

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN- 31261, SAUDI ARABIA

DEANSHIP OF GRADUATE STUDIES

This thesis, written by **MAHMOUD MOHAMMED MAGZOUB** under the direction of his thesis advisor and approved by his thesis committee, has been presented and accepted by the Dean of Graduate Studies, in partial fulfillment of the requirements for the degree of **MASTER OF SCIENCE IN ARCHITECTURAL ENGINEERING**



Dr. Laith A Hadidi
Department Chairman

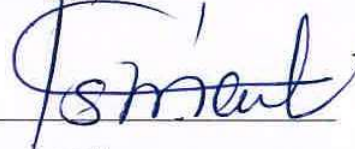


Dr. Suliman Saleh Al-Homidan
Dean of Graduate Studies

Date



Dr. Mohammed Alhaji Mohammed
(Advisor)



Dr. Ismail Mohammad Bedaiwi
(Member)



Dr. Mohammed Saeed Al-Homoud
(Member)



**THE THERMAL ASSESSMENT OF ENERGY ACTIVE
WINDOW SYSTEM IN BUILDINGS IN HOT CLIMATES**

BY

MAHMOUD MOHAMMED MAGZOUB

A Thesis Presented to the
COLLEGE OF GRADUATE AND INTERDISCIPLINARY STUDIES
KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE

In

ARCHITECTURAL ENGINEERING

DECEMBER 2022

© MAHMOUD MAGZOUN

2022

DEDICATION

[This research is dedicated to my father, Mohammed Majzoub and my mother, Ramah Hassan who have been the source of supports and inspiration in my life and career.

Also, it dedicated to my brother, Engr. Moied who has been guiding me in my life as well as teaching me throughout different educational stages. His supports and guidance are extremely appreciated. In addition, I appreciate the supports from the other brothers Dr. Abdurrahman, and Dr. Ahmed and my lovely sister Dr. Wejood,

Of course, this research is dedicated to my nation, the nation of prophet Mohammed- peace be upon him-, that I hope it could contribute in its growth, I also dedicate this research to my great country Republic of Sudan, my home and my only shelter.]

ACKNOWLEDGMENTS

First and foremost, I thank almighty Allah for granting me strength, wisdom, confidence, and perseverance to carry out and complete this research work. In the absence of His grace and mercy, I would not be able to complete this task .

I would like to thank my supervisor gratefully and sincerely, Dr. Mohammed Mohamed for his guidance, support and encouragement throughout my research and my academic years. In addition, I would like to express my gratitude to the faculty members of the department of Architecture Engineering, especially, Dr. Ismail Budaiwi , Dr. Mohammad Saad Al-Homoud for encouraging me during my academic years in this major; and would like to send my greeting to my life guidance Dr. Essam Shawat, Dr. Ahmed Eweda, Dr. Hani and Dr. Abdul Mujeebu,.

I would like to thank my family gratefully and sincerely whose were concerned, supportive, and motivated me to complete my academic years. Without the efforts from my parents (Mr. Mohamed Majzoub and Ms. Remah Hassan), my brothers (Moied, Abdurrahman, Ahmed) and my dear sister (Wejood), I would not be able to complete my academic years .

Finally, I want to thank my friends who shared the information to complete this research as well as my college years .

TABLE OF CONTENTS

ACKNOWLEDGMENTS	III
TABLE OF CONTENTS.....	IV
LIST OF TABLES	VI
LIST OF FIGURES	VII
ABSTRACT	XI
ملخص الرسالة:.....	XIII
CHAPTER 1	1
INTRODUCTION.....	1
1.1 - Background	1
1.2- Problem Statement.....	4
1.3 – Aim & objectives.....	5
1.4 – Scope and limitation	6
CHAPTER 2	7
LITERATURE REVIEW.....	7
2.1 – Windows and building envelope characteristics	7
2.1.1 Aerodynamics characteristics	7
2.1.2 –Thermal characteristics of Window Systems.....	9
2.1.3 –Thermal characteristics of Curtain Wall Systems.....	13
2.1.4 –Heat transfer characteristics of Curtain Wall Systems	18
2.2- Exhaust Air Recovery (EAR) system in buildings	19
2.3- EAW in buildings.....	22
2.4- Other related windows system technologies in buildings	24
CHAPTER 3	28
METHODOLOGY.....	28
3.1-Research Procedure	31
3.1.1- Experiment procedure.....	31
3.1.2- The CFD Simulation procedure.....	43

CHAPTER- 4	45
CFD SIMULATION PROCEDURE	45
4.1 Introduction	45
4.2- CFD Model Development	50
4.3- Discretization (meshing) Scheme:	51
4.4- Boundary conditions of CFD simulation:	52
4.5- Governing Equations.....	53
4.6- Turbulence model in CFD simulations:	58
4.7- Simulation convergence	59
4.8- Simulation post-processing	60
CHAPTER- 5	61
CFD SIMULATION RESULTS	61
5.1- Simulation of alternatives:	66
5.2- Validating/benchmarking results with experimental data from literature:.....	70
5.2.1- Meshing sensitivity analysis:.....	72
5.2.2- Validation model:	75
5.2.3- DGEW in hot climate of Saudi Arabia	79
5.2.4- TGEW in hot climate of Saudi Arabia	91
5.3- EAW experiment implementation guideline in hot climate of Saudi Arabia:	93
5.4- EAW prediction guideline in hot climate of Saudi Arabia:	96
Chapter-6	101
Conclusion and recommendation	101
6.1-Recommendation for future work:	103
Reference	104
Vitae	112
Appendices:	114

LIST OF TABLES

Table. 1. First trial results Outdoor 50 °C, 2cm air gap.....	36
Table. 2. First trial results	38
Table. 3. Second trial results for the 2 nd model.....	41
Table. 4. Third trial results for the 2 nd model	45
Table.5. Trial 05 to test the hypothesisble.12. Trial 05 to test the hypothesis.....	45
Table.6. Experimental model 03 specification -Model Noa	46
Table.7. Meshing, boundary condition and solver specificationTable.13. Simulation material specification	47
Table.8. Summary of simulation results	47
Table.9. Experiment and simulation results for outdoor glazing.....	65
Table.10. Experiment and simulation results for outdoor glazing.....	65
Table.11. Result of CFD simulation for three variables/alternatives.....	68

