CFD Analysis to Optimize Air Quality in Aeroponic Tower Garden

ESAM JASSIM, BASHAR JASEM, FARAMARZ DJAVANROODI
Mechanical Engineering,
Prince Mohammad Bin Fahd University,
1664, 31952 Al-Khobar,
KINGDOM OF SAUDI ARABIA

Abstract: - Aeroponic tower gardens represent an innovative approach to urban agriculture, utilizing vertical structures to cultivate plants without soil. Research highlights the efficiency of this method in optimizing resource usage, such as water and space, compared to traditional farming. Studies emphasize increased crop yields, faster growth rates, and reduced environmental impact. Additionally, aeroponic systems enable precise nutrient delivery to plants, fostering optimal growth conditions. While the technology shows promise, further investigations are needed to address potential challenges and optimize its application in diverse agricultural settings. The study presents the simulation of air temperature and humidity distribution in a closed chamber of the vertical farm for optimization purposes. The environmental conditions inside the chamber are optimized for plant growth, to maintain the temperature at a range of 18-24 °C temperature and the relative humidity at a range of 75-85 %. The paper also discusses the challenges, limitations, and future recommendations for improving the system. Simulation of the system, on the other hand, is crucial not only for prototype fabrication but also for the optimization of sensor locations. The simulation of the tower garden system was performed using ANSYS-FLUENT to portray how the airflow inside the tower garden's enclosed environment was distributed. The system parameters such as humidity and temperature were set to meet the plants' growth requirements, and the system was treated as the steady state with an adiabatic boundary. Based on the simulation results, the best design recommended is to use two humidity and temperature sensors, one at the top and the other at the core of the prototype. Hence, a complete mapping of temperature and humidity distribution that is critical for plant growth would be occurred.

Key-Words: - Vertical Farming, CFD, Aeroponic, Air Quality, HVAC, Humidity.

Received: March 16, 2024. Revised: August 19, 2024. Accepted: September 11, 2024. Published: October 7, 2024.

1 Introduction

As the population of the globe exponentially rises, the demand of providing food becomes a serious concern, particularly in crowded metropolitan regions, [1]. Projections of food security have been addressed in the past two decades through numerous literatures, [2], [3], [4], [5]. The global demand for food is expected to increase up to 56% by 2050, [6], ringing the alarm bell of hunger risk on one hand and promoting the idea of Vertical Farming (VF) on the other hand.

Vertical farming (VF) is a process of producing food by employing a vertical dimension system, [5]. Unlike traditional horizontal farming, vertical farming can adjust the factors that affect plant growth, such as light, temperature, humidity, carbon dioxide, water, and nutrients. This allows for precise and sustainable production of high-quality and fresh crops all year round. It utilizes indoor farming systems in a such manner that every ecological component can be monitored and managed feasibly, [7]. It can also be an innovative method to alleviate greenhouse gas emissions and improve the urban environment by incorporating plants into walls and structures, [7], [8]. Vertical gardens contribute to mitigating the impact of deforestation as well as the urban heat island. The former is done by increasing the forest carbon stocks while the latter occurs by reducing the solar radiation and heat transfer across the surrounding area, [8]. Other pros of VF can be summarized as follows:

- Plants are capable to filtrate air pollutants and improve the Oxygen/Carbon monoxide ratio.
- They can lower the temperature through evapotranspiration, which is the process of water evaporation and transpiration from plant leaves.

In tall buildings or interior structures, plants could grow in layers that are stacked vertically. Such a Vertical growth scenario is already successful even in advanced urban constructions.

Analysis studies have estimated that a 30-story skyscraper in New York City can sustain food sufficiently for up to 50,000 people, which positively impacts the ecological, environmental, and agricultural systems, [1]. Hence, the application of VFs can be easily established in vertically sloped surfaces, like sky-scripture buildings in urban areas, where there is a limited amount of land and space. However, weather conditions such as temperature and humidity play a significant role in hindering such projects, demanding extensive studies on VF both numerically and experimentally.

