancy to optimise the system's energy use [50]. Along with the ACB unit, an additional air supply diffuser can be introduced upon increase in the room occupancy. In such cases, water flow rate through the beam is modulated in accordance with the temperature demand of the zone.

Chilled water temperature controls

Since most of the ACBs are designed to be sensible cooling devices, different control strategies are developed to adjust the temperature of the beam [51]. This may eliminate the need for a separate DOAS for dehumidification. Chilled water temperature controls are essential to avoid condensation. In order to avoid condensation, the temperature of the brine is raised, and this results in decreasing of the cooling capacity

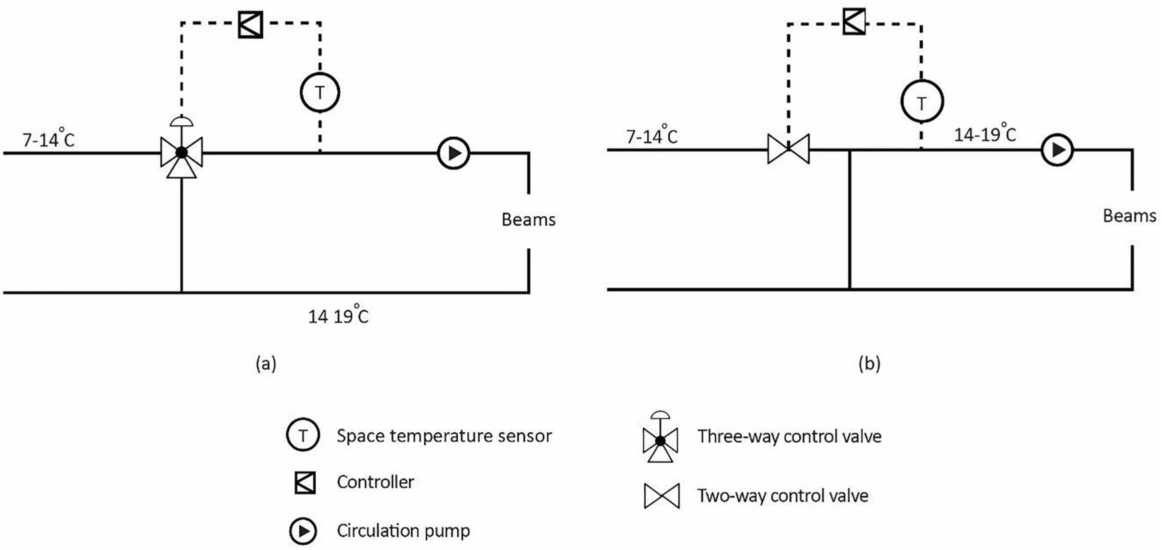


Fig. 9. (a) Open-loop beam chilled-water system supply temperature maintained by mixing primary and secondary chilled water (three-way valve and bypass) (b) Open-loop beam chilled-water system supply water temperature maintained by mixing primary and secondary chilled water (two-way valve and bypass) [23].

of ACBs. Fig. 9a shows the use of a three-way mixing valve to mix primary and return water to maintain the beam chilled-water supply temperature. Fig. 9b shows a two-way modulating valve and bypass are used to mix primary and return water to maintain the beam chilled-water supply temperature.

Three-way or two-way open-loop modulating valves and a bypass are used in beam chilled water systems to maintain supply water temperature by mixing primary and returned water. While, closed-loop beam control systems, as illustrated in Fig. 10, maintain supply temperature by a two- or three-way control valve installed on the suction side of the pump. These control valves maintain the chilled water temperature by regulating primary water flow in the heat exchanger.

Model Predictive Control (MPC) can be applied to optimise system efficiency in terms of energy use or indoor thermal comfort while satisfying system constraints. Using a model of the system, the performance of the system is optimised over a finite future horizon. For instance, in [52], experimental results indicated a 20% electricity saving with MPC control, while an acceptable Predictive Mean Vote (PMV) was fulfilled, i.e. $-0.5 < \text{PMV} < 0.5$. In addition to above-mentioned control methods, there is an opportunity for self-regulation [53], i.e. elimination of individual room control systems in ACBs with high temperature cooling. The self-regulating ACBs provide an effective way to maintain balance between chilled water temperatures of ACBs and indoor air temperature without the need for any control components [54]. The flow rate of chilled water in a self-regulating active chilled beam remains constant, as the cooling capacity is instead determined by the room temperature and by the centrally controlled chilled water temperature [55]. Hence, these self-regulating ACB systems keep the indoor air temperature satisfactorily uniform by supplying the building with enough cooling and keep the building within the desirable indoor air temperature limits [46].

