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Optimizing stack ventilation in low and medium-rise residential buildings in hot and semi-humid climate

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A R T I C L E I N F O

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A B S T R A C T

Nowadays, optimization of methods that can reduce energy consumption is efficient for various reasons, such as the increasing mean temperature, the changes in climate, and the shortage of non-renewable energies like fossil fuels. Hence, the stack effect is one of the passive cooling strategies promoting using renewable energy. In this context, Stack ventilation is studied in a hot and semi-humid climate to introduce AEC industry parties. A notable contribution of this study to the existing knowledge landscape involves the integration of stack ventilation (vertical ventilation) with roof channels (horizontal ventilation). Direct and indirect ventilation are scrutinized and compared. Then stack position in the building is investigated for optimizing it in one-, two-, and four-story buildings in Dezful city. Considering being the most frequent residential building type, the four-story archetype has been the main focus of the present study. The models' behaviors are studied by Design Builder (Energy Plus engine). The CFD (fluid dynamics calculations) module has been used to explore the behavior of air in terms of velocity and temperature quantities by numerical simulation. Findings suggest that indirect ventilation is better than direct ventilation in this climate if individuals do not want to use evaporating cooling strategies inside natural ventilation. Roof channels are particularly effective for collecting and discharging the hot air gathered on the roofs and air circulation within the buildings. The result is appropriate for an architect design in hot regions.

1. Introduction

In recent years, the world's energy consumption to produce electricity from fossil fuel sources has been over 80 % [1,2]. The crisis is expected to worsen due to the current rate of climate change [2]. Now, what has been explicated is that the current level of energy use cannot be sustained in the future [3]. Because 40–45 % of the total energy consumption in the world belongs to residential and large buildings [4], in which most of the energy is used for maintaining a thermally comfortable indoor environment in buildings [5]. According to the Statistics Center of Iran, the amount of energy consumed in the residential building sector in 2018–2019 was 34 % in Iran [6]. Moreover, Buildings are responsible for the dominant energy consumption in hot regions [7]. Consequently, the demand for solutions to reduce energy consumption has increased worldwide, especially in hot areas. Natural ventilation is one of the existing

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passive solutions to reduce excessive energy use, and using passive methods offers a promising pathway to reducing energy consumption and CO_2 emissions from buildings [8]. Additionally, natural ventilation, which is affordable for construction and maintenance, is receiving increasing attention to decrease the energy demand for heating and cooling in buildings. Natural ventilation systems are a solution for inexpensive cooling and heating needs because of their simple design and maintenance requirements. The passive cooling design is crucial in lowering energy usage during the building's operating phase, particularly in tropical climates [9].

One of the ways to control the amount of energy consumption in the building comes back to the field of wind energy and the ways to use and control it. Ventilation in the building has a vital role in controlling energy consumption [10]. Still, the most critical factor for building ventilation is natural ventilation. The effect of external wind and how to deal with it is also one of the most critical factors in natural ventilation. Natural ventilation is one of the passive means of energy-saving solutions. Its effectiveness and performance depend upon many factors, such as the size and location of openings, the location of the inlet gaps, and ambient climate conditions [11–13]. Natural ventilation usually utilizes the wind and thermal buoyancy driving forces to provide airflow and, therefore, strongly depends on the outdoor conditions and the indoor-outdoor temperature difference [14]. There are several passive solutions to natural ventilation, including single-sided ventilation, cross-ventilation, and stack ventilation [11,15]. Recently, the use of stack ventilation applications has increased in modern buildings. Tall vertical structures, such as vestibules, solar chimneys, and double-walled facades, are also consciously incorporated into buildings to aid natural currents and play an important role similar to ventilation stacks [5].

This research aims to decrease the temperature by the stack effect method, which is one way as a passive strategy. It means that the study investigates exploring how ventilation is affected by physical factors. Providing thermal comfort conditions for occupants is the next following goal. In addition, it is studied to choose the appropriate ventilation site within a structure, aspects, and elements affecting natural ventilation in systems with chimneys. Although several studies have been on this subject, they are mechanical and are likely to pay less attention to architectural aspects, and they investigated ACH or velocity rather than temperature. Hence, this article discusses aspects of architecture that have yet to be thoroughly investigated so far. According to the literature review, the following parameters were selected for further investigation. Given the prevalent circumstance of four-story houses within the area, the focal point of this study revolves around the development of four-story structures. The objective of optimization is to enhance the efficiency and effectiveness of four-story building designs.

One of the significant contributions of this study to the current body of knowledge is integrating stack ventilation (vertical ventilation) with roof channels (horizontal ventilation). Furthermore, assessing indirect ventilation can cause the beginning of other research in this area (extreme climate) which is a considerably effective method in decreasing energy consumption. Apart from that, this study has assessed factors including the position of the stack and height of the stack. Moreover, Previous studies have predominantly concentrated on stack ventilation in single-zone or single-story buildings. Its theoretical development in multi-story buildings is dawdling, which excludes its practical applications in multi-story buildings. The present paper addresses the study of stack ventilation in one-, two- and four-story buildings in the summer scenarios of a hot and semi-humid climate, mainly focusing on making the best ventilation shape possible in a hot and semi-humid atmosphere. The study is conducted through a modeling and simulation approach using an advanced building energy simulation tool - Energy Plus. In the simulations, the study focuses on the influence of the different stack heights on the function of the stack and decreasing temperatures indoor spaces.

In the stack ventilation technique, the air is moved through the chimney's effect. This is brought on by the variation in air temperatures between indoor and outdoor spaces [16]. Warming the air inside the channel is done by solar radiation transmitted through the glazing, which heats the absorber surface [17,18]. Stack ventilation works based on two driving forces: buoyancy (hot air) and pressure-driven [18]. In buoyancy, which relates to increased hot air, hot air is lighter than cold air. Besides, hot air has less density, which leads to hot air rising and cold air falling [19–21].

Two methods of using stack ventilation are chimneys and atriums, which are often used to produce driving force buoyancy to access enough flows. That's why they use solar energy in several methods to improve the function of stack ventilation [22]. Stack ventilation can be combined with walls or roofs of buildings for natural ventilation or energy saving [18,23]. A stack ventilation system circulates air in a building, and its effect on its shape and interior layout determines its effectiveness. The condition for ventilation to work correctly is to supply air from outside the room, often done through windows and doors. The main disadvantage is that the volume of the outlet and supply air and the intensity of ventilation cannot be controlled. And the system is completely dependent on weather conditions (i.e., temperature and pressure) [21,22,24]. A more oversized solar chimney can increase the value of an outlet.

Wind direction and flow, the angle and orientation of the building and stack, and materials with different heat capacities can all have an impact [24]. The realized number of air changes per hour (ACH) ranged from 3.5 to 15 depending on the size of the solar chimneys used and the evaluated houses or buildings [18]. With the assistance of solar roof chimneys, induced air speed inside a three-story building in Singapore reached up to 0.49 m/s [25]; in a tiny test home in Thailand, it was between 0.07 and 0.14 m/s [23]. Solar vents have reduced heat gain by 11.4 % [26] to 50 % [23] compared to conventional windows and doors. According to reports, buildings' energy consumption has been reduced by 50 % and 8.8 % for an office building in Tokyo and a test facility in Qatar [18,26]. The critical elements of these systems include "two shells," "solar chimney," and "roof," which work with differential temperature and solar radiation [27]. The solar chimney relies on the sun's radiation and absorption at the top of the structure, and as the sun's radiation increases, the temperature of the upper parts rises. Solar chimneys are a common feature for using solar energy in buildings to ensure sustainable natural ventilation without relying on wind power. For solar roof chimneys, previous studies indicated that the optimum inclination angle to obtain the maximum ventilation rate is not equal to that of the maximum solar radiation [28].