The main challenge in optimizing the VF system is the difficulty of arranging the conventional irrigation frameworks with mechanical-electrical control to apply water for a set amount of time. However, due to their restricted control capabilities, these frameworks find it challenging to attain high water consumption efficiency. Real-time monitoring is the only way to accomplish timely and accurate management of important environmental variables, such as air temperature, soil media temperature, relative air humidity, water level, soil moisture level, soil pH (alkalinity and acidity in soils), and light intensity.

Simulation of the indoor environment should consider many elements like the intensity of light required by the plant, the appropriate air temperature and humidity circulated, the level of carbon dioxide concentration, the amount of water needed, and the nutrients the plant can survive.

Proper air distribution and effective ventilation can be considered as major factors in air quality improvement. However, the pattern of airflow distribution is the prominent aspect in the design of air-conditioning systems, [9].

Future research on aeroponic farming should focus on optimizing nutrient delivery systems to enhance plant growth and yield. Additionally, studies should investigate the potential for integrating advanced technologies such as sensors and automation to monitor and control environmental conditions, aiming to improve resource efficiency and sustainability, [10]. Exploring the scalability of aeroponic systems for commercial agriculture and their economic viability compared to traditional farming methods will also be crucial. Finally, research should examine the impact of aeroponic farming on plant health, including pest and disease management, to ensure consistent and high-quality crop production.

In the present study, the indoor air distribution under forced ventilation is described and the indoor air quality is predicted, which provided a basis for the evaluation of ventilation conditions in a vertical gardening Unit. The simulation aims to present a complete mapping of temperature and humidity distribution in the unit. The study also addressed the optimization factors that influence the performance of the controller, which ultimately impact the growth succession.

2 Governing Equations

CFD simulation of airflow in the 3D VF envelope is obtained by simultaneously solving the continuity, the x, y, z momentum, and the energy equations. Characterization of fluid flow stream is described by the continuity and momentum equations while the energy equation can be incorporated only when energy interaction occurs between the system and its surroundings for optimization purpose of computation time, [11], [12]. However, in our simulation, we have assuming non adiabatic walls, meaning that there is heat transfer between the system and the surrounding resulting in variation in the inner temperature.

The general expression of continuity, momentum and energy equations in deferential form is defined below:

Continuity: $$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho v)}{\partial y}+\frac{\partial(\rho w)}{\partial z}=0 \qquad (1)$$

Where ρ stands for air density. u, v, and w the velocuty components in x, y, and z coordinates respectively.

x-Momentum: $$\frac{\partial(\rho u)}{\partial t}+\frac{\partial(\rho u^2)}{\partial x}+\frac{\partial(\rho uv)}{\partial y}+\frac{\partial(\rho uw)}{\partial z}=-\frac{\partial p}{\partial x}+\frac{1}{Re}\left(\frac{\partial \tau_{xx}}{\partial x}+\frac{\partial \tau_{xy}}{\partial y}+\frac{\partial \tau_{xz}}{\partial z}\right) \qquad (2)$$

y-Momentum: $$\frac{\partial(\rho v)}{\partial t}+\frac{\partial(\rho uv)}{\partial x}+\frac{\partial(\rho v^2)}{\partial y}+\frac{\partial(\rho vw)}{\partial z}=-\frac{\partial p}{\partial y}+\frac{1}{Re}\left(\frac{\partial \tau_{yx}}{\partial x}+\frac{\partial \tau_{yy}}{\partial y}+\frac{\partial \tau_{yz}}{\partial z}\right) \qquad (3)$$

z-Momentum: $$\frac{\partial(\rho w)}{\partial t}+\frac{\partial(\rho uw)}{\partial x}+\frac{\partial(\rho vw)}{\partial y}+\frac{\partial(\rho w^2)}{\partial z}=-\frac{\partial p}{\partial z}+\frac{1}{Re}\left(\frac{\partial \tau_{zx}}{\partial x}+\frac{\partial \tau_{zy}}{\partial y}+\frac{\partial \tau_{zz}}{\partial z}\right) \qquad (4)$$

Where τ is the shear stress, p is the fluid pressure, and *Re* is the Reynolds number.