LIST OF FIGURES

Fig. 1. Existing airflow window types:.....	13
Fig. 2. Research Methodology for testing the theory and different alternatives (ALT)	15
Fig. 3. Temperature and humidity controllers	19
Fig. 4. Experiment model 01.....	19
Fig. 5. Temperature controller setting method.....	20
Fig. 6. Humidity controller installing and setting method	21
Fig. 7. Temperature controller installation method	21
Fig. 8. First trial results-Indoor glazing surface temperature.....	22
Fig. 9. Second trial results - Indoor glazing surface temperature at outdoor 80°C	23
Fig. 10. Experiment model 02 components illustration.....	24
Fig. 11. Experiment model 02.....	25
Fig. 12. Experiment model 02.....	25
Fig. 13. Second model 1 st trial results- Indoor glazing surface temperature	26
Fig. 14. Second model 2 nd trial results.....	27
Fig. 15. Second model 3 rd trial.....	28
Fig. 16. Second model 4 th trial results	29
Fig. 17. Fourth trial results for the 2 nd model	30
Fig.18. Fifth trial results for the 2 nd model	31
Fig. 19. Outer glass Temp. reading.....	32
Fig. 20. Flow air track in the gap.....	33
Fig. 21. Flow air track in the gap.....	35
Fig. 22. Trial 01 to test the hypothesis.....	36
Fig. 23 Trial 02 to test the hypothesis.....	37
Fig. 24. Trial 03 to test the hypothesis.....	38
Fig. 25. Trial 04 to test the hypothesis.....	39
Fig. 26. Trial 04 to test the hypothesis.....	40
Fig. 27. Trial 05 to test the hypothesis.....	40

Fig. 28. Trial 05 to test the hypothesis.....	42
Fig. 29. Trial 05 to test the hypothesis.....	42
Fig.30 Trial 05 to test the hypothesis.....	43
Fig.31 Trial 06 to test the hypothesis-Model Z.....	44
Fig.33 Experimental model 03 -Model Noa	46
Fig.32 Experimental model 03 -Model Noa	46
Fig.34 Experimental model 03 -Model Noa	47
Fig.35 Model 03 measuring points -Model Noa, before (right) and after (left) air blowing	48
Fig.36 Model 03 experiment results-Model.....	48
Fig.37 Model 03 experiment results-Model.....	49
Fig.38 Model 03 experiment results-Model.....	50
Fig.39 Model 03 experiment results-Model.....	50
Fig.40 Model 03 experiment results-Model.....	51
Fig.41 Model 03 experiment results-Model.....	51
Fig.42 Model 03 experiment results-Model.....	52
Fig.43 Model 03 experiment results-Model.....	52
Fig.44 CFD model Meshing	53
Fig.45 Air inlet properties	54
Fig.46 CFD governing equations.....	54
Fig.47 Material properties 02.....	56
Fig.48 Material properties 01	56
Fig.49 Air inlet properties	57
Fig.50 Air inlet velocity reading.....	57
Fig.51 Simulation iteration	58
Fig.52 Heat distribution among the chambers	59
Fig.53 Heat distribution among the chambers	59
Fig.54 Heat distribution among indoor glass.....	60
Fig.55 comparing experiment and simulation	60
Fig.56 Heat distribution among outdoor glass	61
Fig.57 comparing experiment and simulation	61

Fig.58 Solar calculation at month of May	62
Fig.59 Solar calculation at month of May	62
Fig.60 CFD results for alternatives	64
Fig.61 CFD results for alternatives	64
Fig.62 Validating CFD with experimental data from literature.....	66
Fig.63 TGEW model as per Zhang et al model	67
Fig.64 TGEW CFD results as per Zhang et al) inner (a). middle (b) outer (c).....	68
Fig.65 Velocity impact on glazing temperature for DGEW	69

LIST OF ABBREVIATIONS

Abbreviation	Definition
EAW	Energy Active Window
RA	Return Air
EA	Exhaust Air
CFD	Computational Fluid Dynamics
HVAC	Heating Ventilation Air Conditioning System
IAQ	Indoor Air Quality
ACH	Air Change Per Hour
VOC	Volatile Organic Compounds
CW	Curtain Wall
CWS	Curtain Wall System
VIP	Vacuum Insulation Panel
TCFS	Transparent Composite Façade System
LCA	Life Cycle Assessment
EAR	Exhaust Air Recovery
DGEW	Double Glazed Energy Active Window
TGEW	Triple Glazed Energy Active Window
TGW	Triple Glazed Window
EC	Electrochromic
AAMA	American Architectural Manufacturers Association
NFRC	National Fenestration Rating Council
THC	Temperature & Humidity Controller
T	Temperature

ABSTRACT

Full Name :Mahmoud Mohammed Majzoub

Thesis Title :THE THERMAL ASSESSMENT OF ENERGY ACTIVE WINDOW]
[SYSTEM IN BUILDINGS IN HOT CLIMATES

Major Field :Architectural Engineering]]

Date of Degree :[December-2022]

Building envelopes plays a vital role in reducing energy consumption in buildings, especially in heat and mass transfer, HVAC cooling load, infiltration rate, and exfiltration. Using a multi-layer glazing system, Energy Active Window (EAW) adapts window insulation technology to reuse low-grade air from the HVAC system. This technology makes the temperature at the internal surface of the window close to the indoor air temperature, which would minimize heat exchange between indoor and outdoor. It invests the relatively low temperature of return-air airflow in the air gap between glass panes of the windows or curtain system to reduce the temperature of the air gap and the stagnant air film on glass panels. The system uses two basic concepts related to window thermal design: firstly, moving air has a higher ability to reduce surface temperature than stagnant air; secondly, air resistivity has an inverse relationship with its temperature. The glass portion in any building envelope is considered weak, especially in high-rise buildings where the entire envelope is the source of enormous heat inlet. The Energy Active Window (EAW) solution does not affect the visual quality or reduce daylighting entering indoor space, and all the system components are hidden in a specific frame. This study attempted to reduce energy consumption by increasing the thermal resistivity of the curtain system without adding another glass panel, channeling the Return Air (RA) from the HVAC system into the curtain frame to reduce the temperature of the air gap and air film layer. The research methodology used in this study includes experiments and simulation to examine the heat exchange rate between outdoor and indoor building environments. A state-of-the-art CFD program has been used to simulate exhaust/return air behavior in the window system aerodynamically and thermally, to provide the expected reduction of surface temperature. When conducting CFD simulation and validated it with experimental setup detailly described in literature, results show a reduction of 4 to 7 °C based on

type of window, for both inner and outer pane when outdoor temperature is 45 degrees with less than 4% margin of error. Different components of EAW were tested with variety of velocities, air gap width, air volume, outdoor temperatures and using triple of double-glazing layer. Moreover, an implantation guideline was developed to help researchers to develop a solid setup with low margin of error in hot climate of Dhahran; a prediction guideline was developed also to give the optimum values to get best outcomes from EAW in hot climates.

Based on these results such a system would have high potential to reduce surface temperature of the window, a significant reduction of energy consumption is expected, without adding any tangible initial or running cost on stakeholders.