Additionally, the researchers suggested a range of solar roof chimneys. They investigated the angle effect on airflow inside a solar chimney from 30 to 76° [28–30] that depended on climate zone and latitude. They have a glass wall, a narrow space above, and a thick concrete wall that provides heat storage [25,27]. The difference between outdoor and indoor air pressure creates the stack effect [31]. Hence, in summer, hot air exits by outlet until natural ventilation happens; therefore, the cooling load of the whole building is reduced.

In winter, closed diaphragms prevent heat loss by removing hot air to heat the living space [24]. Also, the investigations are mainly limited to winter in a warm climate, such as the Mediterranean [32]. In many stack types, the wind is more critical than buoyancy. The solar chimney relies on the radiation and absorption of the sun on the top of the structure, and as the sun rises, the temperature of the top level increases more. The solar chimney is a common feature of using solar energy in buildings to ensure stable natural ventilation without relying on wind force. Stacks have a glassy wall, a long narrow space, and a thick concrete wall that provides insulation from heat [25], 31, 32].

Natural ventilation has several drawbacks, especially when delivering comfortable thermal and ventilation conditions in harsh regions [32,33]. Solar energy has been used in several applications to increase the effectiveness of natural ventilation. Solar stacks are a typical feature to provide steady natural ventilation in buildings without relying on wind force [27]. They have a solid concrete wall serving thermal storage, a glass wall, and a tall, narrow room. As it enters the solar stack, the air is warmed by solar heat absorption before rising. Through the development of a stack effect, the difference in interior and exterior air pressure acts as the driving force [31]. Warm air in the solar stack is vented out of the outlet in the summer to improve natural ventilation and reduce the building's cooling demand. The warm air is pushed to the occupant compartment for heating in the winter since the closed openings stop heat loss [24]. However, wind direction and speed can impact how well solar stacks work [34]. Even at a moderate speed, an adverse wind direction can lessen the volumetric airflow through the stack [35]. However, the effects of the wind can be disregarded [23] with equal inlets and outlets and a bigger solar stack design [27].

1.1. *Systematic literature review (SLR)*

A comprehensive literature review was carried out using a systematic approach within the Web of Science bibliographic database [36,37]. This was done to identify existing gaps and challenges, providing a holistic understanding. The process of literature selection was organized into distinct steps to pinpoint the most pertinent publications related to stack ventilation in residential buildings. These selections were made from the Web of Science (WOS) database. The sequence of actions in the systematic literature review can be observed in Fig. 1.

The review was conducted in five steps, with specific questions and keywords chosen for each step. This approach ensured precise article screening and the identification of the most relevant materials.

Step 1: the chosen queries for the WOS search engine were constructed around the research questions, centering on the keywords "stack effect" and "stack ventilation," within the broader context of "natural ventilation." The queries were intentionally designed to be straightforward, aiming to yield the most relevant publications related to the specified keywords. The subsequent query entered into the WOS search portal yielded a total of 315 publications as of August 8, 2023, using the following search criteria.

Query: (TS=(natural ventilation)) AND TS=(stack ventilation).

Step 2: To assess and identify articles pertinent to the research topic, a multi-step approach was employed. Initially, articles were assessed based on their titles, followed by a scrutiny of their abstracts. Ultimately, a comprehensive reading of each article led to the selection of the final set (Fig. 1). Additionally, each article was assigned a score ranging from 1 to 5, where those with a score of 1 demonstrated the lowest relevance, while those attaining a score of 5 exhibited the highest similarity (Fig. 2).

Step 3: Table 1 assesses the 35 obtained articles. Additionally, the systematic literature review (SLR) reveals a prominent trend within this field: a majority of the articles initially emphasize a mechanical perspective, followed by a notable proportion proposing mathematical models, many of which lack evaluation via Computational Fluid Dynamics (CFD). Furthermore, a substantial number of articles, whether focusing on mechanics or introducing mathematical models, fail to consider or utilize climate factors, highlighting their overall inadequacy across multiple dimensions.

According to Table 1, Many studies have been done concerning building ventilation. However, they have generally paid attention to the relationship between ventilation and solar radiation and paid less attention to other parameters. Studies have been conducted in different hot and cold climates, but none have been observed in semi-humid environments. Also, most of the research has focused on the vertical connection of the stack, and the horizontal connection is just one; therefore, this research investigated indirect ventilation by integrating ceiling channels (horizontal ventilation) and ventilators (vertical ventilation).

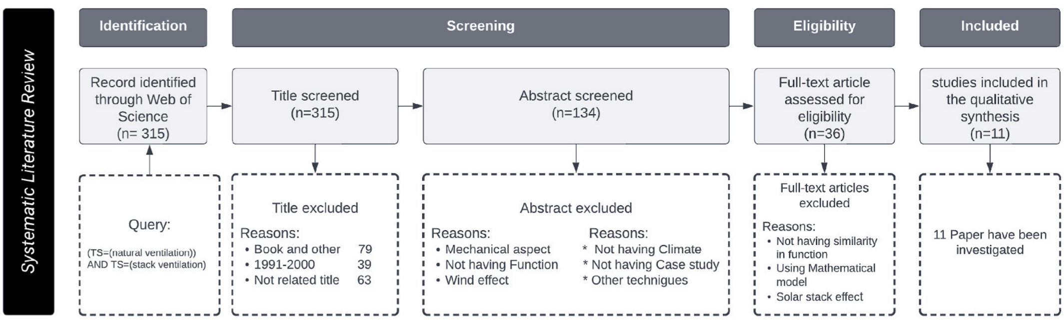


Fig. 1. The graphical process steps of SLR.

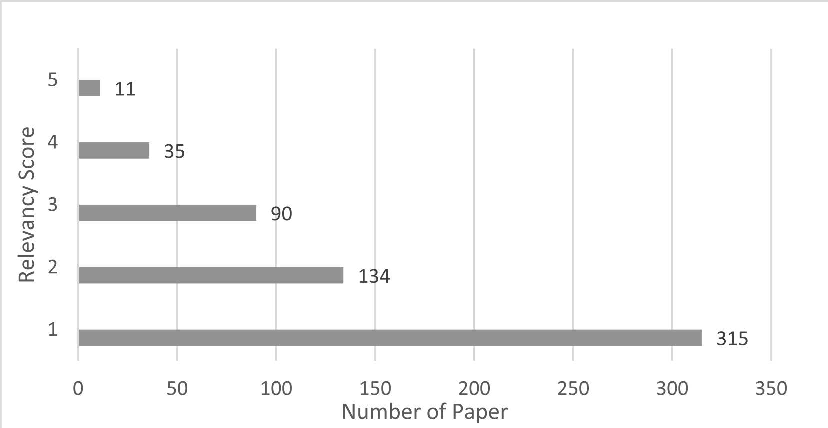


Fig. 2. The eligibility checkout of 315 publications.

Furthermore, most of the research has focused on the ventilation of existing building articles in which ventilation and numerical modeling have also investigated the mechanical aspects of the model, as well as studies on single-story buildings and models [17,18,23,26,28–30] or high-rise buildings, were office function and school. It means that most research has examined very high-rise buildings or single-story models. Medium-rise buildings have been investigated very little. And finally, as shown in Table 1, none of the reviewed articles were in Iran, especially in Dezful City.

Therefore, the main contribution of this article can be characterizing the following items.

1. Considering real climate conditions
2. Using and comparing different archetype building
3. Investigating ventilation in Iran (warm and semi-humid climate)
4. Examination of ventilation and its combination with horizontal ventilation through ceiling channels
5. Study of multi-story buildings and their combination with horizontal ventilation

2. Material and methods

2.1. Methodology

The research process is visually depicted in Fig. 3. The initial step encompassed an exploration of the background. This exploration involved the analysis of articles and reviews within the field, conducted through the utilization of the WOS database. The classification and investigation commenced by utilizing keywords like “natural ventilation” and “stack ventilation” in building contexts, with a subsequent focus on articles emphasizing ventilation.