Energy:

$$\frac{\partial(E_T)}{\partial t}+\frac{\partial(uE_T)}{\partial x}+\frac{\partial(vE_T)}{\partial y}+\frac{\partial(wE_T)}{\partial z}=-\frac{\partial(up)}{\partial x}-\frac{\partial(vp)}{\partial y}-\frac{\partial(wp)}{\partial z}-\frac{1}{Re.Pr}\left(\frac{\partial q_x}{\partial x}+\frac{\partial q_y}{\partial y}+\frac{\partial q_z}{\partial z}\right)+\frac{1}{Re}\left[\frac{\partial}{\partial x}\left(u\tau_{xx}+v\tau_{xy}+w\tau_{xz}\right)+\frac{\partial}{\partial y}\left(u\tau_{yx}+v\tau_{yy}+w\tau_{yz}\right)+\frac{\partial}{\partial z}\left(u\tau_{zx}+v\tau_{zy}+w\tau_{zz}\right)\right] \qquad (5)$$

Where E_T is the energy transport per unit volume, q is the rate of heat flux, and Pr is the Prandelt number.

3 Simulation and Mesh Dependency

In this study, a rectangular section of 1.5 m length, 1 m width, and 1.56 m height is constructed through CAD software due to its ability to capture most of the design intent in the part features. Hence, modifying process of the part features becomes more feasible. The simulation model is also supplied with an inlet and outlet duct for air supply and exhaust, respectively. However, the analysis ignored the thickness of the wall surfaces since it does not have any significant impact on the flow field.

Construction art of computational grid in CFD is crucial and considered as most important and time-consuming part in simulation process. The quality of the grid is prominent since it plays a direct role in the quantification of simulation results, regardless of the solver used for simulation.

An unstructured grid with tetrahedral elements is employed during the meshing process, as seen in Figure 1. For grid optimization and result accuracy purposes, a mesh independence verification test was performed. Models with three different number of grids, namely 509984, 240080, and 329723, respectively, were selected for simulation. The average humidity values at various selected points were compared and it showed that mesh with 329723 grids is optimum since the humidity value was less than 5% in comparison to the case of 509984 while the error approaches 8% when the number of grids drops to 240080. Hence, the system with 329723 grids was selected for simulation analysis.

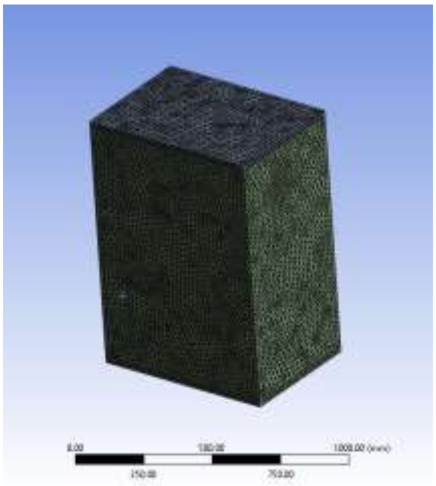


Fig. 1: Elements Mesh for The System

4 Results and Discussion

The main objective of the simulation is to study the indoor temperature and humidity distribution so that the location of the sensors could be optimize. Such optimization will enhance the controller performance as well as minimize the energy consumption in the A/C system. Figure 2 illustrates the air temperature distribution along the entire space of the VF. Vortexes are formed in the core of the system, which the plants' location is. The low-temperature region is predicted to be near the air supply duct where the A/C system is installed. However, the temperature of the air in the space that the plants occupied is around 20.5ºC, which is reasonable. It is noticed from the figure that although the air exhaust portion is located near the supply duct, air stream at high temperatures is mainly discharged outside.