Nozzles

Proper modifications in the geometry of the terminal unit of any mechanical ventilation system can improve its efficiency [56]. In an ACB system, the primary air is discharged through multiple sets of nozzles present on the sides of the heat exchanger. These ACBs come with different nozzle shapes and in different sizes. Bingjie et al. [57] observed uneven air-jet patterns from the nozzles inside the ACB discharge unit. The velocity differences between the nozzles which are close to the ACB inlet and the ones which are away from it cause these uneven air jets. Different design modifications have been applied to produce air velocities of equal magnitude from all nozzles. The uniform air velocities were achieved either by using small nozzles (9 mm diameter) or by adding a board in the middle of the air plenum to produce uniform discharge from the terminal unit. Guan et al. [58] made a regression analysis to show that Induction Ratio (IR) has a negative correlation with the nozzle radius ranging from 1 mm to 10 mm. At the same time, the distance between nozzles has a positive correlation with IR. The radius of the nozzle has a more substantial effect on IR than the distance between nozzles. Another study shows that the smaller ACB nozzle sizes provide efficient heat transfer, which leads to higher IRs for the fixed primary airflow rates [59]. This shows that nozzles with small diameters (up to 9 mm) lessen the primary air resulting in improved IR. Further studies show that choosing the optimal nozzle length between 60 mm and 80 mm in ACBs could increase IR by up to 30% [60]. Ruponen et al. [61] conducted an experimental study by using different-sized circular nozzles with different outlet geometries to indicate that the area ratio of the supply nozzle is another significant parameter that influences the IR. Results indicated that the outlet geometry of the ACB has a negligible effect on the IR. Hence, nozzle sizes and spacing between them are considered key factors by researchers and manufactures when evaluating the performance and IR of ACBs.

Nozzles of ACBs also come in different shapes, as shown in Fig. 11. Commercially, different nozzle designs for ACBs have been tested to improve the IR. The rectangular and elliptic-shaped nozzle geometries have positively affected jet's mixing due to counter-rotating stream-wise vortices and improvement regarding self-induction, respectively [62,63]. Experimental investigations into the performance of ACBs using different nozzle designs have shown that cross-shaped nozzle designs achieve a higher IR than all other nozzle geometries working on constant flow conditions [64].

In addition to this, the shape of these cross-shaped nozzles is further

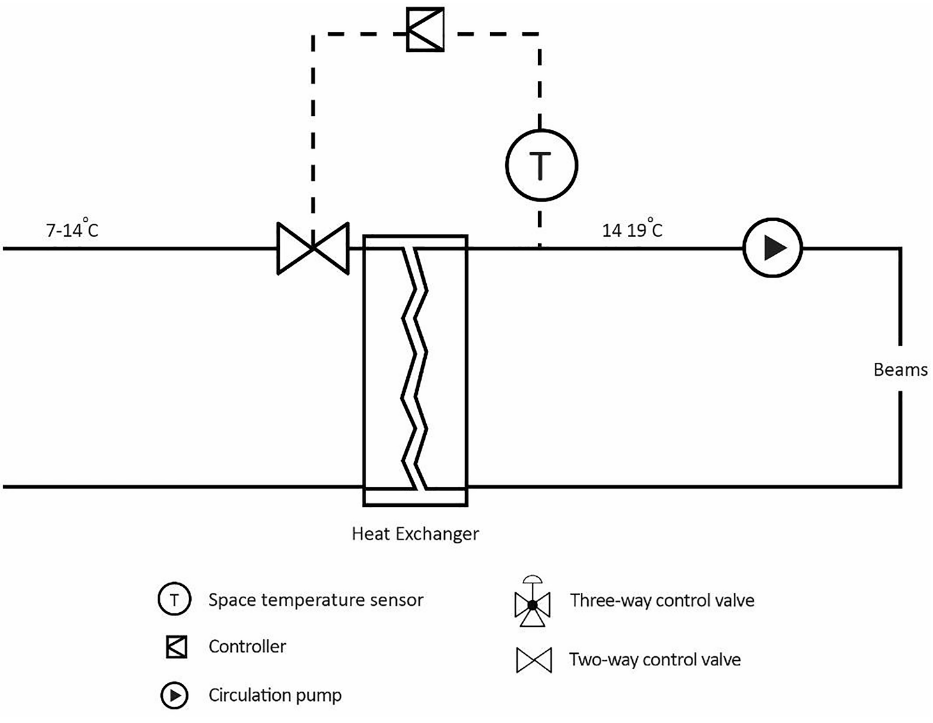


Fig. 10. Closed-loop beam chilled-water system supply temperature maintained by regulating primary water flow in heat exchanger [23].

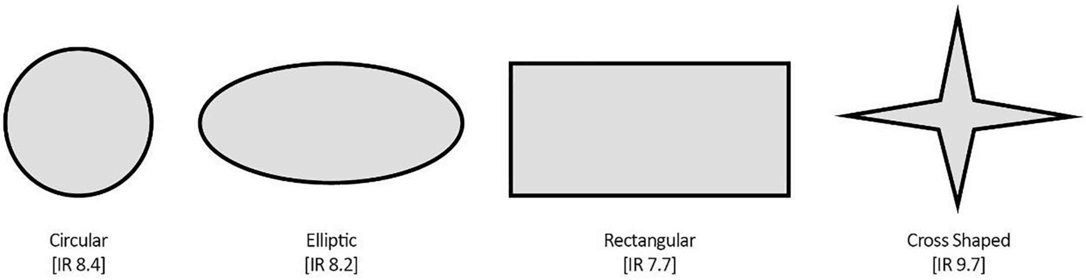


Fig. 11. Nozzle designs for ACBs [64].

modified to lobbed-shaped (by over-lapping cross-shaped nozzles) to enhance mixing and momentum [65]. Jet cones in ACBs can provide better control over supply airflow coming out of the terminal units into the room compared to conventional nozzle designs. This jet-cone feature in ACBs can change the magnitude of airflow rates and the air direction through different pin adjustments [66]. These changes in nozzle designs have a significant impact on the amount of induced air, which is further discussed below.