Aligned with the research’s core theme, which centers on combining roof channels with ventilation to enhance air circulation and indirectly impact indoor temperatures in residential spaces, this study delved into physical parameters. Aspects such as stack height and position were scrutinized. Furthermore, an examination of the interrelation between ventilation and the number of floors was conducted, considering the existing buildings on the site.

This research encompassed the investigation of variables like air speed, air temperature, and ACH (Air Changes per Hour). After optimizing designs for both one and two-story structures, the research’s primary focus shifted to four-story buildings. This optimization process thus encompassed models for one-story, two-story, and four-story buildings. Furthermore, considering the dominant majority of four-story dwellings in the vicinity, this study’s pivotal emphasis rests on advancing four-story building designs.

2.1.1. Validation of method and software

This research examines natural ventilation in residential buildings using experimental methods, using CFD simulation by Design Builder (energy plus engine) in a hot and semi-humid climate. This software is one of the valid simulation engines recognized by the United States Department of Energy [14]. The number of articles simulated in Design Builder indicates the validity of the results energy [68–71], as it is well-distributed among researchers. Furthermore, research conducted in the field of natural ventilation (CFD Simulation) demonstrates that this software has been employed for simulating ventilation and obtaining valid results [72–74]. Additionally, this software has been utilized in hot climates to assess ventilation [75]. The effectiveness of natural ventilation in the Brew House of the new Farsons Brewery was assessed in the hot and humid summer climate [70,74] by the CFD module of this software [76]. Monna et al. did also analyze the energy savings by Design-Builder from a suggested retrofitting program using energy simulation for typical existing residential buildings [77]. Besides, another research about multi-objective optimization of building design and construction parameters to minimize energy requests while maximizing energy production and adaptive thermal comfort was done by Ref. [78] in Design Builder. It shows that this software is an effective for simulating multi objective optimization.

This research also aims to investigate stack position and physical parameters. So, authors [79] claimed that ventilation airflow in a building depends on ambient and geometric conditions and they conducted their research by Design Builder and CFD Simulation. This

Table 1
Systematic literature review.

	Authors	Year	Residential Building	Real climate Condition	CFD Simulation	Case Study	Integration with roof channel	Number of stories	Region
1	Kolokotroni, M., Ge, Y. T., & Katsoulas, D [38].	2002	–	x	–	x	–	2	England
2	Wong, N. H, and Heryanto, S [39].	2004	x	x	x	x	–	1	Singapore
3	Chenvidyakarn, T., and Woods, A. W [40].	2005	–	–	–	x	–	1	–
4	Livermore, S. R., and Woods, A. W [41]	2006	–	–	–	x	–	2	–
5	Fitzgerald, S. D., and Woods, A. W [42].	2008	–	–	–	x	–	1	–
6	Liu., P. C. et al. [43]	2009	–	x	x	x	–	3	Taiwan
7	Walker, C. et al. [44]	2011	–	x	x	x	–	3	–
8	Chow, W. K., and Zhao, J. H [45].		–	–	–	x	–	–	–
9	Tan, A. Y. K., and Wong, N. H [46].	2012	–	–	x	x	–	1	–
10	Acred, A., and Hunt, G. R [47].	2014	–	–	–	x	–	3	–
11	Mohammad Yusoff, W. F. et al. [48]	2015	x	x	x	x	–	1	–
12	Hellwig, R. et al. [49]		–	x	–	x	–	4	German
13	Kalamees, T. et al. [50]		–	x	–		–	–	Estonia
14	Liu, S., and Huang, C [51].	2016	x	x	x	x	–	1	China
15	Nugroho, A. M [52].		x	x	x	x	–	1	Indonesia
16	Mekkawi, G., & Elgendy, R [53].		x	x	x	x	–	1	Egypt
17	Essah, E. A. et al. [54]	2017	–	x	x	x	–	2	China
18	Leng P. C. et al. [9]	2019	x	x	x	x	–	1	Malaysian
19	Nguyen, N. Q., and Wells, J. C [18].		–	–	x	–	X	–	–
20	Franco, L. C. et al. [55]		x	x	–	x	–	1	Brazil
21	Cuce, E. et al. [1]		–	x	x	x	–	18	Japan
22	Yoon, S. et al. [56]		x	x	–	x	–	32	–
23	Wang, Y., & Wei, C [57].	2020	–	–	x	x	–	–	–
24	Raji, B. et al. [58]		–	x	x	x	–	21	–
25	Yoon, N. et al. [59]		–	x	x	x	–	–	USA
26	Teleszewski, T. J., & Gładyszewska-Fiedoruk, K [21].		–	x	–	x	–	2	Poland
27	Layeni, A. T. et al. [60]		x	x	x	–	–	–	–
28	Antczak-Jarzabska, R. et al. [61]	2021	x	x	–	x	–	1	Poland
29	Hsu, H. H. et al. [62]		–	x	x	x	–	–	Taiwan
30	Xie, M. et al. [63]		–	x	x	x	–	127	China
31	He, C. et al. [64]		x	x	–	–	–	–	China
32	Corbett, T. et al. [65]	2022	–	x	x	x	–	7	–
33	Shrestha, M., & Uprety, S [66].		–	x	x	x	–	1	Nepal
34	Kravchenko, I. et al. [14]		x	x	–	x	–	4	Finland
35	Zhang, H. et al. [67]		–	–	x	x	–	7	–
Current study			**x**	**x**	**x**	**x**	**X**	**1, 2, 4**	**Iran**

paper assesses the height of stack ventilation in one-, two-, and four-story buildings because, according to reports, the flow rate for both types of solar chimneys rises with the heat flux, the gap, and the chimney height. This research uses CFD simulation to study the air temperature and velocity behavior. Various software allows coupling approaches to be carried out [74] CFD module in Design builder is one of them.

Additionally, researchers [80] have been reported that Design Builder includes the built-in coupling approach by utilizing the output from Energy Plus as input data for CFD calculations, where the output can be optimized by optimization under one platform. Stack ventilation is scrutinized in residential buildings. Other authors [81] coupled 3D parametric modeling with CFD to assess wind-driven natural ventilation in a residential test building by Design Builder. Furthermore, the article focuses on indirect ventilation that combines with stack ventilation. For natural ventilation or energy conservation, buildings can include solar chimneys on their walls or roofs [18,23] Because direct ventilation without evaporating cooling strategies would not be efficient in this climate. Therefore, based on the presented background, this article executed simulation and CFD method in the investigation of airflow, air

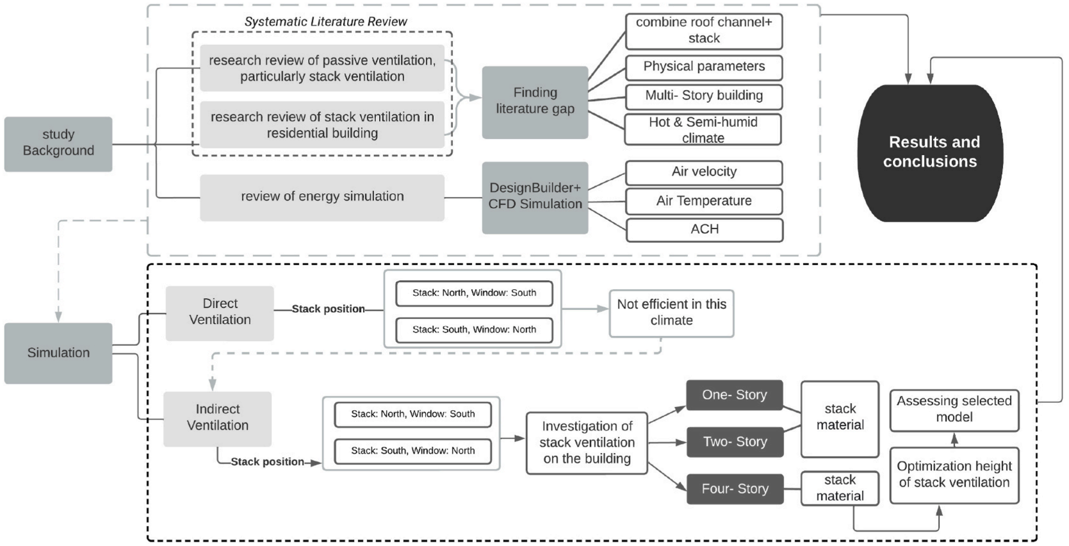


Fig. 3. Flowchart of the research proses.

temperature, and air velocity by amending the parameters and factors that affect the thermal and ventilation performance of the stack.

