Optimization of Natural Ventilation Openings in Mosques Based on Air Change Standards to Improve Prayer Comfort

Kumala Cahya Nurul Huda, Firninda Almas Augusta S, Intan Lathifatuzzahroh, Keysa Zafirah Ismail
Fakultas Sains dan Teknologi, UIN Maulana Malik Ibrahim, Malang, 65144, Indonesia
kumalacahya16@gmail.com

Abstract— **Thermal comfort in worship buildings, such as mosques, is very important to ensure that worshipers can worship solemnly and comfortably. Ulul Albab Mosque at Maulana Malik Ibrahim State Islamic University Malang is one of the buildings that require special attention in terms of natural ventilation. Its strategic location in the middle of the campus, as well as the high level of activity, makes this mosque a very important center of religious activities. However, the management of natural ventilation is often not handled properly, given the limited openings and obstructions from surrounding buildings. This study aims to optimize natural ventilation at the Ulul Albab Mosque to improve thermal comfort for users during worship activities. This research uses Computational Fluid Dynamics (CFD) simulation to model various scenarios of changes in ventilation openings. The simulation results show that the addition and strategic placement of incidental openings and vents in the mihrab, side, and back areas of the prayer room can significantly increase airflow. These additions can reduce areas with stagnant airflow and improve user comfort inside the mosque.**

Keywords— Natural Ventilation, Mosque, Thermal Comfort, Computational Fluid Dynamics (CFD)

I. INTRODUCTION

In Islam, Muslims are required to perform five daily prayers regardless of their busy schedules. Therefore, mosques or prayer rooms are available in many public places and areas with high population density to support the spiritual needs of Muslims.

The word "mosque" originates from the Arabic root "sajada, yasjudu, sujudan," which means "to bow." (al-Munawvir Dictionary, 1997:610). The term refers to a place of worship (noun derived from the verb "sujud"). For Muslims, the mosque is a sacred place that must be built, maintained, and developed in an orderly and planned manner, serving as a place of worship and a center for religious and social activities. Strengthening the spread of Islam, improving the quality of religious life, and enhancing the devotion of Muslims to Allah SWT will, in turn, increase their contribution to national development (Syahruddin, Hanafie, Abdullah Abud, Mimbar Masjid, Jakarta: Haji Masagung, 1986, p. 339).

Campuses are places with high user activity. Campus mosques provide facilities for Muslims to perform prayers amid their academic schedules. Ulul Albab Mosque at UIN Malang not only serves as a place of worship but also functions as a gathering space for students to work on group projects.

With the variety of activities occurring in Ulul Albab Mosque, aspects such as thermal comfort and air circulation in the prayer room need attention. Air circulation is part of the thermal context, supported by openings installed in the building and the positioning and spacing of inlets and outlets.

One aspect of thermal comfort is air velocity. A good airflow velocity is 0.25 m/s or higher, depending on indoor air temperature conditions (SNI 03-6572-2001, 2001). Thermal comfort standards vary by environment, leading to different individual perceptions (Supono, 2019). Key indicators of thermal comfort include air humidity and room temperature (ASHRAE, 2013). Ideally, ventilation inlets should be at the same height as room users, while outlets should be placed higher to facilitate the exit of CO_2 (Mediastika, 2002). The inlet-outlet dimension ratio significantly impacts the ventilation system, with the optimal inlet area being about 12% of the land area (Tantasavasdi, 2001).

Ulul Albab Mosque at UIN Malang functions as both a place of worship and a center for academic and creative activities. To improve comfort for students and lecturers during worship, natural ventilation opening systems must be considered. Factors such as room orientation, layout, and airflow patterns are analyzed to identify the best strategies to enhance healthy and comfortable air circulation for users.

This approach is expected to create a conducive worship environment for all mosque users and contribute to sustainable solutions that integrate religious values with sustainable architectural design principles, benefiting long-term well-being and environmental sustainability.