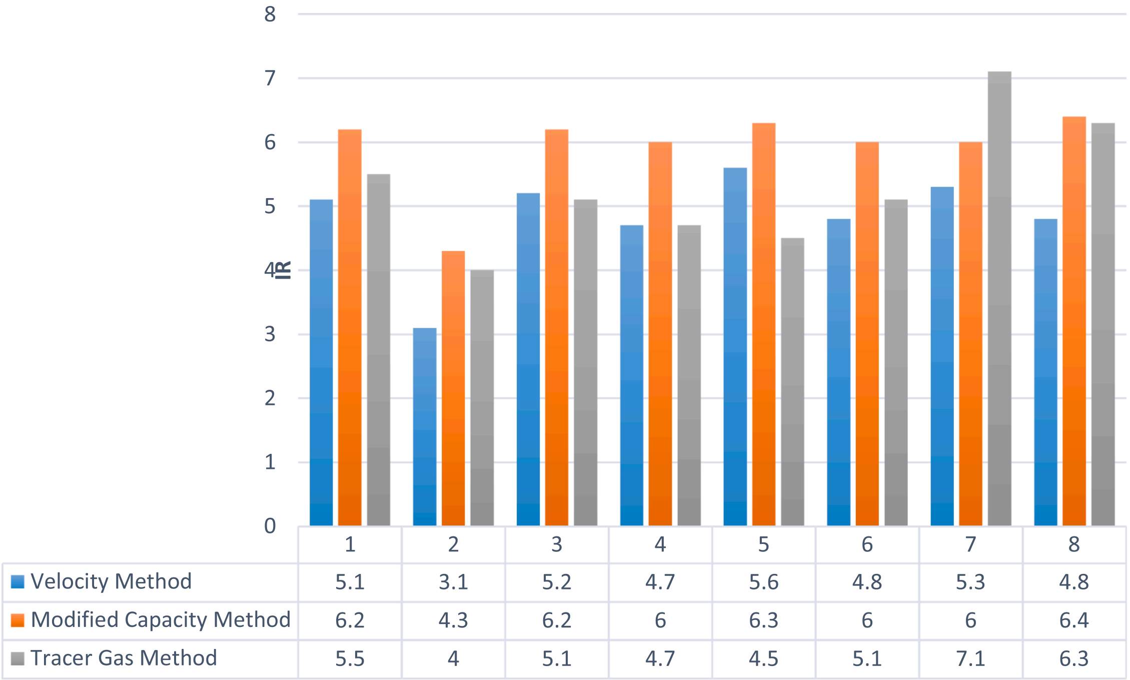
Induction effect

The induction effect is considered a prominent feature of ACB systems. Literature shows that IR is a key parameter for measuring the efficiency of ACBs units. It is defined as the amount of secondary air entrained per second divided by the amount of primary air supplied per second [67]. Different measuring methods [68] are applied in experimental studies to determine the IR of ACBs under different operating conditions [33]. These methods involve measuring the induced flow through capacity method, air temperature method and air velocity method as explained below.

- Capacity method: This method involves applying an energy equation over the cooling coil. The induced flow is determined by measuring the flow and the temperature rise of the chilled water and the temperature drop of the induced air.
- Temperature method: The induced flow in this method is determined by measuring the temperature of the mixed supply air, the primary air, and the induced air downstream of the coil.
- Air velocity (venturi) method: This method involves the induced airflow rate as a function of the air velocity measured at one point in the throat of the venturi.

The induced flow determined from the above methods is divided by primary airflow of ACB to determine the IRs. The venturi method is considered a reliable method for calculating IR when compared with the results obtained from the European Standard prEN 15116 [69]. However, IRs involving both capacity and temperature suffer difficulties measuring the temperature of the induced air downstream the coil. Experimental results, as shown in Fig. 12, show that the modified capacity method [68] used for primary flow rates (q_p) between $15 \le q_p \le 35$ (l/s) gives more consistent and accurate IRs. This method involves combining the expressions of both the capacity method and the temperature method to measure IR without any problem [70].