ملخص الرسالة:

الاسم الكامل: محمود محمد مجنوب

عنوان الرسالة: التقييم الحراري لنظام نوافذ الطاقة المتكيفة للمباني في المناخ الحار

التخصص: الهندسة المعمارية

تاريخ الدرجة العلمية: ديسمبر 2022

لا شك أن غلاف المبنى يلعب دوراً محورياً في تقليل استهلاك الطاقة في المباني، خاصة أحمال التبريد وانتقال الهواء من البيئة الداخلية إلى الخارجية، وانتقال الحرارة من خلال المواد بناءً على طبيعتها وتركيبها الكيميائي. لذلك يعد استخدام النظم الزجاجية متعددة الطبقات مع النوافذ المتكيفة للطاقة عاملاً مهماً في تبني نظام قادر على استخدام الهواء الراجع أو العادم من نظام التكييف. مثل هذه التكنولوجيا تساعد على جعل درجة حرارة السطح الداخلي للنوافذ قريبة من درجة حرارة الغرفة، مما يقلل من أثر عملية التبادل الحراري بين البيئة الخارجية والداخلية للمبنى. هذه التكنولوجيا تستغل أو تستثمر درجة الحرارة المنخفضة نوعياً للهواء الراجع أو العادم من نظام التكييف، فبدلاً من التخلص منه إلى الخارج، يمكن ببساطة استغلال هذا الهواء في تبريد سطح النوافذ الزجاجية من خلال ضخه في الفراغ الموجود بين طبقتي الزجاج. تعتمد هذه الفكرة على مبدئين أساسيين، الأول أنه كلما زادت سرعة الهواء، زادت قدرته على تبريد الأسطح، والثاني أن المقاومة الحرارية للهواء لها علاقة عكسية مع درجة حرارته.

يهدف هذا البحث لتقييم جدوى استخدام مثل هذا النظام أو الفكرة في أجواء المملكة العربية السعودية وقدرته على التكيف في الأجواء الحارة بشكل عام، ومعرفة أي تغييرات في التصميم أو صلب الفكرة قد يتطلبها استخدامه في الأجواء الحارة والرطبة. يأخذ البحث في عين الاعتبار تجريب عدة نماذج لمعرفة مدى جدواها، ومعرفة أفضل تصميم من ناحية المتغيرات المتعلقة بخصائص الهواء كالحرارة والسرعة والضغط، أو ما يتعلق بتصميم النافذة نفسها، كالمسافة الفاصلة بين لوحَي الزجاج.

تعتمد منهجية البحث على التجربة والمحاكاة الحاسوبية، حيث تم نمذجة التجربة عن طريق نظم ميكانيكا الموائع الحسابية، لمحاكاة النظام أو التجربة حرارياً وهوائياً لمعرفة الانخفاض المتوقع في درجة حرارة الأسطح. تظهر نتائج التجربة العملية عدم جدوى النظام في الأجواء الحارة، حيث على عكس المتوقع، تزداد درجة حرارة السطح الداخلي للنافذة بين 2 إلى 4 درجات. على صعيد آخر، تظهر النتائج المحاكاة بناءً على نماذج مأخوذة من الأبحاث السابقة نتائج إيجابية، في مدى 4 إلى 7 درجات انخفاض في درجة الحرارة، بناءً على المتغيرات التي تمت تجربتها أو محاكاتها حاسوبياً، بمعامل خطأ لا يتجاوز 4%. بناءً على النتائج الأبحاث السابقة، يمكن استنتاج حصول توفير معتبر في طاقة المباني، بافتراض صحة النتائج المبنية على الأبحاث السابقة ونمذجة ميكانيكا الموائع الحسابية، على أساس وجود معامل خطأ عالٍ في التجربة العملية.

CHAPTER 1

INTRODUCTION

1.1 - Background

There is no doubt that building envelope play a critical role in energy conservation in buildings; wall systems like curtain walls and cavity walls where always a rich source and topic for researchers and architectural manufacturers to develop it in many perspectives such as structural stability, visual ability, financial feasibility, and physical properties like moisture and heat transfer. Nonetheless, when it comes to windows and curtain walls and their heat transfer properties, all solutions were majorly limited to increased number of glass panes included within window frame, or pane type of material, or focusing on its resistance of solar radiation transmittance. This work aims to increase windows and curtain wall ability to resist heat transfer in unconventional way, by not adding additional glazing layer[1], [2], [3].

Window systems such as curtain walls have been critical and important element in design of buildings in general, and in skyscrapers functioned to serve as offices, that it gives the building occupant ability to enjoy view and sun lighting while they are within the indoor environment, so it was sort of clever way to get best of both worlds[3]. Moreover, such envelope system used to give architects to design the facade with minimum number of elements, on the other hand its relatively low dead load was very attractive for structural engineers to adapt such system, without increasing the structural section of the elements. Nonetheless, when it comes to its physical properties, particularly its heat transfer properties, it was considered as weakness point for such system and for the entire skyscrapers as category of building; however, using Energy Active Windows system (EAW) which uses return air (RA) or exhaust air (EA) to cool its surface temperature could change such a stereotype on these category buildings[4], [5].

Towers and skyscrapers are expected to be type of structure where EAW would be mainly used, having mentioned that, it can be noticed that in the last two decades, no architect or engineer thought that high-rise buildings such as ones built in Manhattan or San Francisco would have a chance to survive in the gulf and specifically Saudi Arabia. However, when Kingdom Tower in Riyadh and Burj Al Arab in Dubai were built, it was amazing development, despite that many building experts still bet on its failure two or three years later. High rise buildings became a reality, and it proves its functionality and feasibility for business owners and real estate developers. Nevertheless, no modification nor development have been added to its architectural or engineering design while adapting such a concept from the west without considering architectural and environmental factors in the gulf region. It is not easy to distinguish the location of skyscrapers from their appearance; they do not get any impact of their surrounding culture or architectural style except Taipei 101. This eventually makes these buildings have no character from an architectural perspective and consume more energy than their footprint. One way to strengthen high-rise buildings' envelopes is using Energy Active Window (EAW), which can increase glazing resistance without affecting thermal visibility or adding tangible margin of cost. On the other hand, it could reduce thermal load building by reducing thermal transmittance[6], [7], [8].

Curtain wall in high rise buildings is considered as architectural system integrated with other building systems and components, nonetheless system require special considerations such as its ability to prevent heat transfer, waterproofing, architectural pleasance, daylighting, and its structural stability and resistance of wind lateral forces. Curtain wall and windows in general are made of two components, glass pane, and the aluminum frame; however, other elements can be added to serve a specified function such as louvers, sunscreens[9], [10].

The application of EAW contributes generally in lowering temperature of return-air flow within the cavity between glass panes of the windows or window ornament framework to diminish the temperature of the cavity and the stagnant surface film on glass boards. The framework employs two essential concepts related to window warm design: firstly, moving

air incorporates a higher capacity to diminish surface temperature than stagnant air; furthermore, air resistivity has an inverse relationship with the temperature[11], [12].

EAW can be sufficient substitute of convictional type of windows or curtain walls, especially where triple glazing pane is been used, that such a system could reduce the thermal requirement to use two panes only, which would reduce the initial cost of the curtain system, and the same applies when using quadruple glazing systems[13], [14].

