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# Thermal performance of atria: An overview of natural ventilation effective designs

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A B S T R A C T

Despite significant impacts of natural ventilation on atria, indoor thermal conditions and decreasing energy usage load, there is lack of knowledge about how various design parameters influence atria thermal conditions. The complexity of natural ventilation design of atria and inadequate simulation design tools may lead to inaccurate atria thermal prediction. In the past 25 years, researchers have developed and suggested various methods such as experimental, theoretical and numerical modeling to identify thermal and ventilation performances of atria. However, the diversity of the modeling conditions makes it difficult to achieve proper conclusions which link all contributing parameters to atrium thermal conditions. This paper provides a comprehensive review of previous studies on the role of natural ventilation in atrium buildings in different climates, efficient design parameters and their application to improvement of thermal performance and decrease of energy consumption. These parameters include various atrium configurations and components such as atrium geometry, opening characteristics, roof properties, materials and fenestration characteristics. The review further highlights different ventilation techniques which can be applied in atria as assisted ventilation methods. The cited parameters can be categorized into those affecting thermal performance and ventilation performance. The outlet opening size is the most influential parameter that affects both indoor thermal condition and ventilation behaviors of atria and consequently decreases energy usage load.



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## 1. Introduction

Atrium space, a large and almost glazed central space, especially in non-residential buildings, is a popular space which has been in use with an increasing trend throughout centuries since ancient times starting in Mesopotamia. Atrium provides impressive aesthetic space, exposing adjacent indoor spaces to daylight, maximizing benefits from direct solar gain, and increasing inhabitants' socialization and interactions [1–4]. It also provides air circulation and communication among different stories of the building. Furthermore, atrium is considered as a factor contributing to scale up of market values of buildings [5].

Modern Atria has its origins in regions with temperate climate and was first developed in the early 1990s, and then spread and proliferated by just adopting their aesthetics in different regions with more unsuitable climates without adequate materials and conditions. The interest in employing the new technology and glass walls, especially in some office and commercial buildings, resulted in neglecting environmental potentials (radiation, wind, and other natural conditions) [6]. Therefore, despite all the advantages mentioned above, providing thermal comfort in atrium requires high amount of energy [7] due to excessive solar heat gain during summer daytime and heat loss during cold seasons from large glazing walls and continuous air stratification [8]. However, it is estimated that consumption of energy in this type of buildings with optimal design is below 150 kWh/m$^2$/year in some regions in Europe [9].

Natural ventilation in such buildings plays a key role in providing optimum quality of indoor circulation of air within the building and maintaining acceptable level of thermal comfort without necessity for employment of mechanical systems such as Heating, Ventilation, and Air Condition (HVAC). Therefore, natural ventilation is capable of decreasing HVAC energy consumption which has substantial contribution to saving energy amount in buildings [10,11] with more than 60% of the total building energy consumption [12].

Although more studies have been conducted in the past decades on natural ventilation system in atria, the investigations relating atria design parameters are still limited. Due to its complexity and lack of accurate measurement tools, predicting thermal performance in atrium is difficult [13]. Many of the studies are without detailed parametrical results or just focus on validation of analytical methods in their experiments. Therefore, providing a comprehensive review of all atrium building designs can facilitate to find an effective use of natural ventilation in a wide range of atria buildings for better energy efficiency. This maximizes atria energy saving potential in various climates by replacing or assisting mechanical systems with natural ventilation, the result of which leads to a decrease in maintenance and operation expenses while providing better thermal comfort and higher indoor air quality.

This paper attempts to bring together the previous studies achievements about naturally ventilated atria and influential atrium design parameters. It demonstrates how they can be applied and improved to provide a better thermal condition for atrium and adjacent spaces. It begins with reviewing the evolution of atria design approaches throughout history, the generic forms of atria and recent considerations about atria effective design factors.

## 2. A brief review of atria

Atrium is a Latin word originally referring to a main room or central court with hearth, which caused the room walls to be covered with black soot (ater) though time, giving it its name (atrium) in a typical ancient Roman house. However, in the modern era, its design has changed in a way that it is usually covered with glass walls and roof creating a common space interconnecting the adjacent galleries and stories within an atrium building.

Atria and courtyards are commonly embedded in some buildings for natural ventilation and cooling purposes. Both atria and courtyards form centerpieces in buildings and connect them to the environment [14] by providing natural ventilation and sunlight through exchange of the internal air with the external one [15]. Comparative analyses of the central atria and courtyard reveal that atrium, with the same geometric dimensions against varying climatic and glazing conditions, is more energy efficient with increasing building height [16], while applying an open courtyard to low-rise dwellings during summer and an atrium for the rest of the year, leads to an optimal balance between energy consumption and summer comfort in tough climates [17].

### *2.1. The evolution of atria through history*

The history of traditional atrium can be traced back to 3000 BC in the archeological remains of a courtyard house in Ur, Mesopotamia [1] as shown in Fig. 1(a). It was later found as a central courtyard in ancient Roman and Greek houses. Atrium has served not only as a climate modifier but also as a space for socialization of the inhabitants of the building. In hot areas courtyards are commonly utilized to fulfill the dual functions [18]. For instance, in the Tropics, courtyard provides natural ventilation and light for "Shop house" buildings [19] (Fig. 1(b)). Including atria in the design of buildings in the modern era started during the Industrial Revolution with the availability of plate glass and slender structural

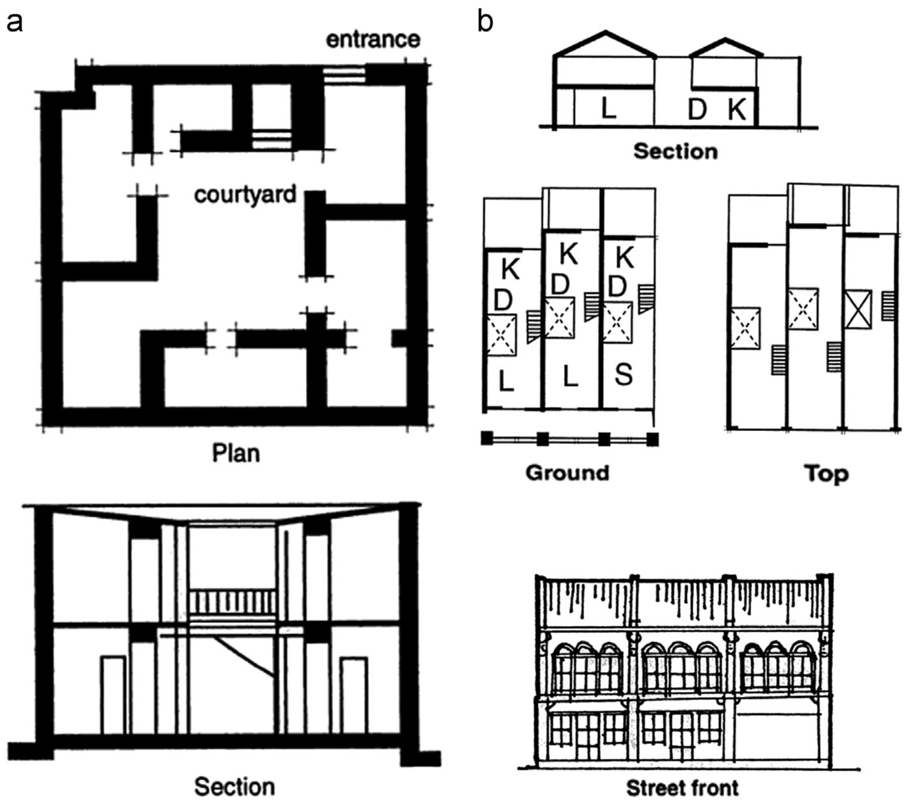



**Fig. 1.** Section and plan of House of Ur, Mesopotamia) a), typical section, plan and elevation of Shop house design in Malaysia (b) [19].

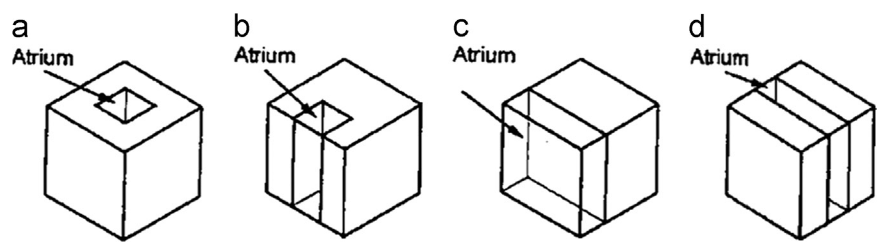



**Fig. 2.** Four different generic forms [21] of atrium and real samples. (a) Centralized, (b) semi-enclosed, (c) attached, (d) linear.

elements of iron and steel. However, modern atria were not common until late 1950s and early 60s. The new form of atria originated from temperate climates in regions of high latitude where it provides an environmentally controllable room and natural sunlight and heat during winter [20].

With increasing number of buildings with atria, especially in non-residential luxury buildings, the demand for ventilation systems to provide high air quality and thermal comfort for occupants has increased. This has consequently led to employment of mechanical systems with high energy demand. Hence, in 1970s and early 1980s, the environmental advantages of the atrium were considered anew as a post-oil-crisis-response to high-energy consumption in building designs [19]. Nevertheless, the consideration was only about the atrium used in temperate climates. The direct application of temperate atrium solution to hotter climates caused significant problems which still need to be resolved. Thus, with the new energy efficient approach, natural ventilation, as the main potential environmental advantage of atria, was highlighted once again.