In literature, different correlations are developed between IR and various ACB operating parameters. Studies show that the primary airflow rate has a weak correlation with Induction Ratio (IR) [71,72], while an increase in plenum pressure gives a slight decrease in IR [73]. The self-regulating effect [54] has a weak influence on the IR of the chilled beam, but large temperature differences can lower the IR to a certain extent [53]. The induction effect for turbulence jet models, especially used for ACBs, is often presented by applying some empirical



	1	2	3	4	5	6	7	8
🟦 Velocity Method	5.1	3.1	5.2	4.7	5.6	4.8	5.3	4.8
🟧 Modified Capacity Method	6.2	4.3	6.2	6	6.3	6	6	6.4
⬜ Tracer Gas Method	5.5	4	5.1	4.7	4.5	5.1	7.1	6.3

Fig. 12. Experimental results from different methods used for measuring Induction Ratios [68].

hypotheses and modelling techniques. This is due to complications of jet interaction and merging across the cooling coils in the terminal unit described below [74–76].

Table 3 shows that ACB can be used for heating, but thermal stratification must be considered. This is due to the risk of discomfort caused by radiant temperature asymmetry in the room [82]. There are ways to solve this problem for an instant through zone heating or modifications in the heat exchanger design [37].

Cooling coils and filters

Induced air is cooled by the coil or the copper tubing, bonded to aluminium fins, and supplied with chilled water to wick away heat. Higher chilled water temperatures (14 °C to 18 °C) are used in ACB cooling coils compared to conventional air-conditioning systems (which use chilled water temperatures ranging from 4 °C to 7 °C). After mixing in the room, the warm room air ascend upwards towards the cooling coil for the heat exchange [16]. Filters can be placed between the cooling coil and the induction grill to clean up the incoming warm (secondary) air and discharge it back to the room as supply air.

Filters

Indoor air consisting of gases and particles is continuously circulated within the room and moves back towards the cooling coil for the heat exchange [87]. One of the key issues of an ACB is the unclean induced air passing through the cooling coil [88]. This is one of the main setbacks of ACB systems for hospital applications. Fibrous filters placed prior to the cooling coil, as shown in Fig. 13, have been used in air cleaning for the past many years [89]. Studies suggest that these filters reduce the secondary airflows between 6 and 15% due to their significant effect on the pressure drop [90], reducing the ACB efficiency between 22 and 38% [27]. ACBs with filters are observed to be more suitable for hospital applications (than office buildings), where even the slightest risk regarding IAQ in accordance with ASHRAE Standard 170 is not acceptable [91]. Most of the ACB studies in the literature have been conducted without considering the filter effect in the discharge unit.

Cooling capacity

The performance of the cooling coils is mostly represented in terms of the cooling capacity of the cooling system. The cooling capacity of an ACB can be defined as the ability of its cooling system to remove heat from the specific space. The total cooling capacity of these air–water systems is a combination of the air-side cooling capacity and the water-side cooling capacity, as shown in equation (1) [59].

$$\mathrm{Ptotal} = \mathrm{Pair\text{-}side} + \mathrm{Pwater\text{-}side} \tag{1}$$

Air-side cooling capacity is given as

$$\mathrm{Pair\text{-}side} = \mathrm{mpa}{*}\mathrm{Cp,a}{*}(\mathrm{tra\text{-}tpa}) \tag{2}$$

Here,

m_{pa}: mass flow rate of primary air; $C_{p,a}$: specific heat of the air

t_{ra} : induced air temperature; t_{pa}: primary air temperature

Assuming no condensation in the cooling coil, the cooling capacity of the cooling coil of an ACB system can be found as:

$$\mathrm{Pwater\text{-}side} = \mathrm{mw}{*}\mathrm{Cp,w}{*}(\mathrm{tw,out\text{-}tw,in})\ (\text{under steady-state condition}) \tag{3}$$

Here,

m_w: mass flow rate of cooling media; $C_{p,w}$: specific heat of liquid media

$t_{w,out}$: existing water temperature; $t_{w,in}$: inlet water temperature

It is important to note that there is a risk that the air will condense on the fins of the cooling coil [21]. This has a substantial influence on the functioning of the cooling coils [92].

Cooling coil simulation models

Most of the research work on cooling coils has been incorporated into the modelling techniques due to their function, complex geometry and positioning in the ACB unit. Different types of model are implemented for the cooling coil studies to investigate their function and limitations in a detailed way. A comprehensive review of these models is provided in Table 4.

Hybrid models [96–101] are more reported for the cooling coil in chilled beams due to all the models' advantages. Static models, [93–95] despite the error of around ± 10%, are reported insufficient in most