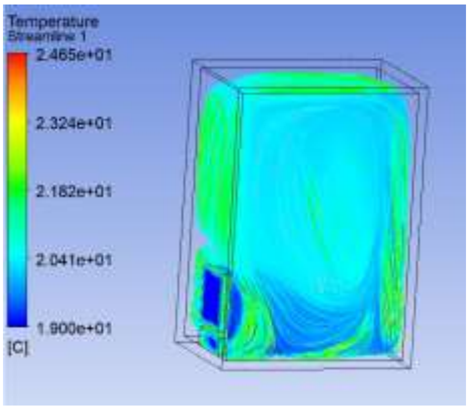


Fig. 2: Air Temperature Streamline

Figure 3 shows the moisture content distribution of the central section under the same ventilation mode. The range of humidity observed in the figure characterizes the formation of water mist. It can also be concluded from Figure 3 that the humidity at the central section is related to the speed of the air supply, and it concentrates near the wall region.

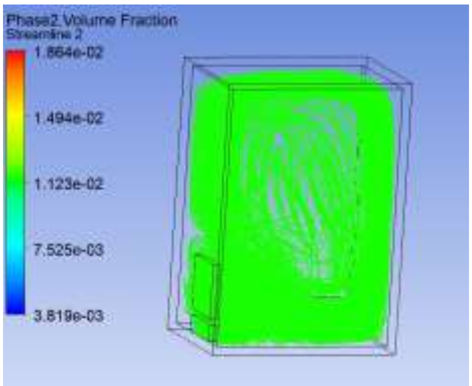
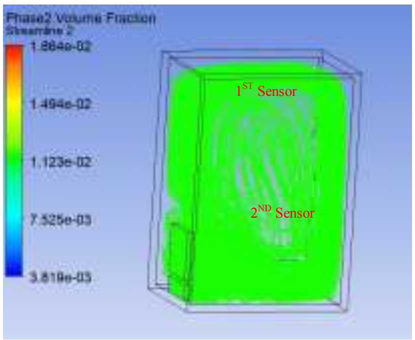
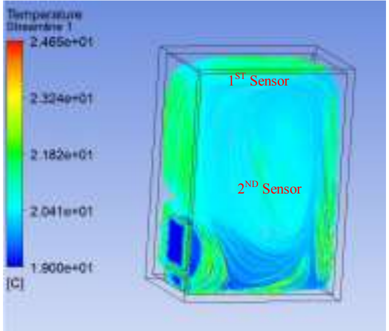


Fig. 3: Water Vapor Streamline

To grow the plants effectively in the VF, it is recommended to install at least two humidity sensors, one of them in the core near the plants (Figure 4a). An extra temperature sensor could assist (but is not essential) in enhancing the system operation performance. In such a case, the proposed location of the second sensor is placed as depicted in Figure 4b.



(a) Humidity sensors



(b) Temperature sensors

Fig. 4: Recommended placement of sensors

5 Conclusion

In this paper, we established a mathematical model and used ANSYS FLUENT software to simulate the air distribution and quality of Vertical Farming operated on solar energy. The simulation is important to figure out the number and proper location of humidity and temperature sensors that should be installed in the system for control purposes. The results indicated that ventilation configuration has a large influence on the distribution, which proposes careful installation of temperature and humidity sensors. Since a split type AC system is used for conditioning the air of the VF, the installation position of the supply duct, exhaust duct, plant placement, and indoor distribution are prominent factors for humidity and temperature field. It is, however, recommended to utilize central air conditioning with fresh and primary return air systems to improve the indoor temperature and humidity distribution as well as enhance the air quality and controller performance.

Nomenclature

CFD Computational Fluid Dynamics
VF Vertical farming
E – volumetric energy transport (J/m^3)
q– rate of heat flux (W/m^2)
t – time (sec)
τ – shear stress (N/m^2)
u, υ, w – fluid velocity (m/s)
ρ – flow density (kg/m^3)

Acknowledgement:
The author gratefully acknowledges the support provided by Prince Mohammad Bin Fahd University for facilitating the utilization of the resources and equipment to complete this work.

Declaration of Generative AI and AI-assisted Technologies in the Writing Process
During the preparation of this work the authors used ChatGPT in order to improve the readability and language of the manuscript. We, as the authors, have reviewed and edited the content as needed and takefull responsibility for the content of the publication.