### *2.2. Generic forms of atria*

The design of an atrium is based generally on climatic conditions, architectural experiments, expected level of thermal comfort, and functions of building. The placement of atrium in building is the main factor which determines the potential environmental advantages of atria in the building. There are four different shapes of atrium, as main category of atria forms, which have been cited in literature based on the atrium location in the building as shown in Fig. 2 [21]. Each form of atria has a particular environmental advantage which is chosen according to its ambient condition, expected ventilation and daylight performance. For example, for temperate climates, in order to have more solar heat gaining in winter time and more attractive view during different seasons, atrium is attached to the building as a glazed façade (Fig. 2c). For hot and humid climates, from the four generic types, centralized (Fig. 2a) and linear atria (Fig. 2d) are the most effective types in minimizing temperature fluctuations during hot and moderate seasons. Besides, the overall temperature performance of these atria types is the closest to neutral temperatures [22]. Hence, these centralized and linear atria are the most common generic forms in use in hot regions [23].

### *2.3. Recent approaches to atria design*

Based on the literature, to achieve the desired indoor thermal condition in designing naturally ventilated atria, two main design approaches have been cited which are: (a) designing atrium

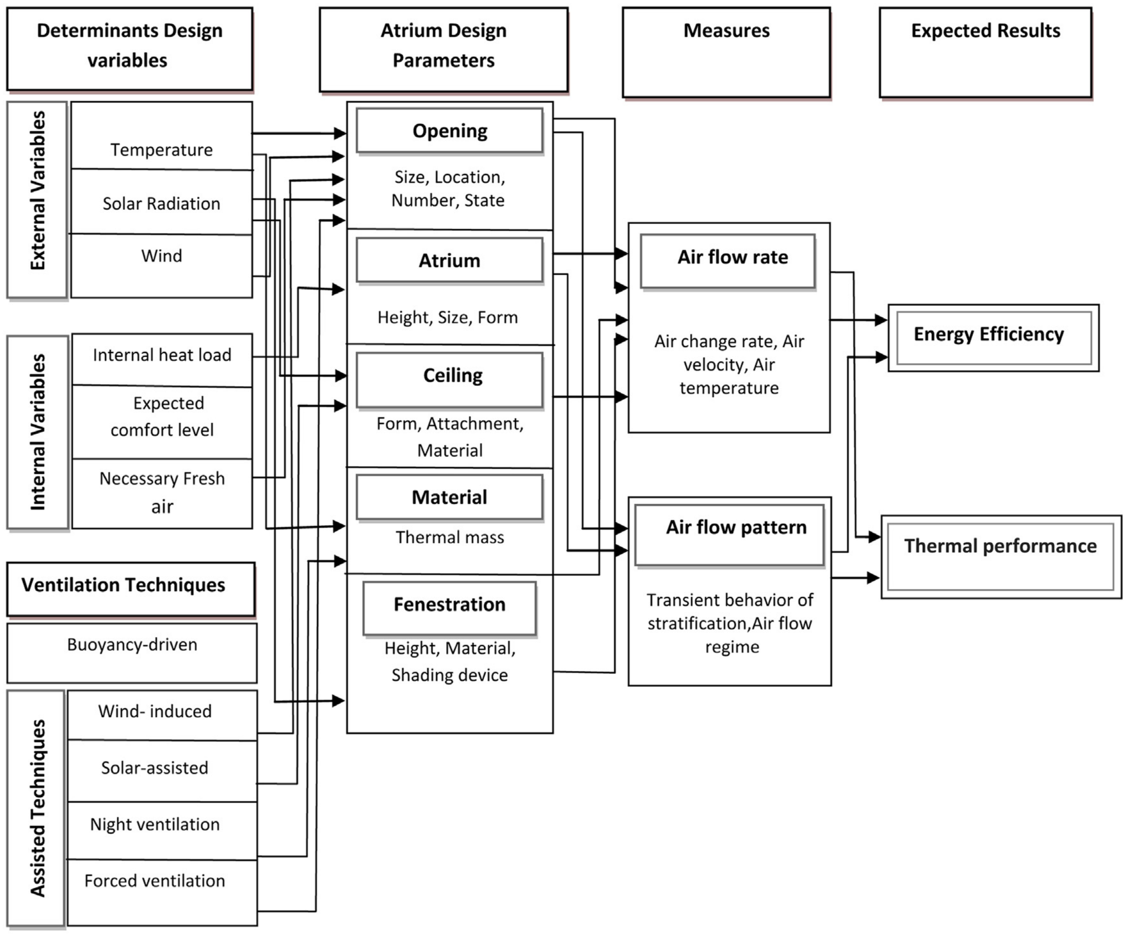



**Fig. 3.** A map of design parameters and variables.

components and configurations and (b) implementing appropriate ventilation techniques. These design parameters are mainly affected by external and internal variables. The efficiency of each parameter has been evaluated based on their influence in increasing air flow rate and expected air flow pattern which consequently lead to improvement of the thermal condition and decrease of the energy consumption in atria. Fig. 3 presents a list of the variables, ventilation techniques and their relationships with other design parameters in the structure of the recent design approaches to atria. The significance of this figure is that it illustrates interdependencies among factors that influence passive design of atria.

The next section assesses the significance of the natural ventilation, the effects of different variables on the thermal condition of naturally ventilated atria, and various implemented ventilation patterns in atria. Furthermore, the effective control technologies implemented to improve thermal and ventilation performances of atria were also reviewed.

## 3. Natural ventilation in atrium

The main advantage of utilization of natural ventilation in building design is not only reducing energy consumption and cost but also providing acceptable comfortable, healthy and productive conditions. The difference in the pressures in the inside and outside environments, resulting from factors such as wind and buoyancy driven forces, causes air movement throughout the building [14]. These factors are elaborated in the following subsections:

### 3.1. Buoyancy and wind effect

As Fig. 4(a) illustrates, natural ventilation in atrium space is based on buoyancy driven force which occurs when the indoor temperature is greater than the outdoor temperature [15]. Three factors are required for creating the buoyancy driven ventilation force: lower level inlet opening, higher outlet opening and heat sources creating temperature differences between the inside and outside environments. Without taking the wind effect into consideration, the indoor and outdoor pressures can be expressed as following:

$$P_{in} = P_0 - \rho_{out} g h \quad (1)$$

$$P_{out} = P_0 - \rho_{in} g h \quad (2)$$

where, $h$ is the height of an indoor or outdoor height relative to reference height, (m), $P_0$ is the static pressure of the outdoor air at a reference height, (Pa), $P_{out}$ is the pressure of the outdoor air at height $h$ relative to the reference height, (Pa), $P_{in}$ is the pressure of the indoor air at height $h$, relative to the reference height, (Pa).

Therefore, pressure differences between the indoor and outdoor environments at height $h$ is: $\Delta P = (\rho_{out} - \rho_{in}) g h$. As Fig. 4(b) illustrates, due to the heated air inside the building, its density is lower than the air outside the building. Hence, the outdoor air pressure is higher than the indoor air pressure, a condition which causes the outdoor air to enter the building as long as the pressures of the air within and without are balanced, after which the outdoor air is let in at lower level and the indoor air leaves the building at the higher level [24]. In this regard, Holford and Hunt [25] believe that increasing the temperature of the warm air layer

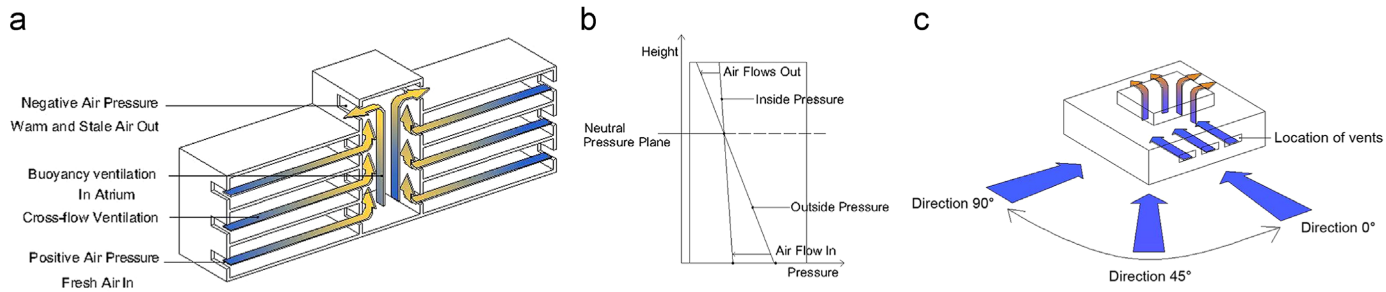



**Fig. 4.** A flow diagram representing natural ventilation through atria (a), the pressure differences across the atrium space (b) [24], the three wind directions in a modified isometric view of the model building (c) [29] shows the impact of wind on ventilation pattern of atria.

can enhance the passive ventilation of a building by increasing the warm air layer depth which collects in the upper regions of the space. However, latter can be detrimental, because it rises the upper air pressure and drives warmed air into adjacent spaces in upper levels and overheats this area.

Compared to wind, stack effect which relies on indoor heat, assures robust control of the air flow. It also makes more reliable performance prediction at the design stage [26], whereas, by using wind, it is hard to predict and control the likely performance of simple naturally ventilated buildings [27] (Fig. 4(c)). Although, wind induced force can create stronger air movement inside the building than buoyancy induced ventilation, with proper buoyancy design, an air flow can be maintained at all times, especially during night time.

Since the nature of buoyancy force is not too strong, in designing natural ventilation of atrium building, wind induced force needs to be compromised with buoyancy induced force simultaneously. It is more important, especially for regions with low exterior and interior temperature differences [28]. Therefore, designing such a ventilation system is complicated and needs more attention. Otherwise, it could change the air flow pattern unpredictably.