II. METHODS

This study employed a mono-method quantitative approach, involving direct observation and measurements as the main data sources. Data were obtained from observations and measurements.

Measurements were conducted over seven consecutive days during prayer times (Dhuhr and Asr) using an anemometer to measure wind speed in m/s.

EXISTING CONDITIONS

- The direction, movement, and speed of the wind are uneven and do not circulate throughout the room.

ANALYSIS

- Simulation results using Autodesk CFD show that the wind speed in the mosque has an average speed of 0.049 m/s, while the ACH standard shows a minimum of 0.4 m/s.
- Air circulation in the mosque space is below the standard determined by the ACH calculation, due to many corners still having very weak airflow, even reaching 0 when measured in the field using an anemometer.
- The research used a Mono-Method approach and the method used is quantitative.

OPTIMIZATION

- Optimization of inlet opening widening and the addition of windows for both inlet and outlet on the building was simulated using Autodesk CFD.

OPTIMIZATION RESULTS

- The results of the first and second opening optimizations showed average data of 0.2 – 0.35 m/s, still unable to reach the mosque ACH standard of 0.4 m/s with 2 to 3 air exchanges per hour.

ANALYSIS

- The inability to reach the standard is due to the existing mosque condition, which is surrounded by 4-story buildings that cause turbulent airflow and reduce wind speed in the mosque.
- This means that the existing building layout does not support optimal airflow, making the air circulation simulation results even lower.

FINAL RESULTS

- The placement of inlet and outlet openings that are not aligned caused turbulence inside the room, resulting in air circulation not being in the same direction.
- The mosque still does not meet the air exchange needs due to poor wind entry and flow.
- An alternative is to increase the number of inlets and outlets or enlarge window dimensions to bring the airflow closer to the standard ACH value to meet adequate air circulation evenly throughout the room.

Field data on indoor airspeed were analyzed using the ACH formula (ASHRAE 62.1 and 62.2) to determine air exchange rates per hour. This involved calculating the natural ventilation level (Q) divided by room volume (V). Room volume was also calculated using the formula below:

Natural Ventilation Level Formula

$Q = 0.025 \times A \times v$

Keterangan:

A = luas bukaan (m2)

v = kecepatan angin bukaan (m/s)

0.025 = pengkali

ACH Calculation Formula

$ACH = (Q/V) \times 3600$

Keterangan:

Q = level ventilasi alami (m3/s)

V = volume ruang (m3)

The analysis continued with simulations using Autodesk CFD to assess opening width, inlets, and outlets in the mosque, based on collected data, and determine whether airflow met standards.

The procedure involved preparing measuring tools, the prayer room and its surroundings, and four researchers who measured wind speed. Measurements were conducted in the prayer areas on the first and second floors using a 6-meter grid system. Wind speed measurements were taken at designated grid points, as shown in Fig. 1.

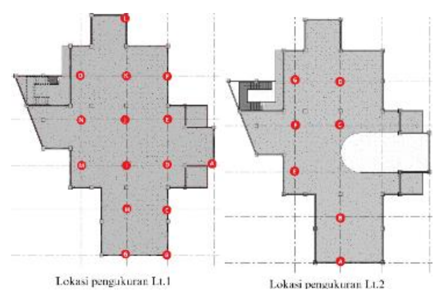
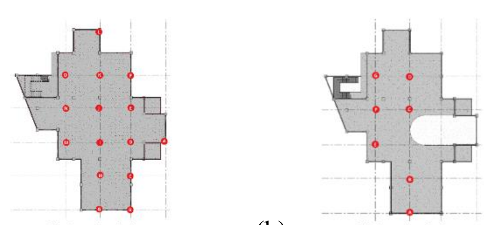


Fig. 1. Prayer Area of Ulul Albab Mosque and Measurement Points (Source: Author's Documentation, 2024)

The next stage involved utilizing the previously collected data as a reference and foundation for simulations using Autodesk CFD software.