Reducing energy consumption in buildings is significant factor during design, construction, and operation, nonetheless, the importance of such factor would increase and make notable challenge in hot climate like Saudi Arabia. In hot environments like middle east and north Africa, building sector is responsible for about 36% of the total energy consumption; having mention that, window to wall ratio would have significant role in cooling load, that enlarging window ratio from 10% to 90% would increase the cooling load by more than 70%. Generally, windows and curtain wall provide tremendous amount of problems comparing to cold climates, moreover, most solution these issues in the market or in literature review were based on high cost and complicated models, which make it difficult to prove its feasibility; for example, for single glass pane, increasing glass thickness on heating load largely, while its impact on cooling load is almost neglected, that to recusing heat transfer through window, it is require to use double glazing system with inert gas such as Krypton or air.

This thesis attempted to reduce energy consumption of window system by increasing the thermal resistivity of the curtain system without adding another glass panel, using Return Air (RA) from the HVAC system into the cavity between the two glasses to reduce the temperature of air gap and air film layer. The glass portion of any building envelope is considered a weak point, so in high rise buildings, the entire envelope is the source of enormous heat flux. Nonetheless, Energy Active Window (EAW) solution does not affect the visual quality or reduce daylighting transmittance into indoor space, as all of the system components that are capable of blocking daylight are hidden in a specific frame[13], [14]. EAW is adaptive window insulation technology using a multi-layer glazing system to reuse RA from the HVAC system instead of returning it to the HVAC system and re-cool it again

or discharging it directly to the ambient. This technology makes the temperature at the internal surface of the window close to the indoor air temperature, which would minimize heat exchange between indoor and outdoor. A window or glazing system can utilize the exhaust or return air in each conditioned room or floor instead of adding additional air-ducts and mechanical fans to gather the exhaust air from different conditioned zones[15], [16], [17].

1.2- Problem Statement

Gulf countries, especially Saudi Arabia, face continuous challenges of high energy consumption in buildings, which consume the capital of the country's primary resource that is oil. Extensive and fast steps are required to find rational and realistic solutions to protect this asset for other generations without degrading the current lifestyle of the people[18]. Saudi Arabia is leading the efforts to reduce energy consumption and reduce over-reliance on fossil fuel by launching a project like NOEM and THE LINE designed to be operated without fossil fuel. The entire country plans to give up on oil and other non-renewable energy sources by 2030, putting engineers and architects in very challenging situations to fulfil this vision. Sustainability of energy resources is essential to the prosperity of any country or society, regarding that, having scientific research which provide and examine prospective solutions to be adapted within the local environment is required [19][20].

Saudi Arabia in 2017 consumed 170.7 million Tonne of oil equivalent, and the breakdown indicates that government, residential and commercial buildings consume 37.5% of that number[18], [19] which is more than the third of total energy consumption in that year. Statistic and numbers like that should be a red flag and create an adequate motivation for engineers and architects to initiate to provide solutions. The literature review demonstrates the importance building envelope when it comes to HVAC design in calculating the cooling load and rate of infiltration and exfiltration[21]. as a result, this work aims to reduce heat transfer through the building envelope of windows and curtain systems to decrease cooling load and reduce energy consumption during the building life cycle.

Building envelope plays a vital role in reducing energy consumption in buildings, especially in heat and mass transfer, HVAC cooling load, infiltration rate, and exfiltration;

these factors and their impact would increase exponentially in hot climates where temperatures could reach 48 to 52 °C, would create a notable challenges for architects and designers to react with such an environment, by adapting a new technologies were building envelope are able to resist these extreme temperature and high cooling loads, especially in high window to wall ratio building like office buildings.

Using a multi-layer glazing system, Energy Active Window (EAW) adapts window insulation technology to reuse low-grade air from the HVAC system. This technology makes the temperature at the internal surface of the window close to the indoor air temperature, which would minimize heat exchange between indoor and outdoor. It invests the relatively low temperature of return-air airflow in the air gap between glass panes of the windows or curtain system to reduce the temperature of the air gap and the stagnant air film on glass panels. The system uses two basic concepts related to window thermal design: firstly, moving air has a higher ability to reduce surface temperature than stagnant air; secondly, air resistivity has an inverse relationship with its temperature[22], [23], [24]. The glass portion in any building envelope is considered weak, especially in high-rise buildings where the entire envelope is the source of enormous heat inlet. The Energy Active Window (EAW) solution does not affect the visual quality or reduce daylighting entering indoor space, and all the system components are hidden in a specific frame.

1.3 – Aim & objectives

This thesis aims to assess and analyze the thermal performance of Energy Active window/curtain (EAW) systems in reducing heat transfer through the building envelope in the hot climate of Saudi Arabia.

The following objectives has been implemented to achieve the above aim:

1. To determine characteristics and properties of EAW.
2. To investigate the thermal performance of EAW under a hot climate.
3. To develop guidelines able to predict EAW surface temperature in hot climate.

1.4 – Scope and limitation

The focus of this work is to study the heat transfer of EAW as a system in the building by studying variations of window surface temperature. It simulates window system thermally and aerodynamically. On the other hand, experiments have been conducted to validate results, taking the hot climate of Dhahran, Saudi Arabia as environmental case study.

CHAPTER 2

LITERATURE REVIEW

2.1 – Windows and building envelope characteristics

2.1.1 Aerodynamics characteristics

Building energy performance depends on several techniques, technologies, and strategies. However, any method that does not reduce heat gain would fail in its cradle. Failure to detect the root of heat gain through the building envelope and reduce energy consumption is like evacuating the boat from water to avoid its sink rather than closing the leakage spot[25][26].

For heat transfer from indoor to outdoor to occur, it needs a medium, which is air. However, heat can be transferred to building through intentional processes, like HVAC system, or through cracks and gaps, in other words, infiltration, which is defined by The American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE) as "the flow of characteristics outdoor air into a building through cracks and other unintentional openings and the normal use of exterior doors for entrance and egress "[27]. However, infiltration is related to the physical characteristics of air, which tends to move from low to the high-pressure area. On the other hand, airtightness is a building envelope feature that is measured by a scientific quantification which is ($\text{m}^3/\text{h}\cdot\text{m}^2$)[28], [29].

Indoor Air Quality (IAQ) is a critical factor to evaluate. On this basis, Dorizas et al. [28] evaluated ventilation rate and IAQ on educational facilities in Athens, Greece, using experiments and measurements comparing the results with the ASHRAE standard for schools. They found that ACH in schools is between 7 to 8, where carbon dioxide was slightly over the level, and that PM10 concentration is 10 times for most cases. They also found that PM concentration is strongly related to student presence, that it has a high concentration at working hours. Another study by Rackes & Waring[22] modelled the impact of dynamic ventilation on IAQ in over six US cities, using multi-contaminant models to simulate office areas in the US. They found that dynamic ventilation has a minor

impact on the concentration of Ozone & CO₂. Nonetheless, they found a daytime concentration of volatile organic compounds (VOC) increased between 7% to 14% depending on the city.