## 3.2. *Effective ambient variables*

Atrium design is directly affected by ambient conditions when natural ventilation is implemented. Weather is a potential constraint in the application of natural ventilation, such as monsoon in tropical climates and sand storms in hot arid regions. On the other hand, some of the ambient variables are influential in creating or increasing air flow in the building. The influential climatic factors in designing naturally ventilated atrium in the building are: outdoor temperature, wind direction and speed, and solar intensity (Fig. 3), which are discussed below:

### 3.2.1. *Temperature*

As reflected in literature, in hot and humid climates, the impact of ambient temperature on distribution of atrium space air temperature is larger than the thermal load inside the building [30]. Neglecting heat transfer with conducting, ambient temperature affects the thermal condition of the indoor environment through supplying cool fresh air for the atria. The air stream inflow at lower temperatures not only decreases the interior air temperature but also increases cooling capacity that results in higher cooling amounts stored in the thermal mass [31]. On the contrary, in higher ambient air temperatures, higher than 35 °C, using natural ventilation is detrimental. Therefore, to avoid the influence of heated external air in indoor thermal condition, upper-opening should be closed [32]. Furthermore, small temperature differences between external and internal spaces can interrupt buoyancy-induced natural ventilation process.

### 3.2.2. *Solar radiation*

Solar radiation that penetrates thorough the glass walls or roof to provide daylight is the most significant factor of discomfort in the buildings with mean radiant temperatures [33]. Solar radiation has the main role in creating thermal stratification in atria mainly by affecting the roof temperature [34]. In the tropics, it causes a serious problem, especially with the radiations emanated from the high altitude of the afternoon sun at the high level of the atrium space [35]. For example, study on a five storey atria in Mediterranean climate of Santiago de Chile showed that protecting solar radiation can lead to reduction of 75% of cooling demand; while night ventilation has only 10% reduction [36]. However, this depends on the solar protection forms and glass types used in the building. As an example, presence of high level internal blinds had approximately equal effect as water spray on roof to lessen the effect of thermal stratification in hot and humid climate [37].

### 3.2.3. *Wind*

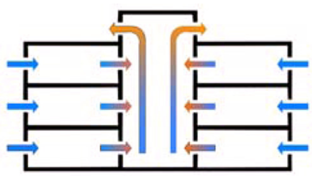
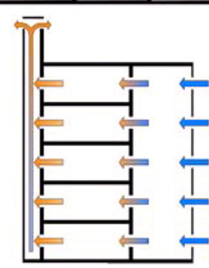
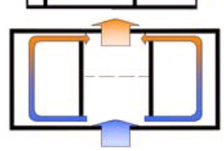
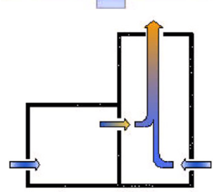
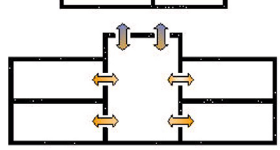
Wind, as a ventilation driving force in atria, is influential in increasing the stack effect [12]. Wind force drives air in the atrium with increasing the positive pressure exerted on the inlet opening toward wind. It also decreases the negative pressure on the leeward outlet opening. However, with the wind direction changing over a certain range of time basis (hourly, daily and seasonal), the pressure field that surrounds a building changes accordingly. Therefore, an inlet opening is changeable from positive pressure in one day to negative pressure in the next day. In such cases, the inlet opening serves as a vent exhaust when there is a counter air flow at the roof exit, which, in turn, results in unexpected downward air movement through the atrium, leading to suppression of the plume from the source of the heat [38]. Wind driven ventilation is particularly effective in areas with relatively high wind speed. However, the function of wind is limited to many factors such as building wind exposure. For example, in dense urban areas in which atria are surrounded with other high buildings, the wind force impact is not as expected.

Horan and Finn [29] have jointly studied the effects of various wind speeds and directions on rate of air change (ACH) inside the atrium space. Their investigated sample was a double storey office building (Urban Institute Ireland, UII), ventilated by a chain of entry vents on one of the walls in conjunction with some other vents embed in roof. External wind speeds ranging between 25% and 250% of the mean site wind speed, that is, 5.7 m/s, were investigated and discovered that it is linear increase in the ACH rate. Regarding a single wind speed, the examination of the relationship between the ACH rate and wind direction revealed almost a linear direction for wind ranging and varying from 0° to 90° (parallel and orthogonal) toward the vent valves in the wall, but non-linear for other wind directions, that is, 90–135°, as illustrated in Fig. 4(c).

### 3.3. *Internal thermal loads*

Internal heat mass in the atrium is based on two heat sources: (a) internal heat sources via occupants and devices and (b) external heat sources like solar radiation. The location of internal heat sources and the amount of heat load they generate cause vertical temperature gradients and consequently air movement inside the atria. To have the consistent buoyancy air flow ventilation, the presence of internal heat load is necessary [26]. However, to prevent thermal stratification in atria space, internal thermal load needs to be significantly controlled. The role of internal heat load in passive heating purpose is highlighted in Woods, Fitzgerald [39] joint study. Their study concluded that in mixing ventilation with internal heat emanated by 0.1 kW per person saving up to 70–80% of the displacement ventilation heat load depending on the internal heat loads emanating from a person and the insulation levels of the building.

**Table 1**
The various designed ventilation patterns in atria based on previous studies.

| Number | Ventilation behavior | Role of atrium | Pattern |
|---|---|---|---|
| A | Atrium surrounding air in and exhaust air out of atrium | Stack ventilation |  |
| B | Atrium air in and exhaust air out of solar chimney [1] | Supply fresh air |  |
| C | Atrium air in and exhaust air out of atrium (from down-to top) [2] | Supply fresh air and drive stagnant air |  |
| D | Atrium and surrounding air in and exhaust air out of atrium [3] | Exhaust warm air |  |
| E | Atrium air in and atrium exhaust air out (from top-to top) [8] | Pre-heating |  |

### 3.4. *Implemented ventilation patterns*

In the previous studies, five kinds of ventilation patterns can be identified [25,30,39–41]. In each pattern, the role of atrium space is different based on the particular ventilation purpose in the building as below:

A. Atrium receiving air from surroundings and exhausting it to the outside.
B. Atrium receiving air directly and conducting it to surrounding rooms.
C. Atrium receiving ambient air to surrounding spaces and exhausting it to the outside.
D. Atrium directly and indirectly ventilated and exhausting air to the outside.
E. Atrium directly ventilated and exhausting air from the roof.

These patterns are based on atria thermal and ventilation comfort requirements, ambient conditions and building forms as shown in Table 1:

Therefore, the role of atrium space can be summarized as, supply of fresh air, air flow displacement, exhausting stagnant warmed air or combination of them. For example, in Type A the atrium just helps to exhaust warmed air from adjoining spaces out of the building. Whereas, in Type D atrium exhausts warmed air and connects to the outdoor to draw in fresh air directly to itself. In Type C, atrium not only exhausts stagnant air, but also supplies fresh air for adjacent spaces and atrium too. Furthermore, atrium can utilize ventilation for heating purposes by supplying fresh air and exhausting stagnant air with less air change ventilation (like type E).

To improve natural ventilation some patterns benefit from available climatic factors. As Table 1 demonstrates, in case of intensive solar radiation, atrium is integrated into solar chimney or double skin façade (like type B). Therefore, implementing assisted ventilation techniques could address the limitations of a building design, such as deep surrounding spaces, where the buoyancy ventilation force is not sufficiently strong to drive the air through

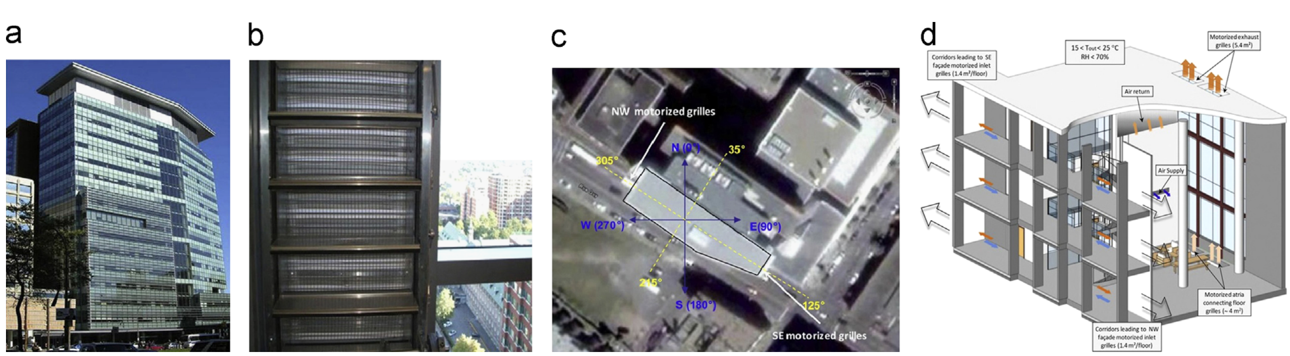



**Fig. 5.** Outside view of the Engineering Building of Concordia University, Canada (a), motorized corridor inlet grilles (b), top view and direction of building (c), hybrid ventilation concept (d) [43].

remote section. Furthermore, assisted ventilation is used in dense urban areas to draw cleaner and cooler air from upper atmosphere layers utilizing upside-down solar chimney (A modified version of model B, with reverse airflow pattern).

