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Effects of the height of supply outlet of façade-mounted hybrid downdraft evaporative cooler on the indoor air quality of an office building

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Abstract. The hybrid downdraft evaporative cooler (HDEC) conditions a building by cooling with humidification and hence, inappropriate location of its supply outlet on a building facade has a great impact on the indoor air quality (IAQ) which affect the health, concentration, and productivity of the occupants. This paper investigates the effect of the height of the HDEC supply outlet on the IAQ of an office building equipped with the HDEC system in Bayero University Kano. The building model was created using DesignBuilder software while DesignBuilder CFD was employed for the parametric simulation using air change effectiveness (ACE) as the performance criterion. The height of the HDEC supply outlet was varyfrom 0.1m to 2.4m step 0.1m above the floor level. The results show that higher values of ACE in the occupants' breathing zone were obtained at lower heights of the HDEC supply outlets with the best ACE of 1.1588 obtained at 0.3m. This information could help engineers to optimally position the HDEC supply outlet on the façade of an office building or any other building with similar characteristics.

Keywords: indoor air quality, office building, evaporative cooling system, window geometry, mean age of air, air change effectiveness

1. Introduction

Office building is a space where high intellectual concentration is required. In public service, people spend about 8 hours daily in their offices.. Therefore, the

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productivity, concentration, morale, efficiency, and well-being of building occupants is largely a function of their indoor environment [1-6]. Indoor air quality (IAQ) and thermal comfort are the major indoor environment in this context and therefore, achieving IAQ in a space is imperative [7, 8].

IAQ is an important issue that has an impact on the health of building occupants [9]. According to ASHRAE Standard-62.1 [10], good air quality ensures that 80% of the occupants are satisfied. Study has shown that IAQ in buildings is affected by context, occupant and building [11]. The positions of the diffusers of cooling and ventilating systems also determines the quality of air in the breathing zone of occupants [12]. The position of supply outlets of cooling and ventilating systems dictate the realization of displacement ventilation or mixed-mode ventilation in the occupied space. The displacement ventilation and the mixed-mode ventilation characteristically have different impacts on the breathing zone of building occupants.

Displacement ventilation is an air-distribution strategy which introduces fresh outdoor air at a low velocity from air supply diffusers that are usually located near floor level. The freshly cooled air accelerates because of buoyancy force and is carried up into the thermal plumes that are formed by heat sources such as occupants and electric appliances [13, 14]. In this type of ventilation, the warm and stale air is consolidated at the upper part of the room for extraction and does not re-enter the occupied space. This type of ventilation can effectively deliver fresh and cooled air to the occupants and displace the contaminated air above the breathing zone of the occupants [15]. In mixed mode ventilation, the fresh outdoor air is supplied at higher velocity and could dilute the contaminants in the room air [16]. Cool air is denser than the warm rising air in the space therefore, as it descends from the diffuser it falls into the warm rising air thereby cooling the entire space [17]. Hence, the position of the air supply diffuser significantly determines the quality of air in the breathing zone of the occupants [18].

Many studies were conducted to investigate the effects of the positions of air supply diffusers on the IAQ and thermal comfort of a space. Ning et al. [18] investigated the effect of heights of conditioned air supply outlets on the IAQ in the breathing zone of a sleeping person using computational fluid dynamics. They found that positioning the supply air outlet at a lower level was effective in improving IAQ near the mouth of a sleeper. Shan et al. [15] experimentally compared mixing and displacement ventilation in tutorial rooms on the basis of students' thermal comfort, sick building syndrome, and short-term performance. They found that mixing ventilation could lead to significantly larger overall draft sensation than the displacement ventilation due to high air velocity from the overhead diffusers. Mutlu and Caliskan [19] investigated the effect of thermostat position on particle distribution, thermal comfort, and energy consumption in a room cooled with cassette type air conditioner using 3D CFD simulations. They concluded that the position of the thermostat significantly influences the particle distribution as well as the thermal comfort and energy consumption in the space. Shi and Chen [14] experimentally and computationally investigated wall-mounted

displacement induction ventilation system. They found that stratified air distribution was achieved with this type of air-distribution strategy.