2.1.2. Simulation condition/case study

The proposed model is implemented in computational fluid dynamics (CFD) and was simulated by Design Builder software version 7, and the energy simulations were done with Energy Plus 9.2 engine engines recognized by the United States Department of Energy [14]. Research models consist of three kinds of zone moods.

2.1.2.1. Assumptions and limitation. The room zone is occupied, and the activity mode is Standing and Moving. The standard room zone is occupied by five people (the rate of people presence is 0.82), and the clothing coefficient is assumed to be 0.5 for summer clothes and 1 for winter clothes (see Table 2). The stack zone was considered cavity mood, and the floor channel zone is a plenum in which activity and occupancy are selected 24/7 off. Cooling and heating systems are designed to determine the normal flow and main air temperature. Air Infiltration has been avoided in the calculation. The window is open in summer and closed in the winter. The materials of the walls and windows are listed in Table 3. CFD condition analysis is based on the turbulence model k-e, though the discretization scheme has been considered upwind, and the surface heat transfer option was calculated.

According to the Housing and Construction Yearbook for Dezful City, the number of one-story buildings is 14 %, two-story buildings are 15, and 4-story buildings are 49 % [82]. Buildings with three-story is 2 % and more than four-story have comprised a total of 20 % of Dezful houses in 2021; therefore, in this research, three types of buildings, one, two, and four floors, have been discussed. Also, according to the Statistical and Technological Information Unit of Dezful City, and on the other hand, the field surveys conducted [83], the number of 4-story buildings is increasing (Table 4). So, in this research, after optimization on one and two-story buildings, the aim of the research is on four-story buildings; therefore, the optimization process involves three types of models: one-story, two-story, and four-story buildings.

The CFD condition has been studied based on the boundary condition. The analysis has been done at 2:00 p.m. on July 1st and the

Table 2
Assumption of the research.

Site Description			
Site		Dezful - 32°22′43″N 48°24′52″E	
Weather file		IRN_KZ_Dezful.407,950_TMYx.2007–2021	
General model description			
Activity Mode	Standing- Moving	**Human Metabolic Rate** 1.6 (Met)- 2.0 (Met)	
Type of Zone	Standard Zone (Room) Cavity Zone (Stack) Plenum Zone (Roof Channal)		
User description for standard Zone			
Window condition	Open in Summer	Close in winter	
Number of people	5	**Rate of people presence**	0.82
Clothing Coefficient	Summer Clothes – 0.5 Winter Clothes- 1		
User description for Plenum Zone			
Activity Mode			24/7 off
Type of Zone			0

Table 3
Information on material models.

Building Component	Construction Layers	U-value (W/ m^2K)
External walls	100 mm normal brick + 5 mm insulation layer+ 20 mm plasterboard	0.570
Internal walls	100 mm normal brick + 5 mm insulation layer+ 100 concrete + 20 mm plasterboard and mortar	0.5
Floor and ceiling	20 mm plasterboard + 30 mm mortar +50 mm concrete + 250 mm concrete slab + 50 floor finish	1.20
External glazing of the stack and Room's external window	6 mm double layer glass + 13 mm air gap	2.665

Table 4
Building permits issued for the construction of buildings according to the number of stories [83].

	2021	2020	2019	2018	2017
1 Story	85	76	75	80	87
2 Story	90	97	90	100	99
3 Story	15	18	18	19	20
4 Story	300	227	198	190	181
5 Story	120	104	89	80	70
Total	**610**	**522**	**470**	**469**	**457**

inlet temperature from the vents and openings is 37C. In addition, the meshing and solving of the equations have been done in this hour according to the software specifications, and the variables of speed, temperature, and for have been checked. In Figs. 4 and 5, the number of meshes in different directions and the model after meshing can be seen.

2.2. Study area description

This study was conducted in one of the residential building models in Dezful, located Between 32° and 16 min north latitude and 48° and 25 min east longitude. It has a hot and semi-humid climate with a summertime temperature above 50° Celsius [84]. The psychrometric chart (Fig. 6) illustrates the design strategy, showing that passive cooling can increase building efficiency by 69%. Additionally, according to the psychrometric chart generated by Climate Consultant software using the EPW data for Dezful, it is evident that natural ventilation cooling strategies, represented by the dark green zone on the chart, can enhance thermal comfort within a specific temperature range. This indicates that natural ventilation has the potential to lower temperatures within this range. This method can have a significant impact on thermal comfort, improving it by 6.7 %. This chart has been validated by Nasrollahei et al. [85] in their research about (local) buildings of Dezful. Table 5 shows that the years warmest are these five months, May, June, July, August, and September. And that July is one the hottest of all. Besides, the predominant wind comes from the northeast, as is demonstrated in Windrose's graph (Fig. 7).

2.3. Direct ventilation (basic model condition)

The temperature and thermal behavior of the building are examined in two separate models (samples 1 and 2) to evaluate stack performance on the north and the south. The results showed that direct ventilation could not be used in this climate to supply fresh air since the input air is an extremely hot table. The exterior air temperature is similar to the stack air temperature. Consequently, since direct ventilation cannot be efficient in extreme weather conditions, indirect ventilation is studied in this paper.

In both models, the average air temperature is higher than the exterior air temperature. Based on the simulating model at 2 p.m. 20th July. In the window location, the air temperature decreases triangularly to the floor and the end of the space. The temperature

Analysis: **stack,** Domain: **Building 1, Grid Statistics**	
Description	**Data**
Number X Cells	28
Number Y Cells	43
Number Z Cells	28
Max aspect ratio	5.702
Required Memory (MB)	4.3
Available Memory (MB)	880.2
Check	**OK**

Fig. 4. Grid statistic of CFD Simulation.

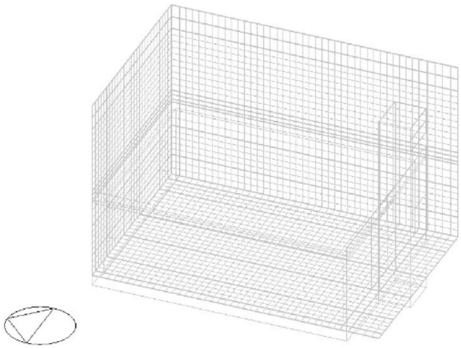


Fig. 5. Model after meshing.

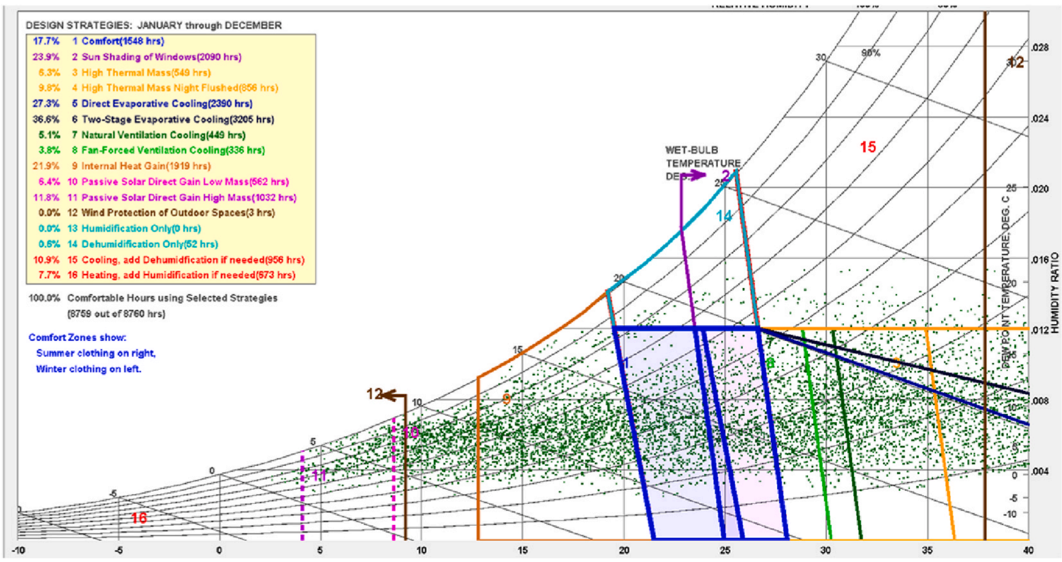


Fig. 6. Dezful psychrometric chart. source: climate consultant.