### 3.5. Natural ventilation control systems

Ventilation control systems can help stabilize the impact of unpredictable and extreme ambient variables in atria to achieve or maintain a desired environmental quality. For example, to benefit from wind in buoyancy-driven natural ventilation and prevent adverse effects of wind on the airflow patterns in the atrium, intelligent control of ventilation openings is recommended [28]. However, control systems generally rely on energy for operation, therefore, increasing the building energy and maintenance cost.

Pfafferott et al. [3] have shown in a study that using controllable valves at the higher levels of atrium to let in the external cool air will reduce the time temperature ($T > 25$ °C) during the daytime by 50% even without need for mechanical ventilation. Study results about utilizing motorized valves in the Engineering Building of Concordia University in Canada, as shown in Fig. 5 agreed with the results achieved by the previous studies. However, the currently available techniques and devices used for night cooling of atrium buildings are not optimal for all buildings in various climates and may result in discomfort of the residents [42]. Thus, a predictive control strategy is required for atria buildings with high thermal mass [43].

## 4. Thermal performance of atria

In designing naturally ventilated atrium, design parameters can be divided into two categories, namely: parameters affecting thermal performance and parameters affecting ventilation performance. The following section reviews the impacts of various design parameters on thermal condition of atrium models. It demonstrates how atrium indoor thermal condition and energy efficiency are improved through implementing convenient passive ventilation techniques and efficient design parameters. To assess atrium thermal performance, different methods such as experimental, analytical, mathematical and numerical modeling have been used.

### 4.1. Opening characteristics

Various aspects of an opening such as its number, position, size, and location have been dealt with in literature. Among all these aspects, opening size has a more significant role. In general, the air temperature stratification within the atrium reduces significantly with the increase in the size of the openings [44]. However, for providing strong and well distributed airflow throughout the building, the proportion of inlet to outlet openings is important. For example, in temperate climates, with buoyancy driven ventilation, an atrium enhances the airflow throughout the storey if only its upper openings are of medium size, while its lower openings are sufficiently small [25]. Whereas, in the tropical regions, with pressurized ventilation, sufficiently lower high outlet to inlet opening area ratio ($1 > n$) can result in improvement of the thermal performance on the other levels occupied by residents [45]. Besides, increasing the numbers of the openings increases the airflow rate through the atrium. However, it decreases airflow rate through each floor causing temperature to increase in almost all heights of the building [46].

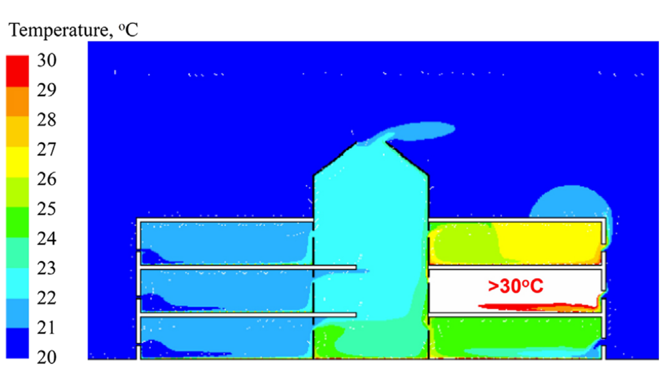


**Fig. 6.** Predicted air temperature in the naturally ventilated building with windward openings reduced to 0.1 m [28].

Outlet opening effects was investigated on a commercial office building with three stories in a temperate climate. The results demonstrated that in case of the opened stack vent, almost as much as twice of air flowed through the atrium, whereas, the indoor temperature differences between ground and second floors rose by almost 7 °C in case of closed stack vent. Despite the necessity of outlet openings in natural ventilation, in high ambient air temperature conditions (over 35 °C), the efficiency of stack openings is limited [30].

Inlet opening in low level windward side of building with fewer obstacles could increase ventilation rate and facilitate airflow providing fresh cool air for atria and/or surrounding spaces. Fig. 6 illustrates the effects of minimizing windward opening size on indoor temperature distribution [28]. However, atrium inlet opening directly connected to exterior spaces in low levels is detrimental to the ventilation of the various stories [25,47] (Refer to Table 1, Type D).

The location of inlet opening has various thermal effects on different stories of a building. For example, with increasing inlet opening height of each floor from 0 m to 1.2 m in a two winged three-storey atrium model in temperate climate, the temperature of the atrium space decreased by 2.5 °C with approximately stable volume of flow rate, whereas, it caused a 1.5 °C temperature increase in the second floor [48] (refer to Table 2). Like location, direction of the inlet affects airflow distribution in the atrium as well. For example, in pressurized ventilation model, vertical side vent provided better distribution of the cooler air on the ground level due to the thermal buoyancy effect. It led to decrease of the indoor air temperature. However, in the same study, with an equal inlet to outlet opening area ratio (i.e. $n = 1$), modification of the outlet location did not have significant effect on the thermal performance of the atrium [49].

The opening areas of each storey should be different to be able to achieve the same rate of ventilation flow in each storey with the same height (refer to Table 1, Type B) [40]. Ji and Cook [50] implemented a general analytical model and computational fluid dynamics (CFD) model to investigate and assess the ventilation flow in stories connected to a shared atrium on one side, and top-down-chimneys in the opposite side, (A modified version of model shown in Fig. 10(b)). The study revealed that the higher the storey is, the less the stack effect provided by the atrium, hence, larger total effective opening area is required.

### 4.2. Atrium geometry

In various climatic regions, total energy use of elongated (central) and narrow or rectangular atria with higher length to width ratio is significantly greater than the atria with square shapes [51]. To have buoyancy-driven ventilation with high efficiency, especially in hot and humid regions, atria need to be high enough to be able to induce enough pressure gradient prompted by temperature differences [30]. Nevertheless, tall atria structures do not necessarily scale up the rate of the ventilation and airflow, especially when the outlet valve is

**Table 2**
Effect of geometric variations on the volume flow rates and inside temperature values at 1.1 m from each floor [49].

| Geometric input parameters | | Output parameters | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Parameters | Values (m) | Volume flow rate ($m^3$/s) | | | | Average temperatures(°C) at 1.1 m from floor | | | |
| | | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 |
| Location of inlets (height from each floor) | 0 | 0.42 | 0.42 | 0.40 | 0.80 | 33.61 | 32.39 | 32.68 | 33.93 |
| | 0.6 | 0.42 | 0.42 | 0.40 | 0.80 | 33.66 | 33.47 | 33.36 | 33.88 |
| | 1.2 | 0.42 | 0.41 | 0.39 | 0.76 | 32.8 | 33.41 | 34.15 | 31.57 |

Ambient temperature 25 °C. 1 – ground floor, 2 – first floor, 3 – second floor, 4 – atrium floor.

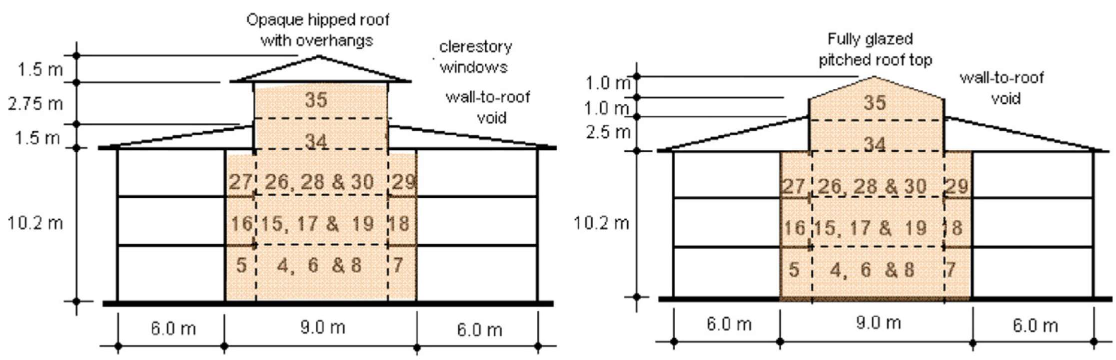



**Fig. 7.** Schematic cross-sections of atrium models; side-lit model with wall-to-roof void and roof overhangs (a) top-lit model with wall-to-roof void (b) [44].

not sufficiently large. The resistance that small opening imposes on ventilation flow may thwart the positive effects of tall atrium building [30]. Therefore, the vent space characteristics should meet design requirements to yield optimal outcome in taller buildings. The vent area increases with building height although the size of the atrium vent need to be limited to prevent possible air exchange flows [52].

In high-rise atria buildings, with increasing atria height, the thermal efficiency is not necessarily increased, but it is limited to atria size and the storey height [53,54]. According to Li et al. [54], adding 1 m to height of building requires an increase of 0.043 $m^2$ of the size of rectangle atrium to meet the need of the indoor thermal comfort. However, in high-rise atria the lower level rooms enjoy the advantage of the buoyancy-driven ventilation while the upper level rooms suffer from its lack or weak presence [53]. The study further concludes that with increase in the size of atrium, the buoyancy-driven ventilation effects of high-rise residential buildings improve until it reaches a certain level, after which further increase in the atrium size hardly improves the buoyancy-driven ventilation effects.