The researches reviewed highlighted the impacts of the positions of air supply diffusers of air conditioners or other ventilation systems on the IAQ of occupied spaces. A research is missing on the optimal positioning of facade-mounted hybrid downdraft evaporative cooler (HDEC) air supply outlet for optimum improvement in IAQ of a space. The cooling characteristics of HDEC system is different from that of the refrigeration-based air-conditioning system, natural ventilation or other ventilation systems because it conditions the outdoor air by cooling and humidification. This process necessitates the windows of the space to be opened to avoid moisture accumulation [20]. The windows are the only means in which the moisture, stale and contaminated air exit the building. HDEC system is an emerging low-energy cooling technology that is environmentally friendly, has lower investment and operational cost, has superior air quality, and lower maintenance requirement compared to the conventional air conditioning system [21-23].

To this end, this paper attempts to numerically investigate the effect of the height of HDEC supply outlet on the IAQ of an office building equipped with the HDEC system in the New Campus of Bayero University Kano, Nigeria. Air change effectiveness (ACE), is one of the most commonly used indicators of IAQ was used in this study [24].

2. Study area

The characteristics of the study area are presented in Table 1.

Table 1. Characteristics of the Case Study

Title	Characteristics
Building type and location	Office, Bayero University, Kano, Nigeria. Latitude: 12.05°N, Longitude: 8.53°E Elevation: 481m above sea level
Floor height	3.0m
Occupancy (person/m ²)	0.068
Office hours	8:00am – 4:00pm
Dimension of office	4.0m long, 3.7m wide, and 3.0m high

3. Methodology

3.1. Creation of 3D model of the office building

The model of the office building dimensioned $4m \times 3.7m \times 3m$ was created using DesignBuilder software. The zone level of the office room model was shown in Fig. 1(a) while the 3D building level of the office room and the integrated HDEC–Office building models were shown in Fig. 1(b).

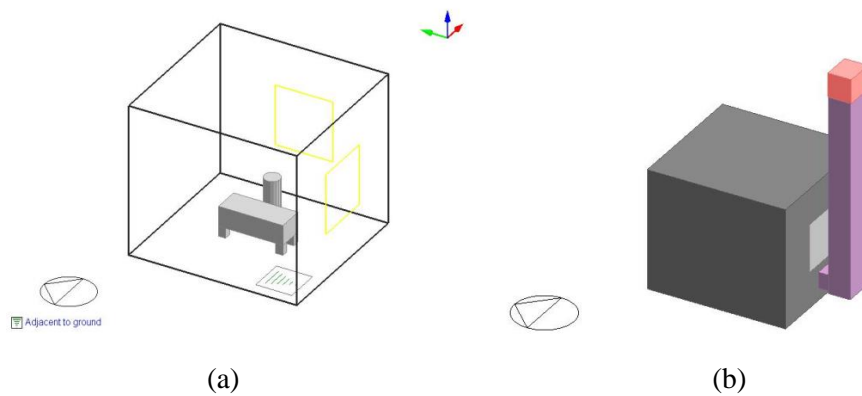


Fig. 1. (a) 3D Zone Level (b) 3D Integrated HDEC-Office Building Model.

3.2. The Boundary Conditions

The HDEC exit air condition largely determines the air quality of the test room. Therefore, the experimental HDEC exit air temperature and flow rate alongside the the occupants metabolic rate, clothing insulation level, and indoor relative humidity, mean radiant temperature, air velocity and dry-bulb temperature were used as part of the boundary conditions for the DesignBuilder CFD simulation. The air velocities through the window opening during the simulation runs were determined using external CFD analysis. One of the external CFD simulations carried out were shown in Fig.2 respectively. The velocities through the window opening were used to compute the airflow rate in (l/s) which were used later for internal CFD analysis.