References:

[1] Van Dijk, M., Morley, T., Rau, M.L, A meta-analysis of projected global food demand and population at risk of hunger for the period 2010–2050, *Nat Food*, Vol. 2, 2021, pp. 494–501. https://doi.org/10.1038/s43016-021-00322-9.

[2] Parry, M. L., Rosenzweig, C., Iglesias, A., Livermore, M. & Fischer, G., Effects of climate change on global food production under SRES emissions and socio-economic scenarios, *Glob. Environ. Change*, Vol.14, 2004, pp. 53–67. https://doi.org/10.1016/j.gloenvcha.2003.10.008.

[3] Baldos, U. L. C. & Hertel, T. W., Debunking the ‘new normal’: why world food prices are expected to resume their long-run downward trend, *Glob. Food Sec.*, Vol. 8, 2016, pp. 27–38.

[4] Alexandratos, Nikos & Bruinsma, Jelle, World Agriculture towards 2030/2050: The 2012 Revision, *Food and Agriculture Organization of the United Nations*, 2012, [Online]. https://www.fao.org/4/ap106e/ap106e.pdf (Accessed Date: August 20, 2024).

[5] Kamil A. Khalaf, Ahmed Gamil, Bashar Attiya, Joel Cuello, Exploring the potential of concentrating solar power technologies for vertical farming in arid regions: The case of Western Iraq, *Energy for Sustainable Development*, Vol. 77, 2023. https://doi.org/10.1016/j.esd.2023.101310

[6] Tomoko Hasegawa, Shinichiro Fujimori, Kiyoshi Takahashi and Toshihiko Masui, Scenarios for the risk of hunger in the twenty-first century using Shared Socioeconomic Pathways, *Environmental Research Letters*, Vol. 10.1, 2015, 014010. DOI: 10.1088/1748-9326/10/1/014010.

[7] Holt-Giménez, E. & Altieri, M. A. Agroecology, food sovereignty, and the new green revolution, *Agroecol. Sustain. Food Syst*, Vol. 37, 2013, pp. 90–102.

[8] Ling, Tzen-Ying & Chiang, Yi-Chang, Well-being, health and urban coherence-advancing vertical greening approach toward resilience: A design practice consideration, *Journal of Cleaner Production*, Vol. 182, 2018, pp. 187-197. https://doi.org/10.1016/j.jclepro.2017.12.207

[9] Esam Jassim, Improvement of Indoor Air Distribution by Utilizing Small Fans Powered by Solar Energy, *International Journal of Computational Physics*, Series 1(2), 2017, pp. 1-8. DOI: 10.29167/A1I2P1-8.

[10] Yi Lin Teo, Yun Ii Go, Techno-economic-environmental analysis of solar/hybrid/storage for vertical farming system: A case study, Malaysia, *Renewable Energy Focus*, Vol. 37, 2021, Pages 50-67. https://doi.org/10.1016/j.ref.2021.02.005.

[11] Yahya, O., Yahya, G., Al-Omair, A., Yahya, E., Jassim, E., Djavanroodi, F., Aeroponic tower garden solar powered vertical farm, *International Conference on Advanced Topics in Mechanics of Materials, Structures and Construction*, Vol 31, 2023, Khobar, Saudi Arabia, pp. 287-298. https://doi.org/10.21741/9781644902592-30.

[12] Alshammari A, Djavanroodi F, Jassim E (2021), Numerical simulation of the erosion phenomenon at the knee tube at different angles using DOE method, In: 7th World Congress on Mechanical, Chemical, and Material Engineering (MCM'21). Prague, Czech Republic, pp 1–7. DOI: 10.11159/icmie21.110.

Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

The authors equally contributed to the present research, at all stages from the formulation of the problem to the final findings and solution.

Sources of Funding for Research Presented in a Scientific Article or Scientific Article Itself

No funding was received for conducting this study.

Conflict of Interest

The authors have no conflicts of interest to declare.