Denny et al [16]. study the performance of cooling and heating systems is significantly affected by the inclusion of nanopowders in the base fluids, the thermal characteristics of the base fluid are changed by nanoparticles, improving thermal conductivity, however, to lower the cover temperature and increase freshwater generation using a pump, the hybrid nanofluid (Al₂O₃-TiO₂) glass cooling flows across the glass. The temperature differential between the zones of condensation and evaporation is increased by hybrid nanofluid cover cooling. The natural convection heat transfer inside the solar still is increased using hybrid nanofluid glass cooling. The boundary conditions of the convective heat transfer coefficient and constant temperature.

When it comes to air movement its impacts on surfaces, such as window glazing glass panes, variety of study related to this part being made, Gosselin et al [17] made study on Airflow windows which have great potential to save energy and improve indoor air quality indoor. Existing airflow windows use a single airflow path; however, their energy efficiency can be investigated using multiple computational models. Double-glazed windows with triple glazing can save more energy than single-glazed windows. However, no suitable computer program can be used to evaluate the energy efficiency of dual airflow windows. Their work presents a four-step computational method for determining airflow and heat transfer through windows using both computational fluid dynamics (CFD) and coded radiation calculations. Experimental testing on a full-scale dual airflow window system was conducted to obtain various indoor and outdoor air and window surface temperatures to validate the computer procedure. The agreement between calculated and measured temperatures is largely acceptable .

Hieselberg et al [18] made a study on using fresh air represented in natural ventilation systems to generate air flow within the window, they studied impact of such system on thermal properties and other related factors like thermal comfort. They provided as summary of their results made by experiment for two different type windows, they found

air flow can be described by traditional theory for jets and stratified flow which models are developed for estimation of thermal comfort parameters in the occupied zone.

Zhang & Yang [19] made study on impact of surface air movement on material emissions that impacts of surface and discuss development on fabric emanations were explored tentatively. Using a velocity-controlled system in real room environment focusing on boundary air layer and its emission properties; It was found that fabric outflow rates are a work of the surface wind current conditions: as surface discuss speed increments, contaminants from materials deplete faster; the turbulent and situation incorporates a lesser impact on fabric emanations .

Flowing the previous part Zevenhoven et al [20] made study on impact of relative humidity and indoor temperature and its relation with exhaust air recovery system, and how it would made impact in regarding of energy performance, they provide energy analysis to prove their results, which show that running and building without reusage of moisture would loss up to 1kg/h, and therefore taking another factors in consideration would imply 10–15% of total electricity use.

2.1.2 –Thermal characteristics of Window Systems

Window thermal performance is a crucial player in reducing heat gain in buildings. Windows are the weakest surface in the building envelope, severely impacting energy consumption, especially in high-rise buildings that usually use curtain walls. Such impact may increase to its limit in a hot, humid climate in the climate typical of Saudi Arabia or the Arabian Gulf in general.

Considering other building components, windows or curtain walls are made from two main elements, which are glass part and frame which is made of aluminum in most of the time. These two elements have a different attitude when it came to heat transfer, that aluminum is good heat conductor, which one way to react to such a dilemma is by making double framing and make air gap between them made by PVC also named as thermal break. Such a way would reduce the heat transfer through the frame but would increase its initial cost

and its wight on the building structure, moreover, the practice in country like Saudi Arabia in these types of cases, is to use steel in the exterior frame and aluminum in the interior frame for it structural needs. On the other hand, glass part is the main source heat the system of curtainwall or window, that a poor design of the system's element it would increase thermal conductivity, therefore, increase heat loss or heat gain based on the climate, without mentioning other type of issues like condensation.

R. Binions et al. [30] Study the use of Vanadium dioxide as a base for intelligent glazing. Vanadium dioxide is a semiconductor metal with structural rutile and the potential to have a palpable impact on optical characteristics and electrical conductivity, therefore it is expected to have a favorable impact on thermal qualities. They also recommend that thin vanadium dioxide sheets be made using chemical vapor deposition. The effect of the chemical vapor on thermal performance and optical qualities was studied using X-Ray. Temperature and color thermochromic qualities play a key influence in energy performance for this sort of coating, according to the researchers. In terms of window thermal performance, however, the coating and glass pane qualities are critical. Boman et al. [31] Study the use of Vanadium dioxide as a base for intelligent glazing. Vanadium dioxide is a semiconductor metal with structural rutile and the potential to have a palpable impact on optical characteristics and electrical conductivity, therefore it is expected to have a favorable impact on thermal qualities. They also recommend that thin vanadium dioxide sheets be made using chemical vapor deposition. The effect of the chemical vapor on thermal performance and optical qualities was studied using X-Ray. Temperature and color thermochromic qualities play a key influence in energy performance for this sort of coating, according to the researchers. In terms of window thermal performance, however, the coating and glass pane qualities are critical.

Iqbal et al. [32] They investigated anti-reflection coating for a specific temperature rate, and they created multi-layer thin films that were sorted by optical qualities and structurally described using a spectrophotometer and an atomic force microscope. They discovered that x-ray transmittance is between 60% and 75%, and that there is no discernible variation in crystal structure and roughness of coatings, which ranges between 9 and 25 nm when

subjected to temperatures between 150 and 650 °Cs Celsius. They measure the thickness of the film with energy dispersive spectroscopy. Energy scattered spectroscopy reveals a 0.67:1 ratio between Silicon and Oxygen as a result of several factors. Exterior convective film coefficient for windows in low-rise buildings was measured by M.Yazdanian and J.H.Klems[11]. To compress the data, they used both experimental and theoretical methods. Despite this compression, data does not fit the employed model, such as the ASHRAE/DOE-2 model. With various temperature ranges of the outside surface, the experimental model based on The Mobile Window Thermal Test Facility (MoWiTT) exhibits film coefficient. They discovered that the MoWiTT model may be used with a low-rise building in the case study area when it comes to wind speed. To judge window thermal performance logically, properties such as U value and SHGC must be investigated.

Brunger et al. [33] looked examined the heat gain coefficient of windows that had insect screens installed. With a base case double glazed window, they took competitive measurements for one type of insect screen. Nonetheless, this research was conducted in a variety of climates. Insect screens may lower U-value by 7% and Solar Heat Gain Coefficient (SHGC) by 46% when installed outdoors, while it can cut U-value by 14% and SHGC by 15% when installed indoors, according to the researchers. Researchers, on the other hand, are making more efforts to generate new ideas. Application of chemical material properties starts making new generation of windows with relatively high performance. Wilson et al. [34] investigated the window model using a selective sun control screen with an air layer. Because silver is sensitive to oxidation and turns into a black body, the model features a silver coating that reflects solar energy near the mid-infrared regions. However, the oxidation rate is designed to be slow enough to be acceptable, with a silver layer possibly placed between two glass panes to minimize the amount of oxygen that diffuses through and reaches the glass layer, and to keep the oxygen diffusion rate stable. On the other hand, Min Li et al. [35] investigated the use of CuInS₂ thin films produced by electrodeposition and sulfurization. To characterize the film, they employed X-ray diffraction, scanning electron microscopy (SEM), and energy dispersive spectroscopy (EDS). The choline chloride:urea eutectic mixture was tested on large

windows, which are commonly utilized. They discovered that, in comparison to aqueous electrolytes, big windows that work by electrochemical technique have comparatively good thermal stability, allowing direct electrodeposition of Cu-In precursor sheets and scattering unwanted rays depending on their wavelength. Comparisons of variant alternatives, on the other hand, are essential for stakeholders to make informed decisions. In the United States, Gessert [36] talked about three different thin-film PV technologies. Depending on the level of toxicity, he divides the PV surface alloy into three categories. By 2030, these three modules are predicted to produce most of the PV-generated electricity in the United States. To calculate the PV film's thermal performance, he consults literature. In comparison to the other two alloy samples, he discovered that the fCdTe alloy had a high rate of electric generation and a high-performance air film insulation rate.