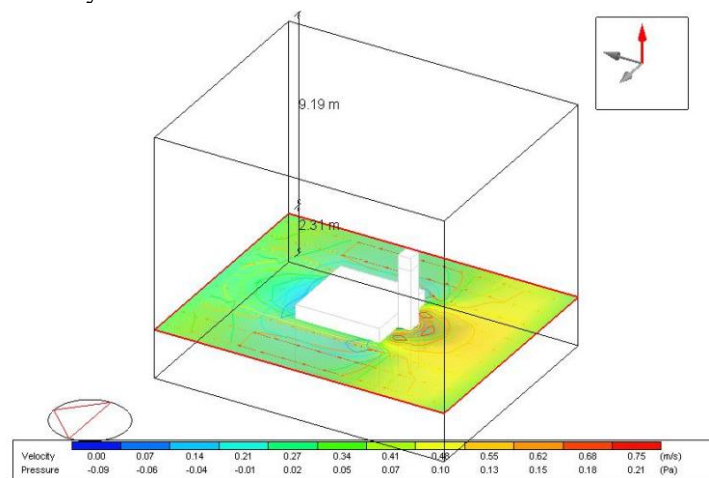


Fig. 2. External CFD Simulation of the Building Model.

The simulated ACE results were obtained using the internal CFD analysis. The computational domain of the internal CFD analysis for the numerical determination of the IAQis shown in Fig.3.

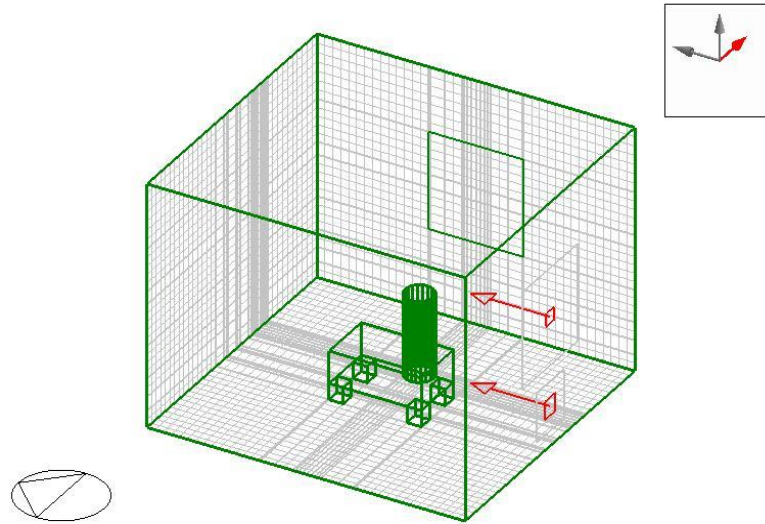


Fig. 3. Computational Domain for Internal CFD Analysis.

3.3. The Governing Equations

The numerical method used by DesignBuilder CFD is known as a primitive variable method, which involves the solution of a set of equations that describe the conservation of heat, mass, and momentum.

The equation of mass conservation, known as the continuity equation is given by equation 1 [25].

$$\frac{\partial}{\partial x_i}(\rho u_i) = 0 \quad \dots \quad (1)$$

The equation for momentum conservation is given in equation 2.

$$\frac{\partial}{\partial x_j}(\rho u_i u_j) = \frac{\partial P}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} + \rho g_i \quad \dots \quad (2)$$

The equation for total energy conservation is given in equation 3.

$$\frac{\partial}{\partial x_i}(\rho u_i h) = \frac{\partial}{\partial x_i} \left(k \frac{\partial T}{\partial x_i} \right) + u_i \frac{\partial P}{\partial x_i} + \tau_{ij} \frac{\partial u_i}{\partial x_j} \quad \dots \quad (3)$$

Where: ρ = Density; u_i = Velocity component in the i direction; P = Static pressure; τ_{ij} = Stress tensor; x_i = Cartesian coordinate; g_i = Gravitational acceleration in the i - direction; P = static pressure; enthalpy; k = Thermal conductivity; T = Temperature.