### 4.3. *Roof properties*

The roof form is a critical part of the atrium design when thermal comfort and low maintenance cost are concerned [44]. The roof receives solar heat based on its apertures and material characteristics and holds warmed air before being exhausted. Sufficient high wall-to roof void area can greatly improve the thermal performance of atrium particularly on occupied stories. For example, as Fig. 7 shows, in top-lit model, the 2.5 m high wall-to-roof void area is capable of lowering the predicted air and mean radiant temperatures on the second floor level around 0.7 K and 1.8 K, respectively [44]. However, it is convenient for hot and humid climate with high thermal stratification and it also has cost construction limitation. They compared two roof forms for atrium, top lit and side lit form, in hot and humid climate. Their modeling study revealed that the side-lit atrium utilizing clerestory windows for the tropic climate was generally more effective in both thermal and energy performance. However, in side-lit atrium natural daylight is not compromised for adjacent spaces. They also recommended the 1.5 m wide roof overhangs above the clerestory areas for side lit form and removable internal blinds with downside surfaces light colored or polished for top-lit form. Since the internal blind probably traps warmed air beneath the roof and increases the upper air temperature, utilizing external blind could be more influential, especially in hot and humid climate. Interior shading with blinds installed 3–5 m below glazed roof is recommended to generate ventilated void and better lighting and thermal in the atrium space [55].

To reduce the possibility of thermal stratified layer in atria, many techniques have been cited for cooling the roof. For example, in a CFD model, utilizing natural ventilation in an atrium roof provided with photo voltaic (PV) arrays, moving the air inlet closer to the roof could raise the ventilation cooling effectiveness of PV arrays by 5 °C reduction. However, doubling the size of inlet causes a rise of temperature about 1.8 °C [56]. Furthermore, various roof materials possess different heat inertia which could lead to thermal stratification [34]. Other techniques such as using air cooling in glazed roof and water spray to cool the warmed roof are also among the recommended techniques [44].

### 4.4. *Fenestration properties*

The optimum atrium design brings daylight into deep surrounding spaces to minimize space conditioning and lighting loads [16]. However, in extreme weather conditions, although atrium provides enough indoor lighting for surrounding spaces, indoor thermal comfort is not compromised despite minimized energy consumption [57]. To control solar heat gain, Chen [58] developed an intelligent shading system for atria in Subtropical climates with extreme hot summers and cold winters. This study supports that by implementing intelligent shading devices not only can excessive solar radiation penetration be controlled, but also adequate daylight can be trapped for better and brighter view of the atrium area. This, in turn, leads to significant reduction of cooling loads in summer. Furthermore, light colored or low emissivity surfaces are the best choice for blinds [44]. Although utilizing traditional shading devices easily solves the problem of high levels of solar radiation penetration, due to the low U-value of the glass, in summer it will decrease the daylight of the atrium as well.

To provide passive heating and ventilation in atria in temperate climates, higher fenestration is recommended. The analytical method was employed to examine the relationship between glass height and passive heating and ventilation load in a fictitious institutional building with four sided atrium in Tehran, Iran. The results of the study showed that the atrium can reduce the heating load maximum up to 25% of the glass height [59]. However, the glazing material is also important for thermal demand of atria, especially for cooling seasons. Rojas [36] investigated the impact of changing different glazing types and solar protection forms on thermal demand of an office building with five stories and a north-facing adjacent atrium in Santiago. The results showed that double-glazing walls can decrease cooling demand from 13.8 kWh/m$^2$ down to 13.4 kWh/m$^2$ a year. With low-emissivity (low E) double-glazing atrium the heating demands are the lowest, nonetheless, the cooling demands reach their peaks in contrast with other cases (14.4 kWh/m$^2$/year) [36].

### 4.5. Materials

The thermal mass of atrium external walls with external insulation provides better internal temperature variations in winter [60]. According to a study carried out on cold climate cases, the heat stored in walls could be useful for the night-time buoyancy-driven ventilation when there is no solar radiation. However, without insulation enveloped walls, the buoyancy-driven flow rate was reduced considerably compared to that with insulated walls [60]. High thermal mass of atria can be implemented for night ventilation and cooling purposes. A full-scale experimental set-up in an occupied institutional building in Canada was carried out to evaluate the cooling capacity of the concrete floor slabs in the three-storey atrium (refer to Fig. 5). The results showed that the amount of the heat removed through convection by an air stream at an average outdoor temperature of 12 °C was estimated to be five times higher than that by an air stream at an average temperature of 18 °C [43].

## 5. Ventilation performance of atria

Predicting the behavior of the airflow in terms of direction and steadiness among the spaces is necessary in designing atria with natural ventilation. This is due to the fact that increasing internal heat source of a space within the building or changing some design parameters could reverse the airflow pattern and consequently cause thermal discomfort or circulation contamination among surrounding spaces. The following section reviews different parameters influencing the airflow behavior inside the atria.

### 5.1. Opening characteristic

An atrium with more stack opening size and a path of direct circulation performs better temperature fields without being affected by the ambient temperature changes [30]. A joint study by Walker et al. [61] confirmed it with testing both opened and closed stack vent cases in naturally ventilated building models. The investigated model was a three storey office building linked to an atrium in a temperate climate through CFD simulation as shown in Fig. 8. Their study concluded that with the closed stacks the neutral plane in the building was lowered and the air was exhausted via both opening sets on the second floor as well as the upper vents equipped on both flanks of the first storey.

The outlet opening size or temperature differences between spaces affect ventilation process. Fig. 9 illustrates a model of two spaces linked to an atrium via low and high level vents maintained at various temperatures levels in excess to the temperature of the outside environment. The results revealed that normal displacement ventilation flow regime changes with minimizing the size of the opening connecting atrium to the outdoor space or increasing the temperature contrast between the interior and exterior spaces, which finally results in increase of the overall energy load and concentration of the contaminant in the warmer spaces [41].

In air conditioned spaces connected to atria, the location of connecting opening is effective in the airflow regime (refer to Table 1, Type D). The model of an atrium building in Shanghai in which many air conditioned zones are connected to atrium space, was theoretically and experimentally analyzed. The atrium had an upper outlet opening on one side and a lower inlet opening on the opposite side. The study concluded that the upper-opening location can be elevated to avoid the negative impacts of the ambient airflow on the air-conditioned areas and effectively exhaust the stale heat trapped in the upper levels of the rooms [32].

### 5.2. Atrium design

Although changing atrium size does not affect the air flow pattern, it has significant effect on the duration of transient behavior of stratification between atrium and interconnected adjacent spaces. Lin and Linden [62] developed a model with two chambers of equal heights but different sizes connected together by two top and bottom openings. The forced chamber, a small chamber with a source of internal heat, was linked to the unforced chamber, a bigger chamber. Theoretical analyses and experimental results show that the stratification evolution within the surrounding rooms occurs on two time scales and varies according to the unforced chamber size. However, this behavior depends on the connecting openings geometry between the two spaces as shown in Fig. 10(a).

In case of multi-storey atria, depending on the number of their levels, different stories show different warmed air exhaustion behavior at night. However, this exhaustion of the warmed

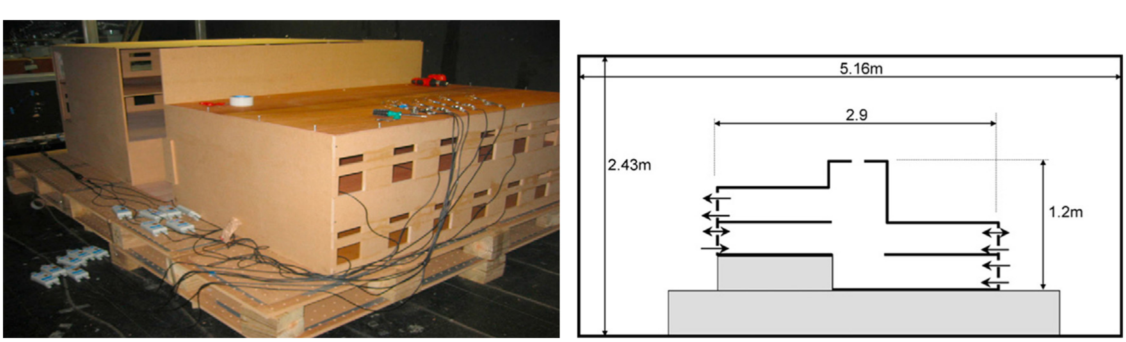



**Fig. 8.** The scaled air model in the test chamber (a), reduced-scale model and test chamber dimensions (b) [61].

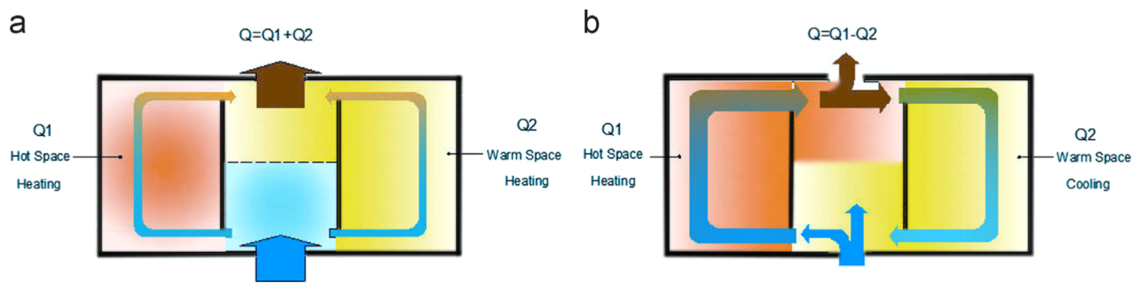



**Fig. 9.** Independent upward displacement regimes (a), unexpected convective circulation regime due to high temperature differences or small outlet opening (b) [41].