Table 5
Dezful weather data.

month	Average air temperature (°C)	Average wind speed (m/s)	Wind direction (degree)	Month	Average air temperature (°C)	Average wind speed (m/s)	Wind direction (degree)
Jan	11	2	280	**Jul**	36	1	**270**
Feb	13	1	270	**Aug**	36	2	**160**
Mar	18	3	30	**Sep**	32	2	**180**
Apr	23	3	70	**Oct**	25	0	**270**
May	30	3	40	**Nov**	18	2	**30**
Jun	34	2	270	**Dec**	12	2	**120**

near the window is 37.9 °C while it reaches 39 °C near the floor. The temperature increases and becomes 43 °C as it approaches the ceiling. In the stack, the temperature of the input air flow is higher. Due to the results illustrated in Table 6, the changes in ACH are limited to a negligible rise in both models. Temperature changes witness a slight decrease and level off in both models. Since direct ventilation cannot be helpful in extreme conditions, indirect ventilation is the base model..

3. Results and discussion

Based on the results, research will continue to focus on indirect ventilation in which the roof is separated from the occupied environment and is ventilated through openings on the façade and stacked on the opposite side. Therefore, the stack position and its characteristics are investigated. In the following section, the two models are introduced and analyzed.

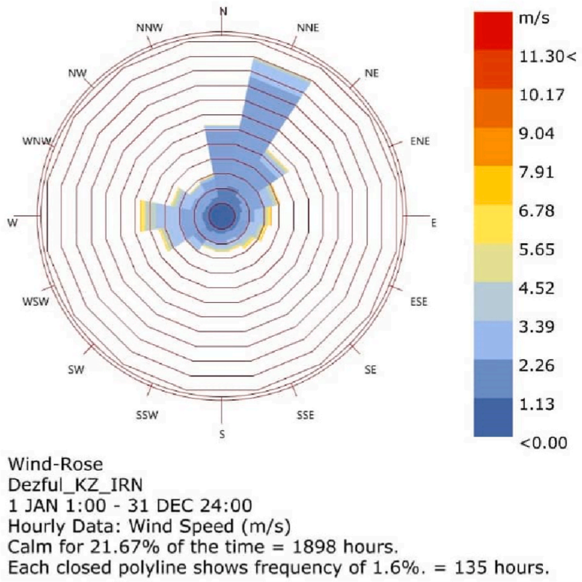


Fig. 7. Windrose's graph of Dezful.

3.1. Investigation between model 1 and 2

As seen in Table 6 and Figs. 8–11, in model 1, the stack is located in the middle of the northern side of the room, and in model 2, the stack is located in the middle of the southern. Openings are located on the façade window on the opposite side of the stack with a projected shader to control the radiation. The airflow through this window is insignificant and is practically closed. All inlet, outlet, and stack vents are also open in the warm months. There is a glass on the southern surface of the stack, which is considered closed (see Table 7). It is only to intensify buoyancy in the stack. Materials are the same for all models.

According to the simulation, the desired temperature has been achieved in the room. The air temperature of both rooms in the model becomes below 36 °C while the air temperature is 38 °C in the basic model at the same time, at 2 p.m.

The air temperature in the room is 36.17 °C. The temperature of the stack varies between 40 and 43 °C. The inlet air temperature in the roof zone is 37.5 °C which can reach 45 °C on the eastern and western sides of the stack as the air does not move directly through it (Appendix 1). The air velocity in the roof zone is significantly higher than in the other areas, reaching 0.3 m/s from the air inlet to the outlet vent, while the velocity in the east and west is 0.08 m/s. The inlet air velocity of the stack is 0.45 m/s. However, the stack and the walls facing the air inlet have higher speeds than the rest.

The room temperature is 36.16 °C. The temperature of the stack also ranges between 39 and 41 °C from the floor to near the ceiling, reaching 45 °C at the stack ceiling. In the roof zone, the inlet air temperature is 38, increasing to 40 °C. On the eastern and western sides of the roof, as the air does not pass directly through it, it can reach 43 °C. the air velocity from the air inlet to the outlet vent is likely higher than that in other parts of the roof, which reach 0.23 m/s. In the east and west, the air velocity is 0.07 m/s In the stack inlet, the air velocity is 0.37 m/s. Lastly, the velocity is higher at the top and on the walls facing the air inlet than at the other stack parts (Appendix 2).

3.1.1. Stack position

According to the simulation analysis of models 1 and 2, the desired temperature variations happened in the room area due to the placement of an air vent channel in the ceiling. The overall air temperature decreased by several degrees from 12 p.m. to 8 p.m. For example, at 2 p.m., the room temperature became 36 °C, while it was 38 °C in the primary condition. Furthermore, the more undersized the temperature change is in the two models, when the stack is positioned on the north side results are more beneficial. However, the conditions are different regarding the ACH in the roof zone, which is an influential parameter of this study.

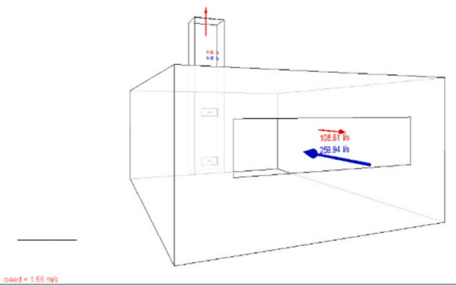
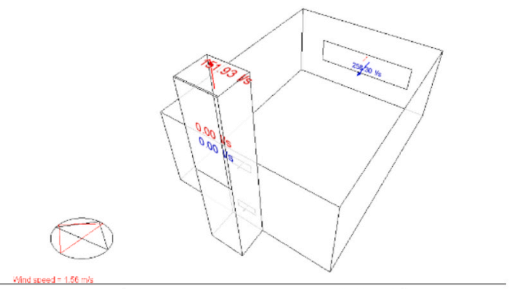
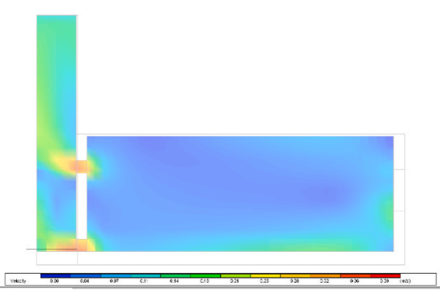
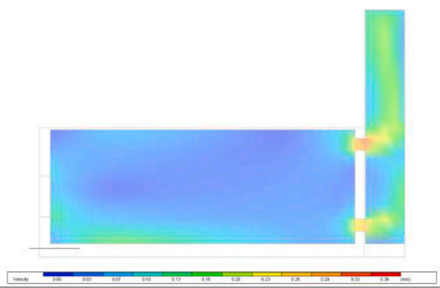
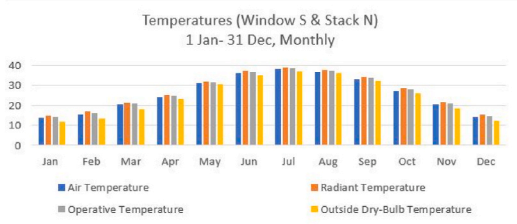
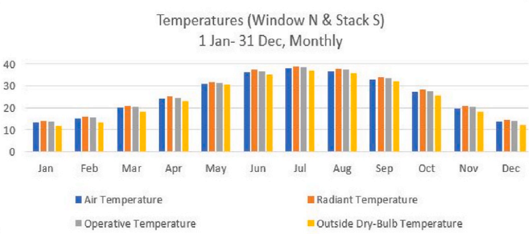
When the stack is on the south, ACH increases and rises at midnight, then it begins to fall at 2 a.m. and reaches 30 times per hour before increasing again at 1 p.m. when it declines. However, when the stack is on the north, ACH changes between 2 and 4 a.m., and although it is higher, it is not as high as that in the opposite model. The ACH is significantly larger at 4:00 p.m. than in the preceding model, although it lowers and increases again (see Fig. 12).