The CFD numerical method used by DesignBuilder software which relate to the set of those equations above, particularly describe the main environmental factors including the conservation of heat, temperature, mass, momentum and where

$k - \epsilon$ turbulence model is used. The equations comprise a set of coupled non-linear second-order partial differential equations having the following general form, in which ϕ represents the dependent variable is given by equation 4.

$$\frac{\partial}{\partial t}(\rho\phi) + \text{div}(\rho u\phi) = \text{div}(\tau \text{grad}\phi) + S \dots \dots \dots (4)$$

The first and second terms on the LHS represent the rate of change and convection respectively while the first and second terms on the RHS represent the diffusion and source term respectively.

3.4. Model validation

Before the validation, different structured grids were employed to establish the grid independence. Using DesignBuilder software, this was achieved by incrementally varying the grid spacing and grid merge tolerance until the check box indicate *ok* on the Grid statistics of the CFD Model.

After the grid independence, the establishment of the accuracy of the model was done through validation process. The model was validated by comparing the measured indoor temperature of the office building equipped with the HDEC system in Bayero University Kano with the simulated indoor temperature obtained from the CFD model. Fig.4 shows the comparison between the experimental and simulated indoor temperature.

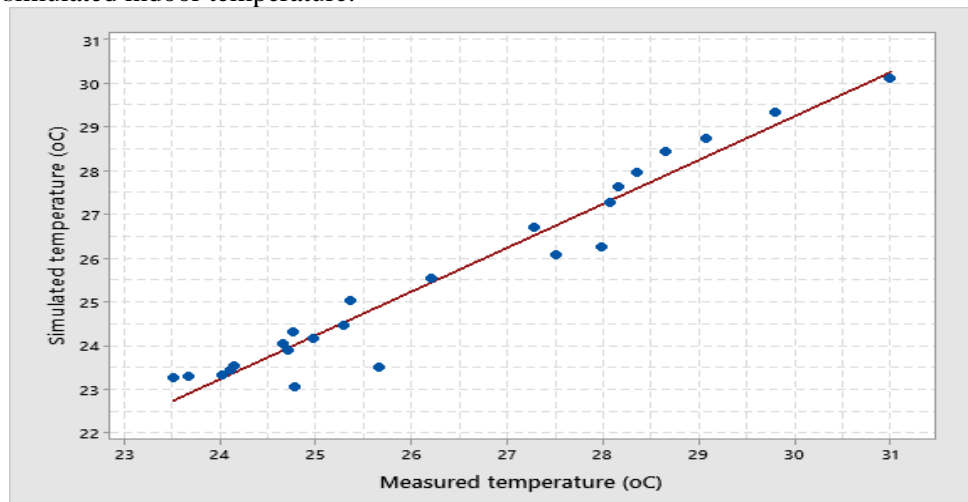


Fig. 4. Comparison between Measured and Simulated Indoor Temperature

The coefficient of correlation between the measured and the simulated temperature at 95% confidence level using Minitab 19 software is 0.974. The high correlation between the measured and the simulated temperature indicates the high accuracy of the building model used for this study.

3.5. Determination of Air Change Effectiveness

DesignBuilder software was employed to map out the breathing zone of the occupants. The software calculates the ACE by adding the ACE 'breathing region' to define the parts of the CFD domain to be considered as part of the ACE calculations. The regions were added by specifying the coordinates of the origin and the dimensions of the region. In this study, the coordinates of the origin and the dimensions of the breathing zone were presented in Table 2 and this complied with ASHRAE Standard-62.1[10] recommendations for breathing zone specifications.