Window condensation in residences and workplaces can be exceptionally troublesome. Not as it were does it discourage the see through the windows, but moreover runs off to quicken the disintegration of paintwork, outlines, and furniture.[37], [38] To assess and diminish the hazard of condensation in buildings, expository and numerical models have been created to calculate the longitudinal temperature dissemination of the indoor coating. It is appeared that the temperature variety is essentially due to buoyancy-driven gas stream inside the fixed walled in area. In any case, the window edge seal and outline have a impressive impact on the temperature dissemination additionally on the U-value of the window[39], [40], [41]. Estimations and a two-dimensional numerical arrangement have been utilized to find out the cold bridge impacts of windows' edge seals and outlines on the temperature dissemination along the stature of the inward coating. This ponder takes into thought all modes of warm exchange, i.e. convection, radiation, and conduction experienced at the foot edge of the indoor coating. The examination gives a strategy for measuring the condensation so common within the European and North American climates[42], [43], [44].

2.1.3 –Thermal characteristics of Curtain Wall Systems

The curtain wall façade has become a recognized symbol of modern architecture all over the world. Insulated spandrels are added between glass sections of curtain wall systems (CWS) to enhance their thermal properties and energy performance. There are, however, a few notable space-technical limitations[15], [45]. First of all, frame systems support CWS structurally. A curtain wall frame's inner length (internal projection) is correlated with the structural requirements. Inner length is typically reduced when good structural performance is not required. The interior length, however, also makes room for insulation[46]. Due to this space issue, the inner length must still be increased to meet the necessary insulation thickness even when good structural performance is not required. Additionally, spandrel sections with large, insulated back panels are typically positioned between slab/plenum regions of consecutive floors behind monolithic glazing or opaque claddings, out of sight from building occupants. Otherwise, protrusions damage aesthetics. As a result, the complete space for curtain wall façade insulation installation has historically been set aside for slab/plenum portions solely. As a result, the window-to-wall ratio may increase or drop unfavorably, and design choice may be limited. Such thin façades need for high-performance, thin insulation. Vacuum Insulation Panel (VIP), one of the super-insulating materials now on the market, is a reliable insulator to incorporate into curtain wall spandrels[47], [48].

Boafo et al [49] made study aims to provide a thorough analysis of CWS combined with VIP as spandrel insulation. Depending on how much of them are prefabricated and how they are constructed, The three main types of CWS are stick, unitized, and structural glazing systems. Curtain walls and traditional windows are fundamentally different from one another because windows are installed between floor slabs, but curtain walls are anchored from a building's floor slabs and hang like a curtain. The VIP integrated into CWS described in literature is made of a fumed silica core material and enclosed in a metalized laminate (Si-VIP). Studies have shown that compared to solo VIPs, VIP spandrel modules offered ten times the protection against severe accelerated aging conditions. The idea is an approach to enhancing CWS's energy consumption footprint while extending the

service life and in-service durability of VIPs. This work is the first cutting-edge review of CWS integrated with VIP spandrels, as far as the authors are aware. Last but not least, potential future research directions for VIP integration in CWS are examined[50].

On the other hand, fenestrations provide access to natural light and views of the outside, but they are also the least thermally efficient part of a building's envelope, making them a potential source of glare and unwelcome direct sunlight. With the right management tactics, a well-designed fenestration system can drastically lower a building's energy consumption while still providing its occupants with a suitable indoor climate. Feng et al[51] conducted study where window design studies for high-performance buildings are reviewed and analyzed. These studies could be seen as decision-making procedures to reach the window performance objectives by regulating several design variables (e.g., location and dimensions of windows, glazing type, etc.). The decision-making methodologies of window systems are categorized and analyzed to present a thorough review, where we present a detailed analysis of sequential knowledge-based design methods and simulation-based optimization methods. First, an overview of the design options that are currently available for window systems is presented. Finally, to support the development of all autonomous simulation-based optimization design approaches for high performance fenestration systems, relevant obstacles and future research directions are highlighted and examined.

In order to meet the growing demand for environmental comfort and the urgent need to improve energy efficiency of new and existing buildings, it is necessary to conduct a detailed analysis of the features and specifications of the structure[13], [52]. This analysis will be transparent closures towards technological solutions that can guarantee, in addition to a maximum level of thermal insulation, the ability to control the incoming solar radiation or produce electrical energy. A new class of very creative glazing systems is making its way onto the market thanks to significant advancements in the field of materials science, largely through utilizing crucial enabling technologies like nanoparticles or smart materials. One of these cutting-edge technologies is active dynamic glass, which increases thermal comfort and visual comfort for occupants by adjusting the quantity of near-infrared

radiation and visible light that enters the building. Casini [53] provides a thorough analysis of active dynamic glazing technologies currently available or under development, such as electrochromics and gasochromics, as well as additional cutting-edge technologies, such as nanocrystal in-glass composites, electrokinetic pixels, elastomer-deformation tunable windows, and liquid infill tunable windows, comparing them in terms of operation, performances, and the potential for use in buildings, and providing pertinent data to help readers understand the effects on energy.

Shoeibi et al.[54] made a study on the performance of cooling and heating systems is significantly impacted by the inclusion of Nano powders in the base fluids. Because they change the base fluid's thermal characteristics, nanoparticles improve thermal conductivity. In order to analyze the glass cooling of a double-slope solar still numerically, a hybrid nanofluid ($\text{Al}_2\text{O}_3\text{-TiO}_2$) at a concentration of 0.4% is used in this research. Utilizing a pump, the hybrid nanofluid ($\text{Al}_2\text{O}_3\text{-TiO}_2$) glass cooling lowers the cover temperature while increasing freshwater production. The temperature differential between the evaporation and condensation zones is increased by hybrid nanofluid cover cooling. The solar still's internal natural convection heat transmission is increased by the use of hybrid nanofluid glass cooling. The boundary conditions for the glass cover and water surfaces of the solar still are thought to be the convective heat transfer coefficient and constant temperature, respectively. According to the simulation results, using hybrid nanofluid glass cooling boosted solar desalination's freshwater production and energy efficiency by 11.09% and 28.21%, respectively, as compared to using sun desalination without hybrid nanofluid. The CFD simulation predicted that 0.45% was the ideal value for nanoparticle concentration. Additionally, a freshwater production estimation model for solar desalination with hybrid nanofluid glass cooling was created and validated. Additionally, solar desalination with hybrid nanofluid glass cooling improved the environmental and exergo-environmental parameters by 12.45% and 3.71 times, respectively.