Fig. 13 demonstrates that there are considerable temperature variations in the roof. Temperatures near the floor reach 45 °C and higher. The temperature of the ceiling zone is higher than the primary temperature conditions despite a few degrees decrease in the rooms' temperature as the roof zone acts as insulation for the space.

3.2. Multi-story buildings' model

Given that the purpose of this study is to optimize stack on the 4-story buildings as they are common on the site, the analysis and research began with one- and two-story models, which are detailed following. Furthermore, considering the logical changes observed

Table 6
Investigation of samples 1 and 2 on direct ventilation.

Stackposition: North, Window position: south		Stackposition: south, Window position: north	
			
Air inlet	259.94 l/s	Air inlet	258.30 l/s
Air outlet	108.81 l/s	Air outlet	151.11 l/s
Air velocity model 1		Air velocity model 2	
			
			
Avarege air temperature		Average air temperature	
			

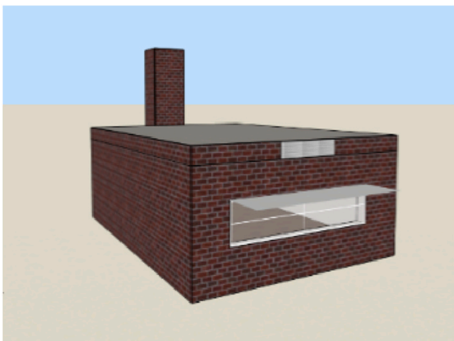


Fig. 8. Stack: south.

in the results for two-story and four-story buildings, as well as the similarity in airflow and temperature behavior between them, it can be inferred that these findings also apply to three-story buildings. As previously mentioned, three-story buildings constitute the lowest percentage of buildings in Dezful city, and the most common type is four stories. Therefore, after examining one and two-story

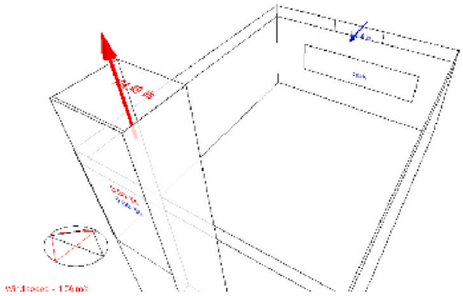


Fig. 9. Stack: south.

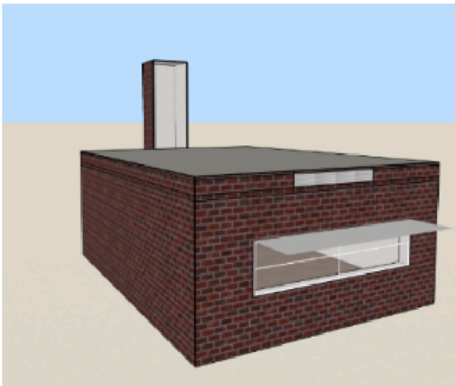


Fig. 10. Stack: north.

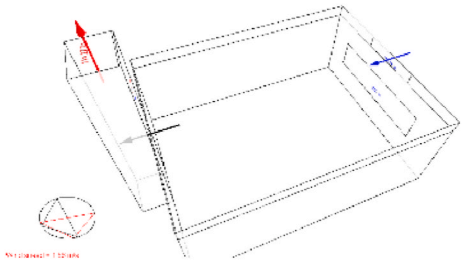


Fig. 11. Stack: north.

Table 7
Details about the physical condition of the indirect model.

Physical characteristics of models (m)							
	Stack position	Stack size	Stack window size	Stack outlet size	Window size	Roof inlet size (cm)	Roof outlet size
Model 1	North	1 × 1.2 x 2.90	1.20 × 2.9	1 × 1.2	4 × 1	300 × 40	0.4 × 1.2
Model 2	South	1 × 1.2 x 2.90	1.20 × 2.9	1 × 1.2	4 × 1	300 × 40	0.4 × 1.2
The amount of air entering and leaving the vent (l/s)							
Model 1			0.00	−111.28	0.00	+111.28	−111.28
Model 2			0.00	−104.50	0.00	+104.50	−104.50

buildings, which serve as fundamental models for assessing conditions and establishing a solid foundation for further investigations, the research has shifted its focus to four-story buildings.

The optimized models have been classified according to the number of stories:

The stack material, insulation, and intake size are studied in the one-story building. Controlling radiation and reducing heat transfer to the roof zone led to lower roof temperature and heat transmission to the room. External thermal insulation is regarded as the standard insulation. Further, the stack material has changed from brick to aluminum, which has lower heat capacity. Since the air is

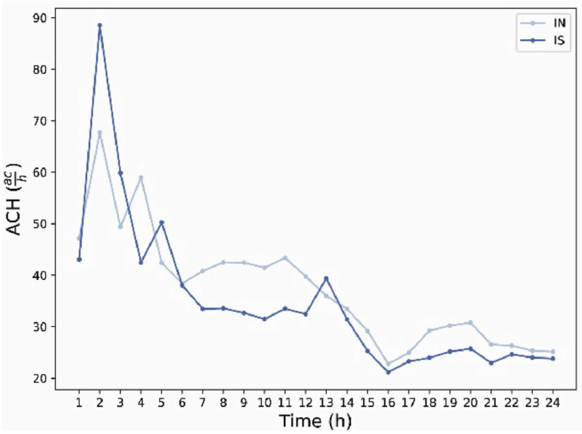


Fig. 12. ACH, Roof zone in the day.

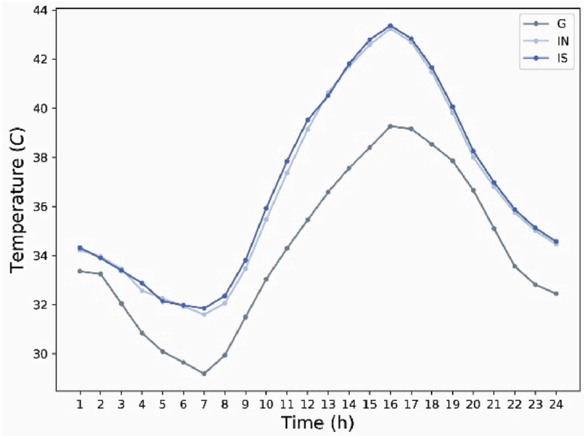


Fig. 13. Changing temperature in the roof zone.

hot, the dimensions and size of the inlet are limited to indirect ventilation. Due to the lack of this limitation in indirect ventilation, the inlet size is increased to 6 m × 40 cm to allow for additional flow.

According to the simulations (appendix 3), the room temperature goes from 36.18 to 33.82 °C. The stack temperature similarly climbs from 40 to 42 °C and higher. The room temperature decreases by 2.36 °C while the stack temperature increases by 2.5°. The roof temperature declines and changes from 40 to 36 °C. The increase in airflow is also directly related to the enlargement in vent size. Furthermore, ACH changes from 100 l/s to 119 l/s. The airflow directly enters the stack from the ceiling zone and moves up at a velocity of 0.32 m/s. The air velocity reaches 0.2 m/s on top of the stack and the walls. However, the ceiling air velocity is 0.09 m/s in the inlet and increases as it arrives at the outlet.