Table 2. Breathing Zone of the Occupied Space

Coordinate of Origin	Dimensions
$X = 10.844$	$Length(m) = 1.544$
$Y = 10.408$	$Width(m) = 1.88$
$Z = 0.667$	$Height(m) = 0.80$

3.6. Parametric analysis of the CFD model

DesignBuilder parametric analysis was employed by keeping the boundary conditions constant while varying the HDEC supply outlet from 0.1m to 2.4m step 0.1m above the floor level. DesignBuilder CFD simulation was then carried out to determine the effect of the HDEC supply outlet on the IAQ using the ACE as the performance criterion.

4. Results and discussions

The numerical results of the ACE of the office building equipped with the HDEC system with the height (h) of the HDEC supply outlet varying from $h = 0.1m$ to $2.4m$ step 0.1m are shown in Fig. 5.

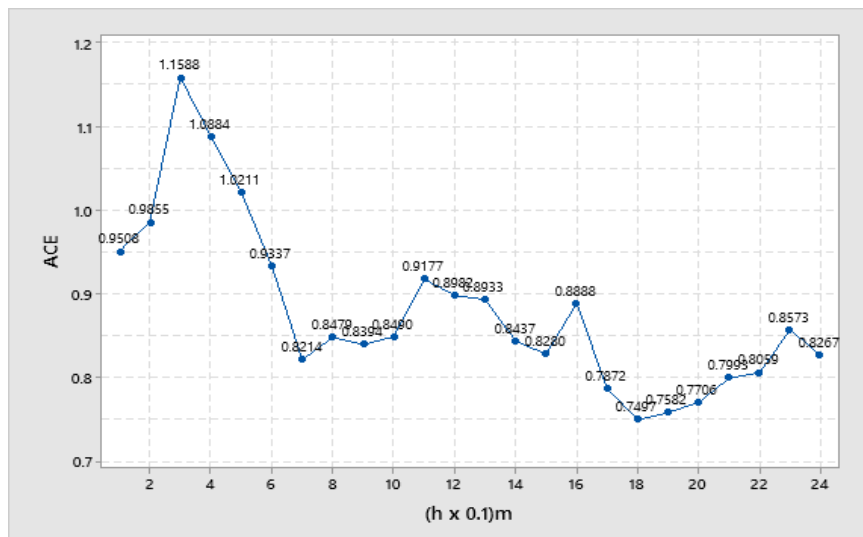


Fig. 5. Plot of ACE vs HDEC supply outlet positions.

The results of the parametric simulations of the ACE in the occupants' breathing zone of the office building with the height of the HDEC supply outlets varying from 0.1m to 2.4m step 0.1m I shown in Fig. 5. It can be seen that higher values of ACE were 0.9508, 0.9855, 1.1588, 1.0884, 1.0211, and 0.9337 which were obtained at HDEC supply outlet heights of 0.1m, 0.2m, 0.3m, 0.4m, 0.5m, and 0.6m from floor level respectively, with the highest value of ACE obtained at 0.3m height of the HDEC supply outlet. This finding might be attributed to the HDEC system behaving purely as a displacement ventilation system. The thermal plumes created by the heat sources such as the occupants and electric appliances allows the freshly cooled air to displaced the warmer stale air above occupants breathing zone. This finding is in consonance with the works of Ameen et al. [26] and Tian et al. [27] who stated that in a displacement ventilation system, the values of ACE are higher primarily due to the displacement of contaminated air above the occupants' breathing zone.

For a perfectly mixed ventilation, the ACE is 1.0[10]. Therefore, from Fig. 5, it can be seen that at the HDEC supply outlet heights of 0.3m, 0.4m, and 0.5m, the values of ACE were greater 1.0 which indictes that at these heights, the HDEC system supplied freshly cooled air directly into the occupants' breathing zone. This finding is in consonance with the work [28] who concluded that the best location for enhancing the ACE in a space is by placing the diffuser of the ventilation system closer to the floor.