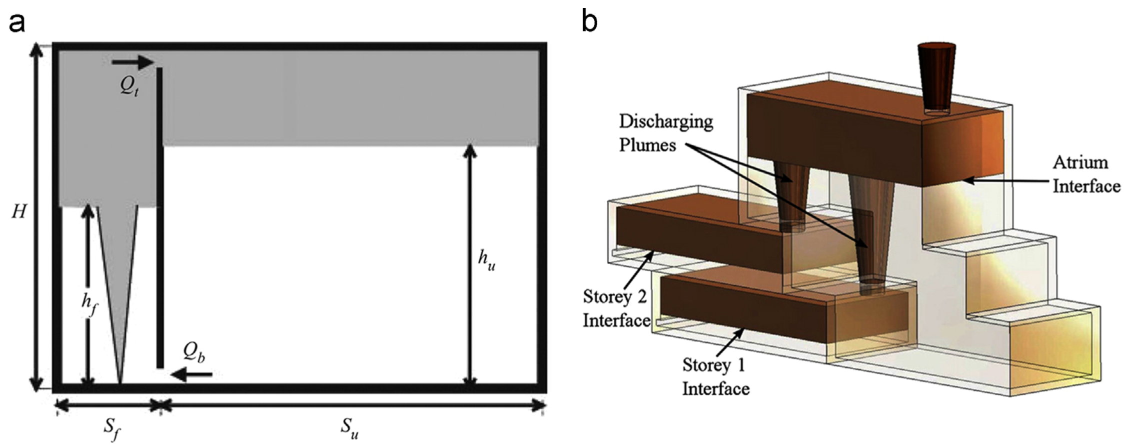



**Fig. 10.** Thermal ventilation in two chambers connected to each other through two openings (a) [62]. A 3D illustration of purging in a double storey atrium building (b) [63].

**Table 3**
Predicted ventilation rates in the offices of the atrium building with 0.5 m high window openings [31].

| Inlet/office | Ventilation rate (L/s per m² floor area) | | |
|---|---|---|---|
| | Buoyancy only | Wind only at 3 m/s | Wind + buoyancy at 3 m/s wind speed |
| L1 | 20.8 | 64.0 | 57.1 |
| L2 | 17.8 | 73.7 | 66.6 |
| L3 | 13.6 | 70.6 | 60.0 |
| R1 | 20.7 | −35.3[a] | −11.0 |
| R2 | 17.8 | −29.9 | −19.1 |
| R3 | 13.0 | −13.3 | −7.8 |

[a] Negative value indicates air flowing out of the opening, i.e. incoming air from the atrium.

air behavior could be controlled with changing the opening size and location. As illustrated in Fig. 10(b), Lynch and Hunt [63] investigated the night purging phenomenon in a two-storey building with naturally ventilated atrium through a mathematical model. The achieved results showed that only when the warmed air of the first storey is completely removed, the atrium starts true purging. In case of the multiple storey buildings connected to a central atrium, night purging at the upper stories may occur with delay waiting for the lower level stories to purge first.

## 6. Assisted ventilation techniques

The air in atria is predominantly moved by a buoyancy-induced force [49]. In extreme climates, buoyancy-only ventilation models are not considered as optimally effective means for this purpose. Hence, additional efforts are exerted to maximize ventilation efficiency in the atria. Wind-buoyancy ventilation, wind-driven ventilation, and mechanically-driven ventilation are the strategies employed to achieve the desired thermal comfort level [30]. This section reviews ventilation techniques which can be incorporated in naturally ventilated atria to enhance their thermal and ventilation performances.

### 6.1. Wind-induced ventilation

The efficiency of utilizing the wind-driven flow in atrium depends on the interaction between wind and buoyancy ventilation which results from many factors such as ventilation patterns, atrium forms and opening characteristics. A model of atrium with two wings was simulated. (refer to Fig.6). The results show that wind can simultaneously assist and oppose the buoyancy in the windward and leeward wings respectively [28]. According to Table 3, in the combined ventilation, increasing wind speed (from 1 m/s to 3 m/s) results in increased ventilation rates in windward openings with average of 350%. However, with the same wind conditions, in leeward opening, not only does ventilation pattern change adversely, but also the ventilation rates decrease with an average of 27% and 52% compared to those under either buoyancy or wind-force ventilation conditions alone respectively. Consequently, the temperature in the windward wing and atrium decreases with an average of 2 °C, whereas, in the leeward wing the temperature increases by 2 °C.

To have a better perspective about these phenomena, wind direction and speed are considered as two important factors. Mouriki et al. [64] investigated two winged atria buildings in which inlet grilles were located at the end of the corridor in the North and South façades of each floor, as shown in Fig. 5(c) and (d). Their study indicated that airflow rates on upper floors (14th–16th) is usually different ranging between 600 and 1000 l/s in windy days with stack effect, which are sufficient to provide enough free fresh and cool air. Moreover, the inflow level is higher when the wind effect dominates with an angle toward the North

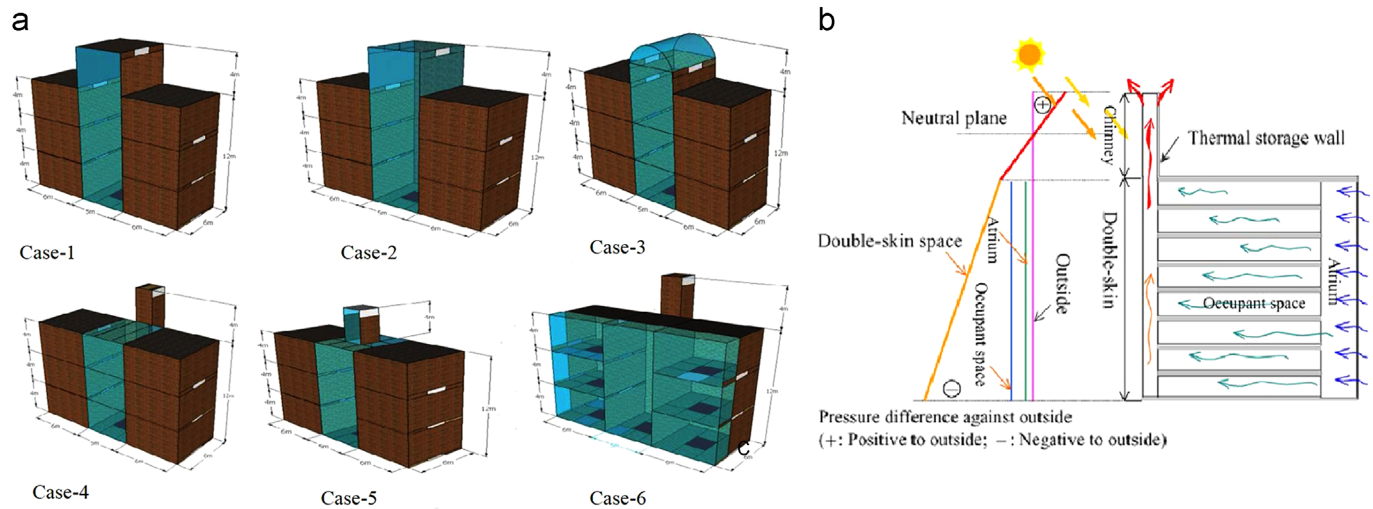



**Fig. 11.** Different atrium geometries with or without solar chimney (a) [48], cross section of atrium model integrated with double skin façade and solar chimney (b) [40].

or South façade. Outflow is higher when the stack effect is dominant with the wind angle directed toward either grill façade. Finally, the inflows at the South and North grilles façades can occur simultaneously when $\Delta T$ of indoor–outdoor is low with wind direction moving at an angle of $\theta = 220–230^{\circ}$. However, in the latter case wind effect on creation of air movement inside the building is less than previous conditions [43].

### 6.2. Solar assisted ventilation

Stack effects resulting from solar heat gain can enhance natural ventilation in atria. Two solar assisted components integrated into atrium, as mentioned in literature, are solar chimney and double skin façade. Solar chimney is a ventilation method to thermo-siphon air via convection of air heated by solar energy through thermal buoyancy [65]. The rate of airflow through the solar chimney is mainly influenced by pressure difference between interior and exterior spaces due to thermal gradient (naturally-driven convention) and wind (force convection) [66]. The direction, height, size, and type of glazing and insulation used in the walls are influential factors contributing to improvement of the capability of solar chimney.

Hussain and Oosthuizen [48] conducted a research focusing on the application of solar energy to inducing buoyancy-driven natural ventilation in atrium buildings with or without solar chimneys with various geometric configurations. As Fig. 11 (a) shows, the three storey atrium model, with the same location and orientation of the Concordia University's Engineering Building, was simulated in six various geometries using CFD numerical simulation. The results indicated that in cases without solar chimney, with increasing glazing area from 80 to 154 $m^2$ (cases 1 and 2), although the volume flow rate is increased in all spaces by an average of about 18%, the temperature increased about 1.1 °C on average, whereas, in cases with solar chimney, increasing glazing area from 118 to 286 $m^2$ (cases 5 and 6) increases the volume flow rate in all floors by an average of about 23% and average temperature decreased about 2 °C on average. It is established that atrium space provided with a solar chimney could be considered as relatively better option to be employed in atrium buildings [40]. However, it is effective in temperate climates with low thermal stratification impact.

A taller solar chimney provided with sufficient glass solar absorptance plates and solar transmittance devices yields higher natural ventilation [48]. However, it does not necessarily provide thermal comfort in the atrium space. In addition, it is cited that the solar chimney height should be more than two-floors high on the top of the double skin façade to raise air change rate of each floor, especially on the upper floors [40] (Fig.11(b)). However, in terms of aesthetic aspects, there is a limitation for its height.

Utilizing double glazed ventilated walls is one of the ways to benefit from daylight and have passive solar heat control. As Fig. 12 shows, Tanaka et al. [67] calculated the cooling load of an atrium with double-glazed exterior walls in typical summer conditions. Maximum rate of air change during natural ventilation via bottom and top openings was approximately 20–25 [1/h] which could reduce cooling loads required for total solar heat gain by about 25%. Overall, double-skin façade is capable to exhaust the solar heat gain by nearly 100 $W/m^2$ per surface area of the inner glass. Although this model is optimally energy efficient, it is limited to designs with at least one free wall preferably facing the west side.