Casagrande[55] study the recent dynamic events, like the earthquakes in Alaska and San Fernando, have exposed flaws in current façade design methodologies, which are made worse by the incidence of non-structural component damage and failure when exposed to

extremely high wind loads or seismic events. As a result, the current work investigates the façade performance while examining the viability of an innovative and cutting-edge dissipation technique. Numerical models are first used to analyze and replicate the reaction of two full-scale façade modules tested in experiments at the Construction Technologies Institute (ITC) labs of the Italian National Research Council (CNR). Then, complex 3D finite element models are calibrated to learn more about the fundamental processes behind the dynamics in façades. Then, creative curtain wall joints are created employing Shape Memory Alloys' (SMA) unique qualities, such as super elasticity and the shape memory effect, with an emphasis on enhancing the overall structural behavior and improving the performance of the façade's energy dissipation. Finally, both globally and locally, the improvements are illustrated. On the one hand, conventional and new curtain wall force-drift capacity curves are compared. On the other hand, the effectiveness of the suggested device, when erected on a reference structure, is proven.

Better thermal performance provided by high performance glass, such as low-E coated or heat reflecting glass, prevents unwanted heat input or loss when a building is being used. These coatings can cause glare issues for neighboring structures and may not be as effective in some temperature zones. In order to give a sustainable alternative to a high-performance glass wall, a transparent composite façade system (TCFS) was recently developed.[49], [54] The airspace between the polymer skins serves as an appropriate insulating layer, and the biofiber composite core operates as a shading mechanism. To evaluate the environmental effects of a TCFS with a glass curtain wall system, Kim[56] made a comparative life cycle assessment (LCA) technique was chosen (GCWS). In this study, the energy use and CO₂ emissions of a façade system are used to assess its environmental performance over the course of its whole life cycle. The overall life cycle energy of the TCFS is assessed to be 93% of that of the uncoated GCWS, and the total emissions of kg CO₂ equivalent for the TCFS are calculated to be 89% of the uncoated GCWS, according to comparative LCA data. While this analysis estimates the impact of transportation and end-of-life management to be negligible, the usage phase for both the TCFS and GCWS plays a major role in decreasing environmental consequences. The life cycle inventory data

and analysis findings presented in this study are anticipated to help designers understand how to choose building materials and enhance systems from the perspective of the whole life cycle.

Because of its various benefits, the curtain wall system is frequently utilized in high-rise structures. The development of curtain wall systems now heavily weighs thermal performance due to the rising need for buildings to be more energy efficient. The percentages of the frame out of the total curtain wall area have not been taken into account in measuring its thermal transmittance, despite the fact that the relative influence of the edge effect becomes more significant as the thermal performance of glass and the frame increases[51], [53], [57]. Bae et al [58] made study aims to assess how the frame ratio affects the thermal transmittance of the curtain wall system. The condition of the curtain wall frame ratio is examined by looking at freshly built office buildings. Eight instances with various frame ratios and three distinct glazing U-value types were chosen, and TRISCO 12.0W was used to determine each case's total thermal transmittance of the curtain wall (U_{cw}). This study discovered that the thermal transmittance of the curtain wall system increases when a greater frame ratio is used. Furthermore, when high performance glass is used with the curtain wall system, the frame ratio has a significant impact on the thermal transmittance of the curtain wall. It is advised that, for a more realistic building energy simulation, the precise U_{cw} value considering the actual frame ratio be given together with the certifications of the curtain wall system.

2.1.4 –Heat transfer characteristics of Curtain Wall Systems

Minimizing thermal heat gain/loss through windows or curtain wall or fenestration in general and maintaining large glazing areas to provide adequate natural lighting in residential buildings are essential considerations for modern architecture, sustainability, and indoor comfort. However, many research works are trying to provide a solution to decrease heat gain through windows. Barth et al. [59] completed a study on various types of flexible solar control window films for retrofit and original equipment. They want to figure out how to use solar energy wet chemistry and vacuum coatings to regulate heat gain and highlight the importance and impact of flexible window film as a method for doing so. They compared a 3M window prototype patent with ordinary 3-mm window glass using WINDOW software. Absorbance, transmittance, and reflectance are the three parameters they measure. They discovered that such a window would have a reflectance percentage that was nearly identical to the basic scenario. Furthermore, they discovered a 35 percent improvement in transmission and absorption within a short wavelength.

The usage of glass curtain walls in contemporary architecture is expanding. However, after being subjected to seismic vibrations, they occasionally displayed damage, which might result in severe risks to pedestrian and building occupant safety as well as large financial losses to owners owing to downtime and repair costs. In order to improve the capacity of designers and manufacturers to deal with the seismic susceptibility of glazed systems and reduce earthquake-induced losses, this effort attempts to explore how such systems behave under seismic stresses. Aiello et al.[57] made study demonstrates the results of cyclic experimental tests conducted at the Construction Technologies Institute (ITC) of the Italian National Research Council (CNR) for the evaluation of the seismic performance of a full-scale aluminum-glass façade that was developed and produced using a standard technology for the European market. Using data from experiments, a non-linear finite element model has been calibrated. The goal is to get a deeper knowledge of certain lateral behavior characteristics of these non-structural parts while also providing helpful data for numerical simulations of comparable façades, which in the near future should be carried out even in the absence of experimental data.

2.2- Exhaust Air Recovery (EAR) system in buildings

The concept of investigating the reuse of Exhaust Air (EA) majorly started in Sweden and Germany in the late 1970s. In both countries, codes, regulations, and energy crises were the primary motivation to adopt such a concept. [60]. Later research by Zhang et al. [61] investigated design optimization in using EA in air gaps of cavity walls. Zhang is leading the EA recovery technologies nowadays to increase the resistance of building envelopes. Exhaust air insulation walls inject EA within porous material to improve insulation material performance, pointing out the shortage of previous works and studies and its expected impact on EA performance in the cavity wall. However, they provide a numerical estimation of energy-saving potential when considering pressure loss in the exfiltration process. Their study finds a strong relationship between pressure loss and total energy saving. Moreover, they found that high permeability and thermal resistance have better performance when used with EA in the wall system[61]. EA was majorly used in heating and cooling application. An indirect evaporative cooler that uses EA was numerically tested in China, considering energy transferred for the type of indirect evaporative coolers. However, using such a system increases heat transfer capacity by around 45%[62]. There were extensive research and studies in using EA to reheat buildings, especially in Scandinavian countries, where the EA heat pump was born due to the prohibition of direct electric heating[60].