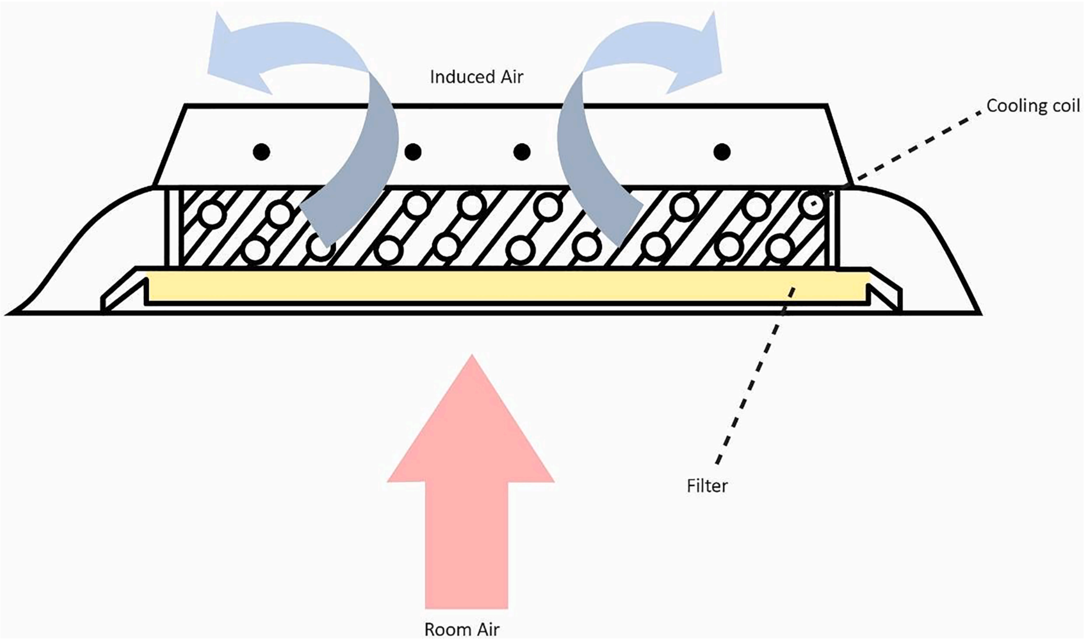


Fig. 13. ACB Cooling Coil with filter [89].

Table 4
Cooling Coil models for ACB applications.

Ref.	Model Type	Function & Applications	Limitations
[93,94]	Theoretical Cooling Coil Model	- The models require dimensions of the fin and the tube thickness, diameter, and spacing as inputs in order to calculate the heat transfer coefficients. Applied for ASHRAE simulation toolkits for annual energy calculations of buildings.	- Insufficient robustness - Models are expressed based on physical & conceptual hypotheses without practical validation.
[95]	Empirical Coil Model	- The coil model works regardless of the type of fluid in the tubes with a set of constants. - This approach has the capacity to simulate the energy performance of other HVAC components.	- Different sets of constants are required for different fluids.
[96–100]	Hybrid Cooling Coil Models	- Model is developed with the air saturation specific heat information. The advantages include simplicity, accuracy, and consistency with the methodology for analysing sensible heat exchangers. - Less computational requirements. - These models have applications in operational optimisation, performance assessment, fault detection and diagnosis in liquid desiccant dehumidification systems.	- Results from these models do not have the sufficient cooling capacity with constant fluid flow rates & exit temperatures in the cooling coil compared with the dynamic models.
[70,101]	Dynamic hybrid models	- These models cover mechanical and thermal aspects of air jets & cooling coils with better accuracy and robustness.	- High complexities, as this approach is new to ACB applications. - More dependent on experimental estimations, which may involve high uncertainties. - Compromise is made in capturing exact underlying physics and suitability for engineering applications.
[102–104]	Dynamic Cooling Coil Models	- The dynamic behaviour of the heat exchanger in these models is characterised by time constant, delay time and gain in these models. - Easily modified for different types of heat exchanger. - Good for the prediction of transient performance of the fluids flowing through the heat exchanger tubes. - Predicts the transient behaviour subject to arbitrary inlet temperatures in shell and tube heat exchangers with parallel or counter current flow.	- These comprehensive dynamic models are developed for computer simulations, which are too complex to be applied practically. - Involve extensive numerical and experimental studies from literature for the validations.

cases compared to dynamic models with less than ± 5% [102–104]. Dynamic models for cooling coils in ACBs take advantage of both the physical and empirical modelling approaches and can accurately predict performance in a wide operating range with real-time operations of heat exchangers. However, additional mass balance equations are applied in the case of wet cooling coils in dynamic models. While dynamic modelling for dry cooling coils involves energy equations to achieve reasonable simulation results [105].

Other factors affecting ACBs' performance

In the ACB studies, humidity control, unsymmetrical heat source distribution, collision of jets from multiple ACBs and large air circulation patterns in the open-plan office spaces also affect ACBs' performance, as described below.

Building humidity control

The chilled water temperature in ACBs must be at a certain temperature above room dew point temperature to avoid condensation. The lower the chilled water temperature the higher the power output of the system. This means that lowering the room dew point temperature makes the ACB system work more efficiently [39]. Building humidity control is required for the proper functioning of air–water systems especially in humid climates [23]. For example, opening a window in a humid climate raises the dew point temperature of the air in the room. To avoid condensation in this room, it is common to use moisture detectors or sensors which detect condensation [33,56], and accordingly close the water valve in ACB resulting in a higher temperature in the cooling coil.

Heat sources

Ventilation produces air currents across a room in directions initially determined mainly by the geometry of the ACB. On the other hand, heating, and cooling cause convection currents, affecting the vertical distribution of heat and outdoor air. In open-plan offices, convective flows coming from the heat sources significantly impact airflow patterns produced by the air terminal devices. These airflow patterns inside the room control the thermal comfort in the occupied zone. Heat sources, especially in open-plan offices with different layouts, cause convection currents, which are equal in strength to those produced due to ventilation [84,106,107]. Another study shows that the unsymmetrical distribution of these heat sources is considered the main reason for draught in the rooms with ACBs [26].