### 6.3. Night ventilation

Night ventilation is a passive cooling strategy that depends on buoyancy and/or wind-driven forces [68]. During night when adequate low temperature is available, night ventilation is recommended as the best method. With decreasing exterior temperature, the potential advantages of night ventilation also increase. However, atrium structure with low thermal mass is not able to store enough coolness and heats up rapidly. To enhance night ventilation performance in temperate regions, high levels of exposed thermal mass are needed which will be achieved by using control systems such as utilizing controllable flaps at the top and bottom of atrium which could halve some hours over 25 °C [3]. Besides, with additional night ventilation time and using mechanical façade control in temperate climates, cooling potential is significantly increased by 30% (during cool seasons) and 54% at 3–7 °C lower outdoor temperatures of 18 °C [31]. The main disadvantages of night ventilation are, nevertheless, lack of control and slowness of charging and discharging processes due to reliance on natural convection [69]. Especially in commercial atrium buildings, security limitation is assumed as an obstacle on the way of application of night ventilation.

### 6.4. Forced ventilation

Natural ventilation is not the best solution for all season air temperature reduction in interior spaces in atrium buildings, especially when the ambient air temperature is too high [32]. Therefore, assisting hybrid cooling system could help to achieve

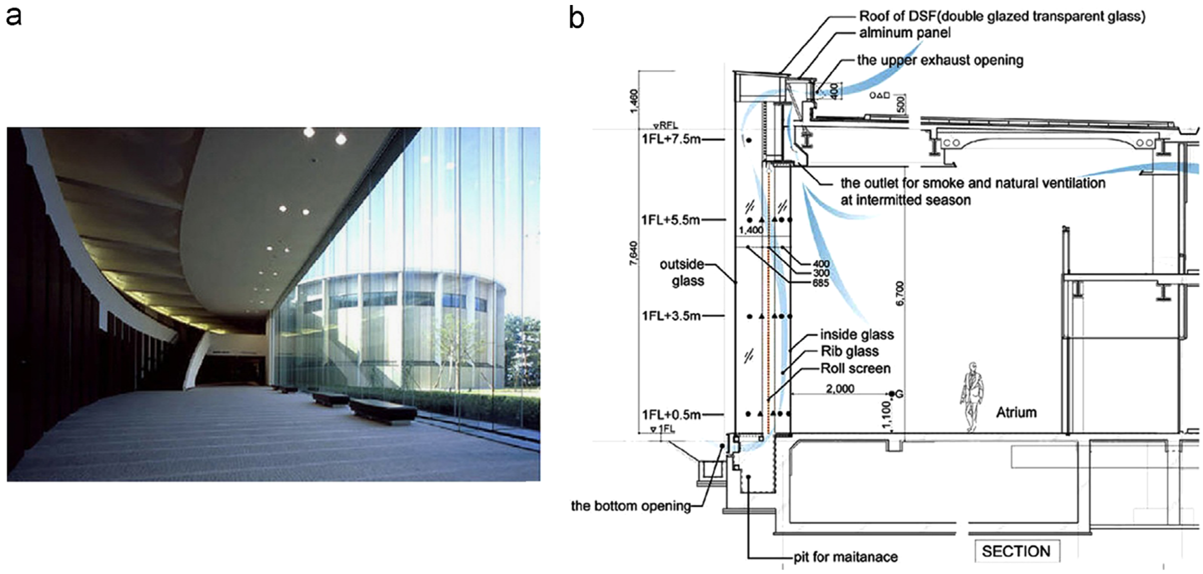



**Fig. 12.** The installed double-skin in atrium is located in the west façade (a), the detailed cross section of atrium with measured points (b) [67].

thermal comfort on occupied levels of an atrium building [70]. Supplying cool air from earth-to-air-heat exchanger is one of the applications of hybrid ventilation to significantly help reduce the maximum temperature of the surrounding spaces [3]. For hot and humid climate exhausted cool air from air conditioned surrounding rooms is considered as a low cost method known as pressurized ventilation. The study results of pressurized ventilation showed that only exhausted cool air from ground floor spaces is enough to provide thermal comfort in atrium and surrounding walkways throughout the year [45]. However, in this case, lack of fresh air can be assumed as a limitation.

## 7. Discussion

Analytical, experimental and numerical investigations of thermal performance in different atrium types have been cited in the literature review of this study. However, a thorough study of atrium performance is restricted due to insufficient accuracy limitations of the available prediction tools [5] and controlled experiments. These limitations vary according to different modeling conditions in various types of atrium structures. Therefore, it is difficult to rely on the previous studies results alone to generalize the achievements for practical usage.

Lin and Linden [62], Holford and Hunt [25], and Wang et al. [32] separately used theoretical and experimental analyses to evaluate the thermal performances of atria with different opening aspects (size, location, and status). Later, Ji and Cook [71] utilized a numerical model to confirm the analytical results obtained from the study by Holford and Hunt [25] concurred with their obtained data. Ding et al. [40], Walker et al. [61] also studied the same subject using experimental analysis and CFD simulation model.

Moreover, Aldawood [51] studied the effects of atria shape on energy consumption in various climates using DOE-2.1 E energy modeling. Liu et al. [30], Li et al. [54] and Hussain and Oosthuizen [72] used also experimental and CFD methods to evaluate the efficiency of various atrium geometries. Good agreement between numerical and experimental results was also observed. Wang and Abd Halid Abdullah [49] used dynamic thermal modeling (DTM) and CFD simulation to compare the efficiency of two atrium roof forms. Assadi et al. [59] employed an analytical model to investigate the relationship between glass height and atrium geometry in heating demand of atria. In a recent, research by Acred and Hunt [73], a mathematical model was utilized to predict the behavior of the air flow through openings with different sizes in a variety of building storeys (atrium location).

Hussain and Oosthuizen [48] and Tanaka et al. [67] used CFD and experimental methods to measure the efficiency of solar-assisted natural ventilation techniques in atria. Pfafferott et al. [3] used a full scale experimental test to analyze the thermal performance of atrium via night cooling methods. Later on, Mouriki [31] and Lynch and Hunt [63] performed mathematical analysis and Karavaa et al. [43] used numerical analysis to investigate atria with a similar cooling method. Recently, Rojas [36] used TAS model to compare night ventilation and solar protection capacities. Gan [74], on the other hand, employed CFD simulation to evaluate the interaction of wind and buoyancy in atria. Mouriki et al. [64] conducted an experimental study and Horan and Finn [29] used CFD modeling to evaluate the impact of wind direction and speed on increasing atria cooling capacity. Furthermore, Woods et al. [39] used laboratory experiments with air chamber model to analyze the effects of mixed ventilation on atria heating capacity.

Table 4 summarizes the outline of the important atrium design parameters which influence the thermal and ventilation performances of atrium buildings, obtained from relevant literature and case studies. Overall, the gained results show implementing natural ventilation in atrium building leads to better indoor thermal conditions in temperate climates than hot and humid climates. Furthermore, most of the investigated parameters have significant impacts more on ventilation rate than ventilation behavior inside atrium.

However, it is obvious that the outlet opening state (opened/closed) has the most significant effect on both the internal temperatures and the airflow through the atrium building. For example, open stack vents allow for almost twice more airflow amount through the model and decreased vertical temperature gradient by 7 °C. Whereas, in case of closed stack vents, the flow pattern changes and the air exhausts into the surrounding rooms in upper floors through openings. Nevertheless, outlet opening location has the lowest thermal effect on atria. However, the location of connecting openings between atrium and surrounding spaces has significant influence in the airflow pattern. Therefore, with changing location design, opening can drive ambient air current into the air-conditioned zone. Furthermore, lower inlet to outlet area ratio in buoyancy-driven natural ventilation in atrium raises the rate of the airflow in the storey, while in pressurized