III. Result and Discussion



(a) (b)

Fig. 2. (a) Measurement Point Locations on the First Floor; (b) Measurement Point Locations on the Second Floor

Measurements were taken from April 25 to May 1, 2024, using anemometers at marked points. The first-floor prayer room area is 464.57 m2, and the second-floor area is 388.09 m2.

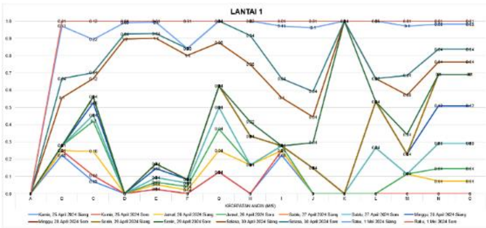


Fig. 3. Observation Results Graph of Ventilation on the First Floor

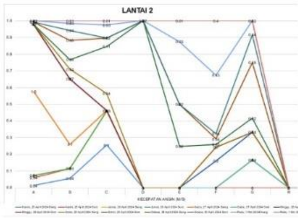


Fig. 4. Observation Results Graph of Ventilation on the Second Floor

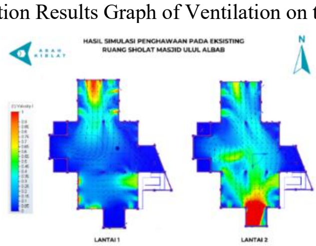


Fig. 5. Simulation Result Diagram of Existing Ventilation Using Autodesk CFD Software

Based on the measurements above, it was found that the ventilation within the prayer area does not yet meet the established standards as determined by the ACH (Air Changes per Hour) calculation. This is due to the presence of several corners within the space where airflow is extremely weak, with measured values reaching zero during field observations. Considering the area and the number of congregants, the following calculations were obtained:

Where:
Mosque volume = 3.593.2 m3
Number of worshippers =
Space requirement per individual during prayer = 0.96m2
Total prayer area = 776.214 m2
Number of worshippers at Ulul Albab Mosque = 776.214 m2:0,96m2 = 808 worshippers
Airflow rate /person = 8 – 10 l/s
Total required airflow rate
= 808 x 10 l/s
= 8080 l/s
= 484.8 m3/min
Formula for natural ventilation level
Q = 0.025 x A x v
Thus, the wind speed required for Ulul Albab Mosque is calculated as follows
484.8 m3/min = 0.025 x 776.214 m2 x v
v = 484.8 m3/min:19.4 m2
v = 0,4 m/s

During the simulation using Autodesk CFD, it was observed that the airflow on the first floor predominantly enters from the north, specifically through the main entrance, and moves westward toward the void opening, then rises to the second floor. A portion of the air also moves eastward, collides with the wall, and disperses in the rear area of the mosque. The air entering the second floor from the void opening on the first floor continues to flow southward.

Based on these measurements, the wind direction illustrated in Fig. 5 appears highly uneven and does not spread uniformly throughout the space. The highest wind velocity was recorded on the northern side of the mosque, ranging from 0.9 to 1 m/s, with the airflow traveling less than 3 meters. This airflow originates from the main entrance, which measures 1.7 meters in width and 1.9 meters in height, and moves southward before being obstructed approximately 6 meters from the opening. The illustration shows the airflow moving from north to south, with a portion diverting toward the staircase located on the eastern side of the mosque. However, the airflow becomes turbulent due to the absence of an outlet on the stairwell wall.

Following the analysis using Autodesk Forma and Autodesk CFD, it was concluded that the natural ventilation of Ulul Albab Mosque can be improved. A thorough evaluation of the spatial openings is necessary to achieve more efficient natural ventilation, including the addition of incidental ventilation and increasing the number of openings. Currently, the incidental ventilation area of Ulul Albab Mosque accounts for only 2.5% of the total floor area, which does not meet the minimum requirement of 5% as stated in the Indonesian National Standard (SNI). However, the total area of windows and doors amounts to 12% of the floor area, thereby complying with the SNI standard issued by the Ministry of Public Works, which sets a minimum of 10%.