Air circulation patterns and colliding jets

The office spaces with high occupancy density (or heat sources) are designed with multiple chilled beams units, which work together to produce favourable indoor climates for the building occupants. Studies show that the collision of inlet jets from these multiple beams is another source of draught discomfort [34,108]. The multiple nozzles in ACB units produce several jets that travel in parallel downstream directions in the same plane and spread along the ceiling as confluent jets [109].

The momentum is conserved better by confluent jets than any other type of jets [110,111]. These jets stay attached to the ceiling until they get deflected by a room wall [112]. Experimental studies show that large air circulations are observed in rooms installed with ACBs because of asymmetric layout of their terminal units [113].

Outdoor conditions

Studies show that outdoor conditions also significantly impact the airflow patterns of rooms and occupant's productivity [107]. Cool windows and outer wall surfaces can create downward flows, and warm surfaces upward flows, which affect the thermal comfort in the room [114]. One study shows that the most critical zone in which people often suffer draught is located close to a wall and floor [83]. However, the risk of a draught is reduced if ACB systems are arranged efficaciously to avoid high induction.

Testing techniques for the ACB study

Most of the studies on ACBs are related to office setups, as shown in Table 2. Different experimental and simulation methods are applied to study the airflow patterns and performance of the ACBs for the different operating parameters. The validated results are used further to improve the ACBs designs and minimise office occupants' draught discomfort.

Simulation tests

In recent years, CFD has been successfully applied to indoor airflow analysis and produced results by using different airflow models [115]. CFD has been a valuable tool for visualising such 3D flows and effective air distribution patterns inside rooms with ACBs [116–118]. Applications of CFD in building ventilation were introduced by P.V. Nielsen, and now, it has become an integral part of scientific research into complex air distribution and ventilation systems [119–121].

Table 5 shows that LES models have the potential to provide more accurate and reliable results than other RANS models in ACB studies but at the expense of higher computational cost [133]. The standard K-epsilon model [124] is reported to be widely used due to its robustness and applicability for a wide range of flows in ACB studies. This model is found to be suitable for observing the internal flow of ACB models with less computational time. The comparative analysis from the literature in Table 5 shows that the k-ω-based turbulence models [134] offer better performance than k-ε models regarding free shear flows and airflows near the walls. The k-ω SST turbulence model [122] provides detailed characteristics of flow patterns and combines advantages from the k-epsilon and k-ω models [135]. However, the implementation of the required turbulence model is also dependent on the computational facility; therefore, inconsistency is observed in the literature for choosing any specific model for the given ACB application. Other 2D and 3D modelling techniques (using different tools) are also used to predict the fluid-dynamical and thermal performance of complex ACBs [72,136]. However, the simulation software available today has multiple issues when it comes to modelling ACBs, specifically with respect to their accuracy and ease of designing for real-time building applications [41].

Table 5
CFD Turbulence Models and their use in ACB studies.

References	Models	Characteristics
[34,36]	k-ω Shear Stress Transport (SST) [122]	- Study on airflow near the walls and ceilings, induction plates, and airflow with strong buoyancy. - Not suitable for the ACB studies involving mixed convection
[57–59,123]	Standard k-epsilon model [124]	- Robust and reasonable accurate for indoor climate ACB applications. - Low computational cost - Not applicable to near wall region
[125,126]	RNG k-epsilon model (Surface-to-surface) [127]	- Enables to use lower Reynolds numbers than standard model. - Better results on mixed convection and impinging jets in ACB study
[128–130]	Realisable k-ε model [131]	- More accurate than standard model in predicting round jets and complex secondary flows in studies associated with ACB thermal comfort applications - More computational power required than standard model
[128,131]	Large Eddy Simulation (LES) Model [132]	- More accurate than all RANS models to investigate external and internal airflows of an ACB - Better for predicting jet width and the jet bending caused by the induction in ACB study - Requires high computational time and cost

Field tests

Generally, the cooling capacities of ACBs are tested and rated by European Standard EN/DS 15115 approved by European Committee for Standardization (CEN) [137]. CEN specifies methods for measuring the cooling capacities of chilled beams with forced airflow. The purpose of the standard is to give comparable and repeatable product data that can be further used for conducting laboratory studies. Most of the experimental studies on ACBs are done in climate chambers or mock-up office setups, see Table 3. In ACB studies, the simulated data obtained through simulations is validated with the field data. Literature shows that during ACB field tests, air change rates, IRs, and IAQ are measured using the tracer-gas method [26,68,82]. Particle image velocimetry (PIV) is another optical measurement technique that validates chilled beam models through field tests [79,135]. The velocity field of an entire testing region with the airflow can be measured through PIV. The flow region is then subdivided into small areas of investigation to make a detailed airflow analysis. As ACB systems involve complex internal geometry, Laser Doppler velocimetry (LDV) is used to observe the internal airflow inside ACBs [77]. In comparison to traditional flow measurement techniques, this optical technique makes a very high spatial resolution possible.