**Table 4**
Summary of thermal and ventilation performance of Atria's under review.

| | Design parameter | Impact | Method | Relevant parameters | Requirement/efficiency | Limitation | Case study | Reference |
|---|---|---|---|---|---|---|---|---|
| **Thermal performance** | **Opening** Size, Location, Number, State | Air flow rate and Temperature Energy demand | DTM, CFD, Small scale, Theoretical, Mathematical, Experimental, Energy simulation model | Storey height, | (**Size**) The upper opening with intermediate size and the lower opening in sufficiently small.(In pressurized ventilation), ration of higher inlet to outlet opening area (i. e. $n>1$). (**Operation**) Controllable outlet opening will halve the number of hours with $T>25$ °C. | (**Size**) Higher the storey is, larger the total effective opening area is needed (**Number**) The more numbers of opening floors causes higher temperature in the building. (**Position**) Direct inflow ventilation to atrium is detrimental for store ventilation. (**Operation**) Controllability of opening relies on mechanical devices. | Commercial office building three stories in temperate climate | [3,7,31,32,34, 44–47,49,50] |
| | **Atrium** Size, Height, Form | Air flow rate, Energy load | CFD, Analytical model, Energy, DOE-2.1E | Outlet opening size, Glass height | (**Size**) Bigger atrium size provides higher ventilation in high rise atrium building. For heating, higher the glass height, lower the diameter of atrium. (**Form**) Atrium with rectangular shape and high ratio of length to width is more energy efficient. The three-storey linear side-lit atrium form is more effective in the Tropics. | (**Height**) When the atrium outlet opening is small tall atrium is not efficient. Adding 1 m of the height of high-rise residential building caused the increase of 0.043 mof the atrium size. Building with significant height is needed in hot and humid. | The planned Center for Education in the Green Building, Taiwan | [12,32,51,52, 54,55,60] |
| | Ceiling Form, Height, Attachment, Solar chimney | Flow rate, Temperature distributions | Site measurement, Dynamic thermal model DTM, CFD | – | (**Height**) The 2.5 m high wall-to-roof void area. (**Attachment**) For side-lit model, the 1.5 m wide roof overhangs above the clerestory areas. (**Solar chimney**) Taller solar chimney with higher solar absorptance and transmittance. | (**Form**) Prominent of side-lit ceiling form to top-lit in Hot and Humid with less daylight. | A guesthouse in China | [1,36,39,44, 49,57,65] |
| | **Fenestration** Height, Size, Shading device, Double skin | Air flow rate, Solar heat gain, Energy efficiency | Analytical model, Field measurements | Atrium dimension | (**Height**) Decrease the heating load at maximum 25% of glass height. (**Orientation**) The exhausted solar heat gain is approximately 100 W/m$^2$ per surface area of inner glass in double-skin façades. (**Operation**) Implying intelligent shading device reduces cooling load and provides good daylight. | (**Attachment**) Internal blinds for clerestory in Hot and Humid is necessary. | An office building in the city of Wuxi, Jiangsu province, China. | [38,44,49, 58–60,67] |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **Material** Thermal mass | Airflow rates, temperature distribution | Full-scale experimental, CFD, Reduced scale | – | (**Mass**) The amount of removal of heat through concrete floor slabs is 2–5 times higher when the inlet airflow average temperature is 12 °C, in comparison with that when the air stream average temperature is 15 °C or 18 °C respectively. | (**Mass**) High thermal mass and low exterior temperature is needed. | The Engineering Building of Concordia University, Canada | [32,43,49] |
| **Ventilation performance** | **Opening** Size, Location, Operation | Flow regimes | CFD, Reduced scale, Mathematical model, Theoretical analysis | Size of atrium | (**Size**) An insignificant temperature difference between large openings or spaces from the atrium to the exterior. (**Location**) To effectively exhaust the upper stagnant heat, the upper-opening location is elevated. (**Operation**) To avoid wind affect air flow pattern, intelligent control of ventilation openings would require. | (**Geometry**) The transient behavior strongly depends on the connecting openings geometry between the spaces. | The planned Center for Education in the Green Building, Taiwan, | [2,31,32,34, 47,62] |
| | **Atrium** Geometry Enclosure level | Transient behavior of stratification, Night purging | Theoretical analysis, Experimental Mathematical model | Geometry of the connecting openings Enclosure level | (**Size**) Bigger size of atrium and connecting opening. | (**Enclosure level**) In multiple storey buildings linked to a central atrium, night purging in upper storey of atrium may be delayed. | – | [62,63] |

**Table 5**
Summary of assisted ventilation techniques in Atria's under review.

| Ventilation method | Effective variables | Relevant parameters | Ventilation efficiency | Requirement/limitation | Case-study | Reference |
|---|---|---|---|---|---|---|
| **Wind-induced** | Wind speed and direction, $\Delta T$ indoor–outdoor | Leeward and windward opening | (**Rate**) With strong stack effect, the total inflow is significant, about 15,000 l/s .The relationship between the ACH (air change) rate and wind direction is linear for wind directions between 0° and 90°. (**Behavior**) Inflow in wind dominant case, outflow in stack dominant, both inflow and outflow with low $\Delta T$ indoor–outdoor and wind direction angle in range of $\theta$=220–230°. | Motorized damper or intelligent control of ventilation openings is needed to achieve or maintain a desired environmental quality (**Limitation**) Instability of created air stream rate. | A two storey office building (Urban Institute Ireland, UII) | [31,32,41,64] |
| **Solar-assisted** | Solar radiation, solar heat flux, $\Delta T$ indoor–outdoor | Solar chimney, double skin wall, atrium orientation | (**Rate**) Atrium space integrated with a solar chimney would be a relatively better option to be used in an atrium building. With double-skin system, the reduction ratio of total solar heat gain is about 25%. | Proper Insulation for preventing penetration solar heat to surrounding spaces is needed. (**Limitation**) It relies on solar intensity. | An existing building in Japan | [1,49,66,67] |
| **Night ventilation** | Exterior temperature, thermal mass | Materials, controllable opening | (**Rate**) The amount of heat air removed by air stream at an average outdoor temperature of 12 °C was estimated to be 5 times greater than the heat removed by an air stream at an average temperature of 18 °C. The controllable valves at the bottom and top of the atrium walls will reduce the number of hours over 25 °C by 50% even without mechanical ventilation. (**Behavior**) In multiple storey atrium building, night purging of upper stories may be delayed while lower level stories are being purged. | Expose the internal space to external air, adequate external low temperature. (**Limitation**) Lack of control and slowness of the charge and discharge process. | The Engineering Building of Concordia University, Canada. | [7,33,38,43,63,68,69] |
| **Forced ventilation** | External temperature, | Inlet vent direction, inlet to outlet opening area ratio, atrium ceiling type | (**Rate**) In hot and humid climates, utilization of exhausted air from AC adjacent spaces provides thermal comfort in atrium and surrounding walkways. Mixing ventilation (passive pre-heating and supplying fresh air) significantly contributed to saving energy up to 70–80%. The cooler air on the ground floor was better displaced for model with vertical side vent. It leads to reduction of indoor air temperature. | Efficiency of heating is dependent on the level of insulation and the loads of internal heat per person. (**Limitation**) It relies on mechanical ventilation. lack of fresh air in pressurized ventilation. | A guesthouse in China | [7,8,34,50,70] |

ventilation, higher ratio of inlet to outlet opening area (i.e. $n > 1$) is required.

Table 5 summarizes different ventilation techniques which can be incorporated into atria to enhance ventilation and thermal performances as cited in the relevant previous studies. It is observed that, generally among the passive cooling techniques, the highest influence in atrium thermal condition for temperate climates was achieved from incorporating night ventilation into the atrium. The removal mass of heat from atrium floor is 2–5 times higher with inflow air temperature of 3–6 °C and lower than 18 °C respectively. However, in Mediterranean climate, night cooling has only an average reduction of 10% on cooling demand compared to the solar radiation protection reduction which is about 75%.

Despite night ventilation cooling potential, lack of control and slowness of the charge and discharge processes and security limitations to expose indoor construction mass to outdoor cool air could be assumed as disadvantages. To optimize the night ventilation, mechanical control for opening at the upper and lower parts of atrium is recommended. This control leads to 50% of reduction in the number of hours of higher than 25 °C in temperate climates.

In Hot and Humid climates, using buoyancy-driven ventilation alone has an insignificant effect on the atria thermal conditions. Therefore, assisted hybrid systems such as pressurized ventilation as a low cost solution are recommended. Although the pressurized ventilation depends on the energy consumed by air conditioning from surrounding rooms, it cannot be assumed as fully passive technique. Furthermore, as a result of using exhausted cool air from air conditioned surrounding rooms, fresh air will be absent from the atrium. Therefore, supplying fresh air utilizing natural ventilation associated with passive pre-cooling ventilation could improve atria thermal and ventilation performances.

## 8. Conclusion

This paper presents an overview of the previous studies achievements on the naturally ventilated atrium structure and influential atrium design parameters. The review demonstrates how these parameters can be employed and improved to provide a better thermal condition for atrium and adjacent spaces. This paper further reviewed various atria models implementing buoyancy-driven natural ventilation as basic atria passive ventilation technique, with or without other assisted ventilation techniques, to improve their indoor thermal conditions. It started with a brief overview of the evolution of atrium through history, atrium's new design approaches and their problems, while giving insight into the importance of natural ventilation in atria and its potential capability to replace current mechanical ventilation systems with high-energy consumption. This study emphasized the significance of atrium components and configurations, as design parameters and their application to improve indoor thermal conditions and ventilation regime. The capability of each parameter was summarized with its efficiency, requirements and limitations. Studies on the efficient atrium design parameters and their thermal effects can provide a strong standing point for further researches required to develop empirical guidelines for future atria designs.

The review also highlighted various assisted ventilation technique integrated into buoyancy driven ventilation in atrium to improve its thermal performance. The corresponding capabilities, advantages and limitations of these techniques and models were summarized. The achieved conclusion is based on various research results of different atrium models and case studies utilizing natural ventilation as whole or part of cooling or heating systems. The paper further noted the various experimental analyses and simulation methods used to test the atrium thermal performance. Key variables, including the ventilation rate and air flow regime, were evaluated to determine the potential advantages of the atrium design parameters in various design conditions with different thermal and ventilation expectations.

## 9. Recommendations for further studies

According to the cited literature, potential application of pre-cooling, evaporative cooling integrated with natural ventilation, and humidity control in hot and humid climates are required to be covered in future studies. Moreover, the data available on the effectiveness of some of the design parameters such as roof form, material and attachment, opening attachment (like damper shape, size and angle), and atrium enclosure components on airflow and temperature distribution in surrounding spaces is minimal. It is also recommended that more studies should be conducted on the capability of the wind-driven and solar assisted natural ventilations in atria to maximize their thermal performances.

Although many studies have been carried out on the efficiency of natural ventilation in atrium, the knowledge about atrium passive design is incomplete regarding its complexity and lack of accurate measurement tools. Many of the relevant studies focus on validation of analytical methods. Comparing with other similar subjects, the investigated parameters of naturally ventilated atria have less detailed results. Therefore, there is a requirement for further researches on innovative solutions for naturally ventilated atria and developing reliable test procedures.

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