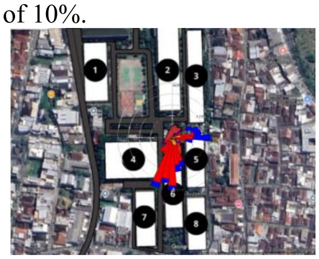


Fig. 6. Windrose Analysis Data from BMKG Malang City

Based on climate data from the Meteorological, Climatological, and Geophysical Agency (BMKG), the prevailing wind direction shown in Fig. 6 primarily flows from south to north and from east to west. Therefore, the inlet openings on the southern side can be optimized to enhance natural ventilation.

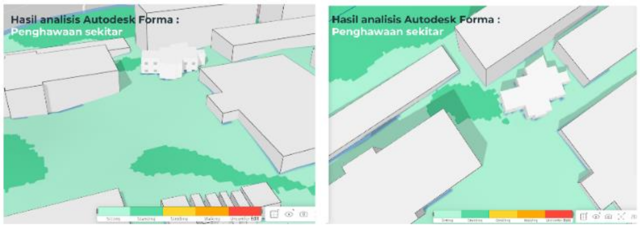


Fig. 7. Ventilation Analysis Data of the Area Using Autodesk Forma Software

The ventilation analysis using Autodesk Forma, as illustrated in Fig. 7, indicates strong wind flows approaching Ulul Albab Mosque from the west (open field and parking area) and from the north (the road between Buildings A and B). As an alternative, the positioning of openings can be optimized by aligning them perpendicular to the west-east wind direction.

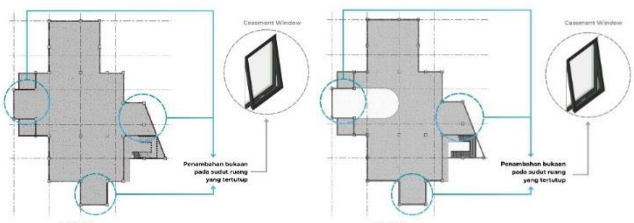
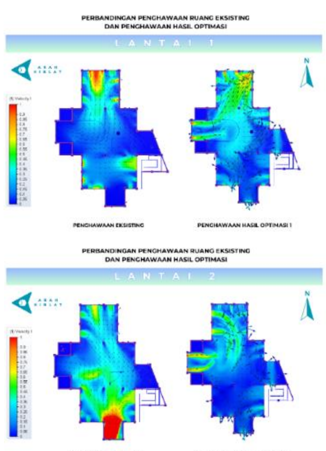


Fig. 8. Wall Position with Added Openings

In the first optimization trial, based on the evaluation of several alternative options, additional openings were introduced in specific areas as shown in Fig. 8. This decision was made due to the presence of several zones within the prayer hall that lacked effective ventilation. Furthermore, the intervention was informed by the broader ventilation analysis of the surrounding area.



(a)

(b)

Fig. 9. Simulation Result Diagram of Optimization 1 Using Autodesk CFD Software on First Floor (a) and Second Floor (b)

From the first ventilation optimization trial, improvements in airflow distribution were observed, indicating a more optimal condition overall. However, certain areas remained suboptimal, as indicated by the dark blue regions in the diagrams in Fig. 9(a) and Fig. 9(b), where airflow measurements registered at zero, signifying the absence of air movement.