From Fig. 5, it can also be seen that lower values of ACE were obtained at relatively higher HDEC supply heights above the floor level. This might be attributed to the fact that at higher HDEC supply heights, the freshly cooled air supplied by the HDEC system falls into the rising warmer stale air thereby diluting it. When this happns the quality of air in the breathing zone of the occupants would be lowered. That is why the ACE at higher HDEC supply outlets are less than unity

for a perfect mixed ventilation. This finding agreed with the work of Lee et al. [29] who experimentally compared high wall jet from grill diffusers with typical ceiling diffusers and concluded that the ceiling diffusers is better in terms of air change effectiveness.

6. Conclusion

The effect of the height of HDEC supply outlet on the IAQ of an office building equipped with the HDEC system in Bayero University Kano was numerically investigated. Lower heights of the HDEC supply outlets gave better ACE in the occupants' breathing zone with the best result obtained at the height of 0.3m above the floor level. Therefore, in an office building equipped with the HDEC system, an enhanced IAQ could be achieved using lower heights of HDEC supply outlets. This information could help building designers and engineers to locate HDEC supply outlet for achieving maximum thermal comfort in an office building or any other building with similar attributes.

References

- [1] Daisey J.M., Angell W.J., Apte M., *Indoor air quality, ventilation and health symptoms in schools: an analysis of existing information*, Indoor Air, **13**, 2003, p. 53-64.
- [2] Mavrogianni A., Mumovic D., *On the use of windcatchers in schools: climate change, occupancy patterns, and adaptation strategies*, Indoor and Built Environment, **19**, 2, 2010, p. 340-354.
- [3] Haverinen U., Moschandreas D.J., Shaughnessy R.J., *Association between substandard classroom ventilation rates and students' academic achievement*, Indoor Air, **21**, 2011, p. 121-131.
- [4] Sadick A.M., Issa M.H., *Occupants' indoor environmental quality satisfaction factors as measures of school teachers' well-being*. Build Environment, **119**, 2017, p. 99-109.
- [5] Huttunen K., *Indoor Air Pollution in Clinical handbook of air pollution-related diseases*, Springer, 2018, p.107-114.
- [6] Ben-David T., Rackes A., Lo L.J., Wen J., Waring M.S., *Optimizing ventilation: theoretical study on increasing rates in offices to maximize occupant productivity with constrained additional energy use*, Build Environ., **166**, 2019, 106314.
- [7] Abdullah F.H., MajidN.H.A., Othman R., *Defining Issue of Thermal comfort control through Urban mosque façade design*, Procedia-Soc. Behav. Sci., 2016.
- [8] Ahn J., *Improvement of the performance balance between thermal comfort and energy use for building space in the mid-Spring Season*, Sustainability, **12**, 2020, 9667.
- [9] Gharehchahi E., Mahvi A.H., Amini A., Nabizadeh R., Akhlaghi A.A., Shamsipour M., Yunesian M., *Health impact assessment of air pollution in Shiraz, Iran: a two-part Study*, Journal of Environmental Health Science and Engineering, **11**, 2013, 11.
- [10] ASHRAE-62.1, *Ventilation for acceptable indoor air quality*, Atlanta, GA: American Society of Heating, Refrigerating, and Air Conditioning System, 2016.
- [11] KorsaviS.S., Montazami A., Mumovic D., *Indoor air quality (IAQ) in naturally-ventilated Primary schools in the UK. occupant-related factors*, Building and Environment, **180**, 2020, 106992.
- [12] Amai H., Novoselac A., *Experimental study on air change effectiveness in mixing ventilation*. Building and Environment, **109**, 2016, p.101-111.
- [13] Yang B., Melikov A.K., Kabanshi A., Zhang C., Bauman F.S., Cao G., Awbi H., Wigo H., Niu J., Cheong K.W.D., Tham K.W., Sandberg M., Nielsen P.V., Kosonen R., Yao R., Kato R.S., Sekhar S.C., Schiavon S., Karimipanah T., Li X., Lin Z., *A review of advanced air distribution methods - theory, practice, limitations and solutions*. Energy Build., **202**, 2019, 109359.