Fig. 14 shows the velocity vector profile of an office setup equipped with ACB by using CFD and PIV techniques. PIV technique is commonly applied for observing jet visualisation during ACB experiments, while CFD tools are applied for the prediction of air distributions in different ventilated spaces.

Energy use and energy savings

Different design strategies are proposed in the literature to minimise the energy use in buildings through modifying conventional HVAC technologies [138–140]. Most of the research on chilled beams is focused on techniques to enhance the energy efficiency and performance of these space friendly ACB terminal units. ACB systems are considered one of buildings' reliable technical solutions due to their energy-saving potential [141]. Below are the reasons why ACB has helped to save energy in buildings.

- One of the main reasons ACBs provide energy savings is because they supply sensible cooling directly to the occupied zones, which ultimately reduces the ventilation fan power consumed to deliver cooling to spaces [16].
- Chilled water flow at higher temperatures (14 °C to 18 °C) in ACBs compared to conventional chillers (4 °C to 7 °C) makes chilled beams up to 20% more efficient (in cooling) than conventional air-conditioning systems [21].

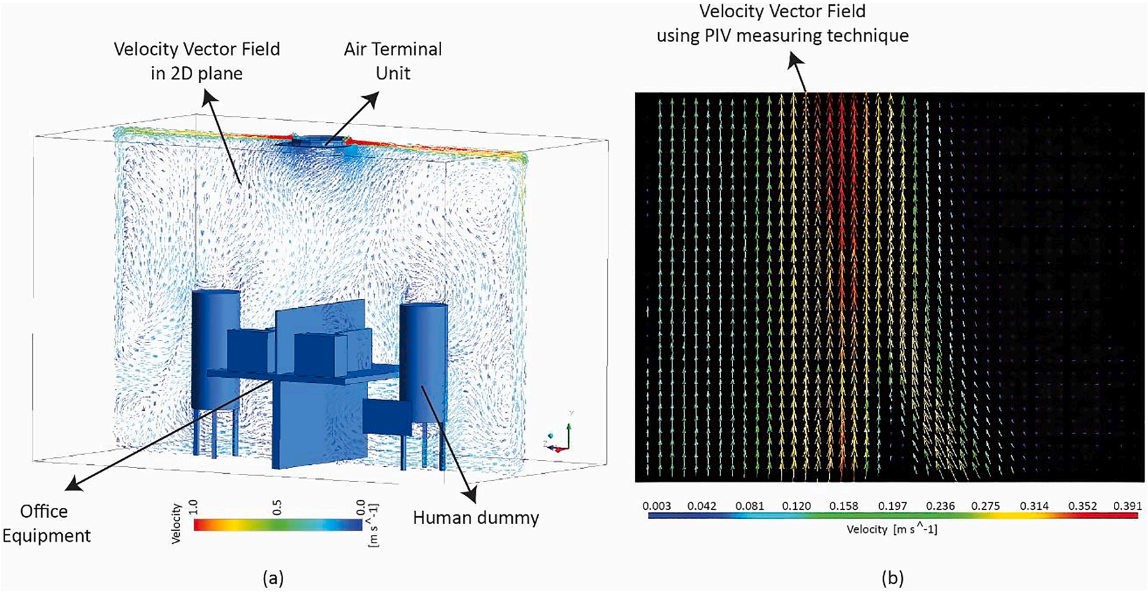


Fig. 14. (a) Velocity vector field in a 3D office room (b) Velocity vector field visualisation through PIV technique [135].

- Water has a higher specific heat than air and can transport a greater amount of energy through the building. This makes ACBs more energy-efficient than all-air systems.
- Built-in precision quality of Dedicated Outdoor Air System (DOAS) helps ACB systems (when coupled together) to provide less airflow to the individual zones in buildings [42]. This reduces the quantity of outdoor air (OA) to be conditioned while meeting Standard 62–2001 ventilation requirements and saves energy [142].
- The induction phenomenon in ACBs eliminates the need to reheat the cooled air, which saves a considerable amount of money and energy [56].
- Energy is saved by using an innovative 2-pipe system for simultaneous heating and cooling through ACB systems. However, a balance point temperature is required to save this annual primary energy [143].
- Chilled beam zone pump modules for controlling the pump speed (according to the requirement) can save energy or increase capacity [144].
- The energy performance of an ACB can be improved by increasing the air-to-water cooling capacity ratio of the system. This air and water-side cooling capacity can be increased by increasing the primary airflow rate and water inlet temperature [59].
- A self-regulating ACB requires less energy for heating and cooling than a system with individually controlled active chilled beams through the control of the chilled water supply temperature aiming at an exhaust air temperature set-point of 24 °C [145].