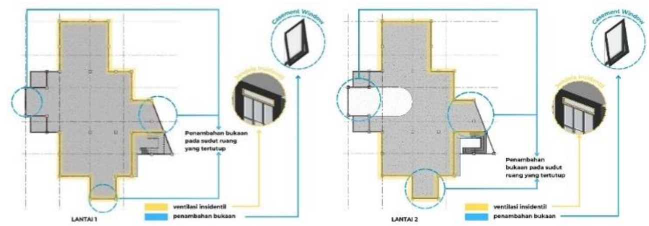


Fig. 10. Wall Position with Added Openings

Due to the identified inefficiencies in the first optimization simulation, an alternative strategy was implemented in addition to adjusting the position of the openings—namely, the addition of incidental ventilation on selected sides, as indicated by the yellow areas in Fig. 10. Incidental ventilation helps to expel hot air from the interior, as warm air naturally rises toward the ceiling. Therefore, these incidental windows were positioned at the uppermost section of the passive windows along the wall.

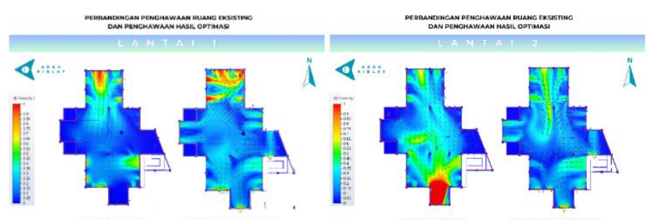


Fig. 11. Simulation Result Diagram of Optimization 2 Using Autodesk CFD Software on First Floor (a) and Second Floor (b)

The results of the second optimization diagram indicate a significant improvement compared to the first simulation trial. This is evidenced by the reduced area of poor ventilation, as shown by the diminished dark blue regions in Fig.s 11(a) and 11(b). The addition of an opening in the mihrab area now functions as an inlet, allowing air to circulate and eliminating stagnant airflow in that zone. Openings added to the sides of the prayer hall serve as outlets, preventing the recirculating airflow pattern observed in the previous (existing) condition. Furthermore, the new openings at the rear of the prayer hall act as both inlets and outlets, promoting continuous airflow and eliminating the previously stagnant and circular airflow in that area.

TABLE I.
COMPARISON BETWEEN EXISTING CONDITIONS AND OPTIMIZATION RESULTS

No	ACH Standard	Condition	Simulation Results	Suitability
A	0,4 m/s	Existing	The average wind speed is **0.049 m/s** with **uneven airflow distribution** and **significant turbulence** occurring at one point.	Not suitable
B	0,4 m/s	First optimization	The average wind speed ranges from **0 to 0.35 m/s**, with **uneven airflow distribution** compared to the existing condition, showing **variable and unsteady wind movement**.	Approaching ACH standard
C	0,4 m/s	Second optimization	The average wind speed ranges from **0.2 to 0.35 m/s**, with **more even airflow distribution** than the first optimization, and **directed wind movement**.	Approaching ACH standard

The optimization process was carried out in two stages to achieve more optimal results. However, the outcomes of both the first and second opening optimizations still failed to meet the mosque's ACH (Air Changes per Hour) standard, which requires an airflow velocity of 0.4 m/s with 2 to 3 air exchanges per hour. This shortfall may be attributed to the mosque's existing condition, which is adjacent to a four-story building. The proximity of this tall structure likely causes wind turbulence and results in reduced wind speed by the time it enters the mosque. Additionally, the types of openings used are not well-suited to support sufficient wind velocity, further slowing down the airflow and contributing to suboptimal ventilation performance inside the space.

IV. CONCLUSION

ACH is the air exchange rate per hour, calculated by user needs, room volume, and wind speed. Proper ventilation achieving the right air exchange enhances comfort in a space. Ulul Albab Mosque lacks optimal ventilation. Airflow speed and movement do not meet ACH standards, resulting in discomfort and increased reliance on artificial cooling like fans, which are inefficient.

ACH calculations guided the ventilation optimization. Meeting ACH standards ensures thermal comfort. Two optimization attempts were made but still fell short of the required wind speed. One cause is the existing condition of the mosque, including differences in indoor and outdoor wind speeds. Thus, further research is needed with alternative approaches considering the existing building conditions.

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