- [14] Shi Z., Chen Q., *Experimental and Computational Investigation of Wall-mounted Displacement Induction Ventilation System*, Energy and Buildings, **241**, 2021,110937. .
- [15] Shan X., Zhaou J., Chang V., Yang E., *Comparing mixing and displacement ventilation in tutorial rooms: students' thermal comfort, sick building syndrome, and short-term performance*, Building and Environment, **102**, 2016, p. 128-137.
- [16] Liu J.Y., Dalgo D.A., Zhu S.W., Li H., Zhang L.H., Srebric J., *Performance analysis of a ductless personalized ventilation combined with radiant floor cooling system and displacement ventilation*, Build. Simulat., **12**, 5, 2019, p. 905-919.
- [17] Kim J., de Dear R., *Is mixed-mode ventilation a comfortable low-energy solution? A literature review*, Building and Environment, **205**, 2021, 108-215.
- [18] Ning M., Song M., Chan M., Pan D., Deng S., *Computational fluid dynamics (CFD) modelling of airflow field, mean age of air, and CO₂ distribution inside a bedroom with different height of conditioned air supply outlet*. Applied Energy, xxx, 2015, xxx-xxx.
- [19] Mutlu M., Caliskan E., *Effect of thermostat position on thermal comfort, energy consumption, and particle distribution in a room cooled with a cassette type air conditioner*, Alternative Energy Sources, Materials and Technologies, **1**, 2019, p. 71-72.
- [20] Kang D., Strand R., *Modelling of simultaneous heat and mass transfer within passive downdraft evaporative cooling (PDEC) tower with spray in FLUENT*, Energy and Building, **63**, 2013, p.196-209.
- [21] Kulkarni R., Rajput S., *Theoretical performance analysis of jute fibre rope bank as media in evaporative coolers*, Indian Journal of Science and Technology, **3**, 1, 2010, p.1075-1080.
- [22] Ford B., *Downdraught Cooling: an overview of current research and practice*, Architectural Science Review, **55**, 4, 2012, p.237-240.
- [23] Pandelidis D., Anisimov S., Drag P., *Performance comparison between selected evaporative air coolers*, Energies, **10**, 2017, p. 577.
- [24] Villafruela J.M., Castro F, J.F., San Jos J.F., Saint-Martin J., *Comparison of air change efficiency, contaminant removal effectiveness and infection risk as IAQ indices in isolation rooms*, Energy Build., **57**, 2013, p.210-219.
- [25] Phonekeo P., Lopez-Jimenez P., Guillamon I., *CFD model using for natural ventilation study in the local building of hot-humid climate in Vietiane capital, Lao PDR*. International Journal of Energy and Environment, **7**, 1, 2016, p.37-48.
- [26] Ameen A., Cehli M., Larsson U., Karimipannah T., *Experimental Investigation of the ventilation performance of different air distribution systems in office environment-cooling mode*, Energies, **12**, 2019, p. 1354.
- [27] Tian X., Zhang S., Awbi H.B., Lio C., Cheng Y., Lin Z., *Multi-indicator evaluation on ventilation effectiveness of three ventilation methods: An experimental study*, Building and Environment, **180**, 2020, 107015.
- [28] Sinha S.I., Arora R.C., Roy S., *Numerical simulation of two dimensional room airflow with and without buoyancy*, Energy Build., 2000,
- [29] Lee E., Khan J.A., Feigley C.E., Ahmed M.R., Hussey J.R., *An investigation of air inlet types in mixing ventilation*, Build Environ., **42**, 3, 2007, p. 1089-1098.