- The stack height is assumed to be 2 m from the roof in two story building, and other changes are similar to those in the one-story model. The applied changes are increasing the inlet flow and changing the stack material to aluminum (see Table 8).

The stack air flow increases from 38 to 41 °C from the bottom to the top. The first-floor and second-floor temperatures were 35.2 and 37.16 °C, respectively. The roof zone temperature has reduced from 1 to 1.30 to 2.30. The air velocity is near 0.00 m/s in the room. The roof air velocity goes from 0.11 to 0.22 m/s on the second floor, the velocity of 0.1 m/s has risen, and the rate of velocity remains

Table 8
The airflow in vents before and after the changes (l/s).

Vent position			Before the changes	After the changes
First floor	**Entry**	**Ceiling 1**	0.00	22.22 83.43
		Ceiling 2	92.11	5.34 61.98
Stack outlet		**Exit**	92.11	117.74

mostly 0.44 m/s on the stack inlet. Furthermore, the stack's air intake goes to 117.8 l/s, showing that 25.7 l/s output air has increased. (For more information: appendix 4).

- The first and fourth room temperatures are 34.93, 35, 35.63, and 36 °C, respectively, in the four-story model. While in the roof zone, the temperatures are 35.63, 36.36, and 37 °C. The temperature of the stack also varies from 37.5 to 41 °C. The roof zone air velocity from the bottom to the top in the zones is as follows: the velocity is from 0.28 to 0.35 m/s at the outlet; 0.21 on the next two floors; and on the last floor, it reaches 0.49 m/s. According to the airflow direction, the air movement path initially enters the ceiling from the inlet. Then the flow converges towards the vents that go towards the outlet in the ceiling after entering the stack and slightly descending. (Appendix 5)

3.2.1. Stack height

With the dominant majority of four-story houses in the area, this study centers its focus on the advancement of four-story structures. The optimization's goal is to augment the efficiency and efficacy of four-story building designs. In alignment with this objective, the optimization process specifically targets the stack height of four-story buildings; Therefore, Table 9 shows that five models are introduced and verified, and the optimum model is chosen. Finally, computations and CFD simulations for the chosen model are presented.

Following the flow rise, the airflow velocity increases, which causes a rise in the air movement velocity. Therefore, improving airflow is crucial. As the cases above show, the flow rate grows while height increases. The airflow rate is significantly lower in the H and H1 models than in the H2 model. Although the flow rate in the H4 and H3 models has risen considerably compared to the previous condition, both provide the same result of 1 l/s, indicating equivalent performance (see Table 10). As a result, the H3 model is superior to the opposing model since it is of a shorter height (see Figs. 14 and 15). As follow the optimized model have been explained.

Model H3 has been examined in the following graphs. The air temperature in the room, the ceiling channel, and the ventilation are checked before and after height optimization (see Fig. 16).

In the process of selecting an optimal stack height, the primary emphasis has revolved around boosting the outflow from the stack as well as enhancing the inflow of air into the roof channels. Although the temperature drops during the critical hours of the day, and this rate of change is more prominent in the lower zones, air temperature did not decrease. On the roof, exterior side the temperature rises sharply during the afternoon, but the roof cavity is 3–4 °C cooler than even on the higher floors, where the change is less; up to 2–1.5 °C. The temperature decreases in the crisis hours of the day are seen. The air inside is warmer than the outside of the stack, which can cause an uprising stack effect.

The temperature and air velocity have been changed in the room. The stack temperature reaches 38.97 °C. The roof zone temperature is changing from 58.35 to 16.36 °C. the rooms' temperatures are 34, 34.70, 35.58, and 36.16 °C From the bottom to the top. The temperature of the warmest area is 1.90° less than that of the primary condition, indicating that the most generous space is cooler than the outside temperature. Since there is no flow in the room zones, the airflow velocity is up to 0.06 m/s. In the roof zones, on the last roof, the velocity is higher and goes up to 0.38 m/s. But in the stack on the south wall, the velocity is more elevated and reaches 0.45 m/s. The direction of the airflow in the roof zones goes from the inlet vent to the outlet vent, and because of this, the velocity at the outlet increases. (For More information, Appendix 6).

In summary, the investigation presented in this study sheds light on the transformative potential of integrating a stack effect-driven system with innovative roof channels in multi-story building designs. Through the implementation of prototypes varying in height – one-story, two-story, and 4-story structures – the study successfully unraveled the intricacies of the proposed system's impact on thermal and ventilation performance. By affixing roof channels to the room zones rather than merely the roof, a substantial improvement in stable cooling and ventilation conditions throughout the occupied spaces was achieved, mitigating the need to rely solely on external wind forces.

1. Efficacy of Indirect Ventilation:

One of the key takeaways from this study is the recognition of the inefficiency of direct ventilation, particularly during the warmer months (May to September), within the specific climatic context under examination. This finding underscores the need for a paradigm shift towards indirect ventilation strategies, which offer more effective means of temperature reduction. Such insights serve as a crucial

Table 9
Selected models for height optimization.

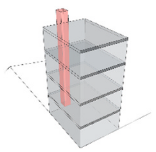
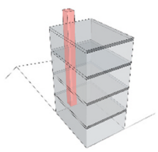
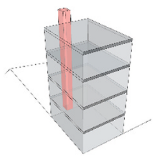
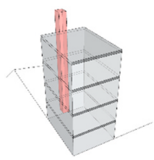
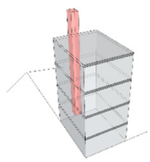
Model name	H	H1	H2	H3	H4
Model shape					
Stack heigh(m)	1.40	1.60	2	2.40	2.80

Table 10
The airflow amount (rate) in vents (l/s).

Vent position			H	H1	H2	H3	H4
Roof inlet	**Output**	**Ceiling 1**	62.13	55.35	53.56	47.93	45.03
	Input		45.98	52.17	55.10	62.64	65.21
	Output	**Ceiling 2**	53.98	48.70	46.87	60.26	37.66
	Input		44.12	49.54	53.06	66.57	62.36
	Output	**Ceiling 3**	31.43	29.71	17.88	22.55	22.64
	Input		57.91	60.53	62.83	76.05	68.97
	Output	**Ceiling 4**	3.16	3.52	1.35	0.2	5.24
	Input		46.16	48.69	48.91	59.90	57.25
Stack outlet			46.43	73.65	90.46	142.22	143.12

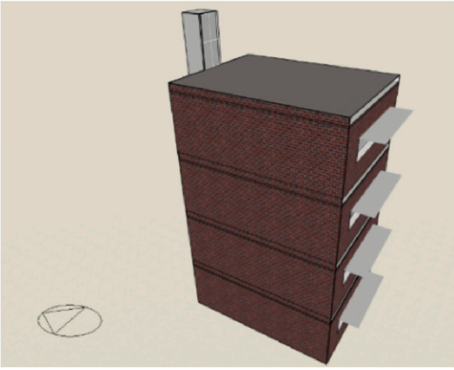


Fig. 14. Model H3.

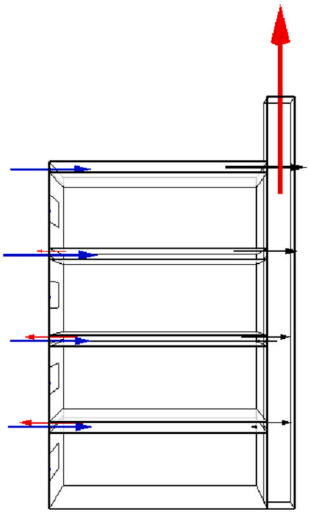


Fig. 15. Section of model H3.

guideline for architects and engineers aiming to optimize indoor comfort and energy efficiency.

2. Role of Roof Channels:

A salient achievement of this study is the observation of the pronounced effectiveness of roof channels in the context of multi-story buildings. The innovative inclusion of these channels facilitates the collection and efficient discharge of hot air amassed on rooftops. This process results in a notable enhancement of air circulation within the structures, leading to improved thermal comfort levels for occupants. The implications of this finding resonate significantly within the field of sustainable building design, as it highlights a tangible solution to alleviate heat buildup.