Thermal comfort is one of the main factors that influence occupants' productivity in office buildings [146]. ACB systems have overall proven successful in providing an acceptable thermal uniformity, even with less air flow rate, than other conventional air distribution systems [71,147]. Along with this, ACBs are integrated with other ventilation systems to further improve local thermal comfort and have more energy savings [148]. Sekhar et al. integrated personalised ventilation (PV) and local fan-induced active chilled beam (PV-ACB) air conditioning systems to achieve 16% energy savings (compared with a conventional VAV system) at 100% peak cooling load [149]. Demand-controlled ventilation (DCV) systems with ACBs, operating at optimal controls, use 7–8% less total primary energy compared to constant air volume (CAV) systems [50]. Kosonen et al. compared chilled beams and radiant panel systems for mock-up office setups and figured out that both the systems are equally effective in regard to mean radiant temperature and radiant temperature asymmetry at different internal loads in both heating and cooling modes [150]. Wu et al. developed a model-based multi-objective optimisation strategy by combining energy models for the whole ACB system and a PPD model for the building zones [49]. This model controlled primary airflow rate, water flow rate, and zone temperatures to develop a trade-off between energy use and thermal comfort for ACBs. Different heat loads were compared with optimised cases under steady-state experimental conditions. The proposed model provided energy savings of 39.32% with an improved thermal comfort environment. Rahimi et al. used a combination of ACBs and air-cleaning technologies to improve the indoor climate in offices but reported a 38% decrease in efficiency of the chilled beam in exchanging heat [27].

Discussion and future research

As shown in this paper, ACB systems have lots of advantages over conventional HVAC systems in terms of better thermal comfort and energy savings. However, several topics still remain to be discussed in order to promote a healthy dialogue between the HVAC research community and field engineers for long-term future research. Some of these points are discussed as follows:

- Despite the valuable studies on ACB air distribution patterns, most of the studies have been carried out in climate chambers or with simulation tools, which lack realism. Much work needs to be done to evaluate ACB performance and energy savings under real conditions, and this can be done through field tests and by receiving feedback from end-users.
- Most of the authors highlighted the conventional disadvantage of condensation forming on the coils of chilled beams. But no practical solution is addressed in detail. Some recommended having humidity controls within the occupied space to prevent condensation, and others proposed using drainage pans, which does not seem practical and would further increase the cost of the units. ACBs are located inside ceilings, where a separate pump for each beam would be required to drain them. Condensation prevention strategies should be considered as a part of designing ACB systems, which can function well both for sensible and latent cooling modes.
- No known experimental study was found on ACB heating capacities for the office mock-ups. Minimal literature is found to address

thermal comfort by ACB devices in the heating mode. In most of the experiments, the room temperature is raised by using heaters or radiant heating panels. Practically a separate heating system is used in offices equipped with ACBs, which likely will increase the overall cost of building a HVAC system.
- ACBs are not that energy efficient when it comes to dealing with high sensible cooling requirements in large office spaces. Their commercial applications are restricted mainly to offices, school labs and rooms with low ceilings. However, different design strategies are required for ACBs in case of latent load requirements for large office spaces.
- The efficiency of other sustainable energy sources in relation to ACB systems should be investigated. Geothermal heat pumps, solar panels and phase change materials (PCM) seem like favourable technologies to further reduce the primary energy use of these systems.

Conclusion

Over the years, ACBs have become an alternative to conventional HVAC systems in offices due to their advantages in terms of energy and space savings, economy, and thermal comfort. These systems work more efficiently in the cooling modes than heating due to the significant risk of discomfort because of radiant temperature asymmetry. In the cooling mode, operating conditions of the system and humidity levels are controlled to avoid condensation. Literature shows that the suitable geometrical design along with optimal operating conditions for ACBs play a key role in establishing desired thermal comfort for offices while minimizing energy use. Most of the ACB studies are carried out in climate chambers installed with 2-Way ACB designs, where PIV visualisation techniques are applied in experiments to observe 3D airflow patterns and refine CFD models. In addition, studies show that cross-shaped nozzles give high induction rates than conventional round-shaped nozzles, whereas the size of the ACB nozzles has a more significant impact on their efficiency than the nozzle shape. In terms of modelling, hybrid and dynamic cooling coil thermal models are preferred in applied research for ACB cooling coils. This is due to their ability to cover wide thermal aspects close to real conditions and because they have better robustness than static cooling coil models. The use of the filters for cleaning the induced air, placed between the induction grill and cooling coil, is not encouraged in ACB office applications to have low-pressure drop and high induction. Regarding the control of ACB systems, the water-side and air-side controls are used to achieve room temperature control by regulating the water flow rate and variable-volume primary airflow, respectively. However, self-regulation in ACB systems even effectively controls room temperature without the need for any control device or changing water flow rates. Literature shows that energy savings of between 25 and 30% can be achieved from ACBs compared to traditional VAV systems. These energy savings are mainly due to increased chilled water temperature, reduction in reheating cooled air and fan energy, and integration with the other HVAC systems.

CRediT authorship contribution statement

Haider Latif: Conceptualization, Data Curation, Formal analysis, Investigation, Writing - original draft. **Goran Hultmark:** Supervision, Visualisation, validation. **Samira Rahnama:** Supervision, Writing - review & editing. **Alessandro Maccarini:** Supervision, Writing - review & editing. **Alireza Afshari:** Supervision, Funding acquisition, Resources.

Declaration of Competing Interest

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

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