3. Regional Stack Dynamics:

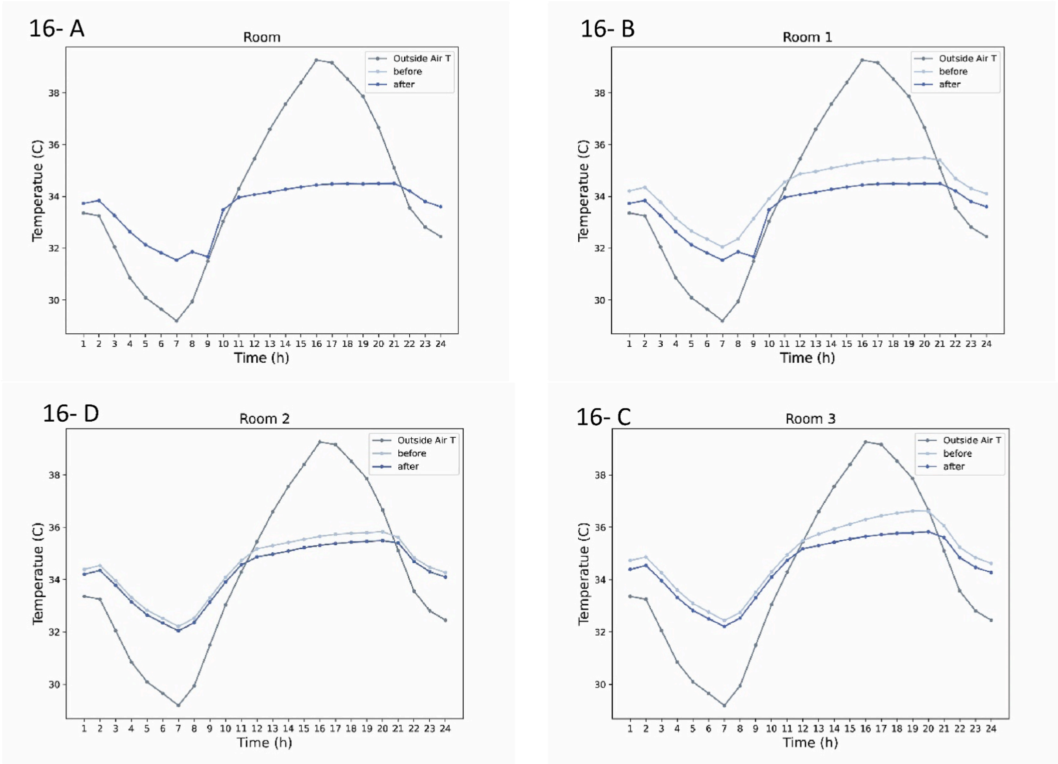


Fig. 16. Showed after and before changes in temperature in rooms 1–4.

The study's detailed exploration of regional stack dynamics, focusing on both southern and northern stack orientations, reveals nuanced variations in air changes per hour (ACH) rates. While the southern stack exhibited occasional increases in ACH compared to the counterpart model, the northern stack consistently maintained optimal conditions. This insight emphasizes the versatility of the proposed system, accommodating diverse stack orientations without compromising on ventilation performance.

4. Optimization Strategies and Stack Height Rationalization:

The employment of an optimization model yielded practical strategies for enhancing system performance. Changing the dimensions of the roof inlet vent to 6 × 0.4 m emerged as a pivotal intervention, significantly raising ACH to 100 l/s. Moreover, the identification of an optimal stack height of 2.40 m underscored the importance of careful dimensioning. This height adjustment resulted in a substantial increase in stack output from 90 to 142 l/s, further affirming the efficacy of systematic optimization in achieving desired outcomes.

5. Material Impact and Insulation Strategies:

The transition from conventional brick stacks to aluminum, boasting a higher thermal conductivity, demonstrated marked improvements in ACH rates. This material-driven enhancement speaks to the potential for material innovation to significantly impact system performance. Furthermore, the integration of external insulation showcased its capacity to manage extreme conditions within the final roof channel. This is particularly significant as it speaks to the resilience of the proposed design in face of challenging environmental conditions.

6. Temperature Regulation:

The transformation of the roof into a roof channel design, as exemplified in this study, yielded a notable reduction in room air temperature during uncomfortable periods. The substantial 4-degree decrease observed between 12:00 p.m. and 08:00 p.m. underscores the practicality of this design intervention in enhancing occupant comfort, particularly during peak heating hours.

4. Conclusions

This study addresses the pressing need for energy-efficient solutions in the face of rising temperatures, changing climates, and diminishing fossil fuel resources. It focuses on the stack effect, a passive cooling strategy harnessing renewable energy principles. Particularly, the study introduces an innovative integration of stack ventilation with roof channels, combining vertical and horizontal airflow dynamics. This method can be a stable cooling and ventilation alternative, which means the inclusion of a roof channel within the roof zone because the result of optimization shows that employing roof channels for air conditioning proves to be effective in this climate. Despite the challenges posed by passive cooling research compared to heating, this study underscores its value, exemplified by its successful reduction of air temperatures through stack ventilation, further enhanced by integration with roof channels for indirect building air ventilation, particularly in extreme climates. Indeed, this approach resulted in a significant reduction of up to 4° Celsius in air temperature during extreme conditions, therefore when the result has been effective in the extreme condition it means that the method is obviously useful in usual conditions. And it can result in positive contributions to enhance other ventilation systems such as HVAC for controlling thermal comfort in the buildings. The findings underscore the efficacy of indirect ventilation and the transformative role of roof channels. This integration enhances air circulation and provides architects with a novel approach to energy-efficient designs tailored to hot regions.

Findings can be implemented in architectural practices to enhance building energy efficiency as well as in research studies with the aim of testing different passive energy efficiency strategies which also consider the occupant thermal comfort. Moreover, the research contributes to guidelines for government bodies, local authorities, Iran Building By-Law practitioners, and policymakers. It should be mentioned that while the findings can be generalized for regions with similar climates, caution in extrapolation to other regions is necessary. Future research should explore broader climate zones to validate applicability.

Authorship statement

All persons who meet authorship criteria are listed as authors, and all authors certify that they have participated sufficiently in the work to take public responsibility for the content, including participation in the concept, design, analysis, writing, or revision of the manuscript. Furthermore, each author certifies that this material or similar material has not been and will not be submitted to or published in any other publication before its appearance in the *Hong Kong Journal of Occupational Therapy*.

Please indicate the specific contributions made by each author (list the authors' initials followed by their surnames, e.g., Y.L. Cheung). The name of each author must appear at least once in each of the three categories below.

Category 1.

Conception and design of study: H. Bazazzadeh, R. Rezadoost Dezfuli.

Acquisition of data: H. Bazazzadeh, R. Rezadoost Dezfuli, M. Taban.

Analysis and/or interpretation of data: H. Bazazzadeh, R. Rezadoost Dezfuli.

Category 2.

Drafting the manuscript: H. Bazazzadeh.

Revising the manuscript critically for important intellectual content: R. Rezadoost Dezfuli, H. Bazazzadeh, M. Mahdavinejad, M. Taban.

Category 3.

Approval of the version of the manuscript to be published (the names of all authors must be listed):

R. Rezadoost Dezfuli, H. Bazazzadeh, Mohammadjavad Mahdavinejad, Mohsen Taban.

Declaration of competing interest

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

Data availability

No data was used for the research described in the article.

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All persons who have made substantial contributions to the work reported in the manuscript (e.g., technical help, writing and editing assistance, general support), but who do not meet the criteria for authorship, are named in the Acknowledgements and have given us their written permission to be named. If we have not included an Acknowledgements, then that indicates that we have not received substantial contributions from non-authors.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.csite.2023.103555.

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