A novel dual-cylinder rotary compressor with independent suction and discharge ports was designed by Jia et al [63] to drive an inverter parallel-loop exhaust air heat pump because the interior space of residential buildings is constrained, particularly in building retrofits. This will improve the utilization of the interior space and the efficiency of the exhaust air heat recovery system. The improved approach is suggested and experimentally validated by tests and analysis of the parallel-loop exhaust air heat pump system operating characteristics under changing compressor frequency and varying fresh air volume flow rates. The seasonal performance factor and seasonal average input power under the suggested yearly energy-efficient operating plan in three representative countries/organizations were then computed. Results indicate that using a mixed air supply

strategy during the winter can significantly increase the system COP. When the fresh-to-return air ratio is 1:1 and the outside temperature is below 5 °C, the system's coefficient of performance (COP) attained 10.18, the highest value among the studies that are relevant to this one. By raising the ventilation volume flow rate during the summer, the system COP is raised. The heating season performance factor, heating season average input power, cooling season performance factor, and cooling season average input power are, respectively, 7.22, 0.6909 kW, 2.83, and 0.8167 kW when the operation of the parallel-loop exhaust air heat pump system complies with GB 21455-2013 and the energy efficient operation plan to ensure the temperature effectiveness over 100%. The research would offer recommendations for the design of a residential building's exhaust air heat recovery system. one. By raising the ventilation volume flow rate during the summer, the system COP is raised. The heating season performance factor, heating season average input power, cooling season performance factor, and cooling season average input power are, respectively, 7.22, 0.6909 kW, 2.83, and 0.8167 kW when the operation of the parallel-loop exhaust air heat pump system complies with GB 21455-2013 and the energy efficient operation plan to ensure the temperature effectiveness over 100%. The research would offer recommendations for the design of a residential building's exhaust air heat recovery system.

The issues with indoor comfort and energy consumption in solar buildings, such as overheating of BIPV systems, excessive cooling load, and cold-heat offset of HVAC systems, have attracted a lot of attention. Yayun [64] made study suggests an innovative exhaust ventilation double-glazing PV curtain wall system (EVPV) coupled with an air handling unit (AHU) based on waste heat recovery to address these issues (HR). This hybrid system uses exhaust air as a coolant to cool the PV curtain wall. In addition, the exhaust air is recycled to precool the fresh air and preheat the dew-point supply air. Thus, solar energy is gathered, transformed into heat and electricity, and effectively recovered as thermal energy. The method produces more power, uses less energy for cooling, and saves significantly on reheating. A case study based on a restaurant building in Hefei with a south-facing EVPV and one with a non-ventilation BIPV façade system without HR is

undertaken to fully forecast performance (NVPV). Based on the validated model, the results of a typical summer week operation show that the EVPV system can accomplish the following: (1) 7.87 kWh/day power generation; (2) 7.68 kWh/day heat recovery from the PV double-glazing façade; (3) 8.41 kWh/day mitigation of reheat demand; 2.97 kWh/day reduction of room cooling load; 39.94 kWh/day fresh air-cooling capacity; and (4) additional fan power of 16.29 kWh/day. Overall energy consumption is decreased by 63.12 kWh/day (19.26%) by integrating the PV curtain wall with the AHU utilizing HR. Investigations are done into how the electrical and thermal behavior of EVPV is affected by the air cavity depth and PV coverage ratio. The findings imply that 0.08 m air cavity depth and a greater PV coverage ratio provide the building a more attractive potential for energy savings.

Bai et al [65] made research examined heat recovery technologies and how they may be used in chilly residential buildings. Improved insulated and airtight structures are the outcome of the increased efforts to reduce building energy usage in recent years. Poor indoor air quality can be caused by reduced infiltration because of inadequate ventilation rates. An energy-efficient mechanical ventilation system with heat recovery promotes good indoor air quality while consuming little energy in cold conditions by supplying regulated airflow rates. This is especially crucial during the heating season when windows and doors are often shut to maintain a comfortable inside temperature. This analysis looks at the many heat recovery techniques used in homes, including cutting-edge methods designed for cold locations. Different criteria were used to compare these technologies. Heat exchangers used in cold climates have a tendency to frost, which lowers their efficiency. In this review, several frosting management techniques, such as frosting prevention and defrosting, were covered. The current frost control methods either result in poor indoor air quality or higher energy costs. Finally, the impact of mechanical ventilation with heat recovery on interior air quality was discussed. Future research recommendations are put forth considering the current review.

2.3- EAW in buildings

EAW falls under the airflow windows category, which has good energy-saving potential and plays an excellent example of reusing building wastages. In this case, EA is being recycled to reduce the gap between the curtain system and the indoor air temperature. Moreover, airflow windows improve daylighting performance, indoor air quality, energy conservation, and management. EAW is the best airflow window to reduce cooling load[66]. Nonetheless, the EAW central concept is being operated by a forced convection system, unlike other airflow windows, which use free or passive convection technology to move air through the window system. Airflow windows can be divided into supply, exhaust, indoor curtain and outdoor curtain; however, all airflow windows use buoyancy force to operate, in one way or another.

There were varieties of techniques, technologies, and strategies engineers and architects are trying to investigate to reduce the energy consumption of built environments. Nonetheless, when it comes to the building environment, reducing heat transfer indoors, infiltration and exfiltration, and ensuring airtightness are critical factors in reducing the size of the HVAC system, which is the leading energy consumer in buildings[29], [67]. Windows that use the airflow concept can conserve energy and improve indoor air quality[68].

Zevenhoven et al. [21] studied the energy performance and efficiency by focusing on minimizing heat exchange indoor and outdoor, taking air humidity as a focal point; they investigate using exhaust air windows as a strategy of EA recovery, which is heated by a geothermal heat pump. Using experiment in a condition of 22 °C and relative humidity of 50 or 30%, where inlet and outlet temperature and humidity are variant in each experiment made, they found that 1kg/h of moisture water may be lost during the process. However, such a system may conserve 15% kWh of electricity due to their calculations. Nonetheless, EAW can use EA from a traditional HVAC system to insulate building envelopes.

Zhang et al. [69] investigated a triple glazed exhaust-air window (TGEW), which can switch between cooling mode and heating mode in different seasons, and experiments were conducted to validate the outcomes of 2D numerical simulation. they found that the

conventional triple-glazed window (TGW) reduces cooling load by 25%, heating loads up to half. Prior to this study, they proposed a new switchable window system with two cavities; using a numerical simulation within Wuhan weather conditions, they found that it could reduce heat gain by 2% more than conventional TGW in summer and 28% in winter[70]. Jennifer et al. [71] proposed CFD simulation with the four-step computational method in line with full-scale experiments to evaluate airflow windows and computational fluid dynamics to calculate flow and temperature without considering radiation. It was replaced by a calculation formula to estimate surface heat exchange radiation.

The energy-saving potential of dual airflow windows under five different climate zones in China was simulated through the EnergyPlus model for middle-sized apartments. Nonetheless, applying Low-E and blinders reduces the heating load by 16–48% based on the climate[68]. Generally, airflow windows can be divided into supply, exhaust, indoor curtain and outdoor curtain, as illustrated in Figure 1. However, it can be noticed that EAW has good performance in reducing the heating load in winter, but these outcomes need to be improved to be more attractive to be used and risk installing such a relatively new concept in any building, especially in a hot, humid climate.

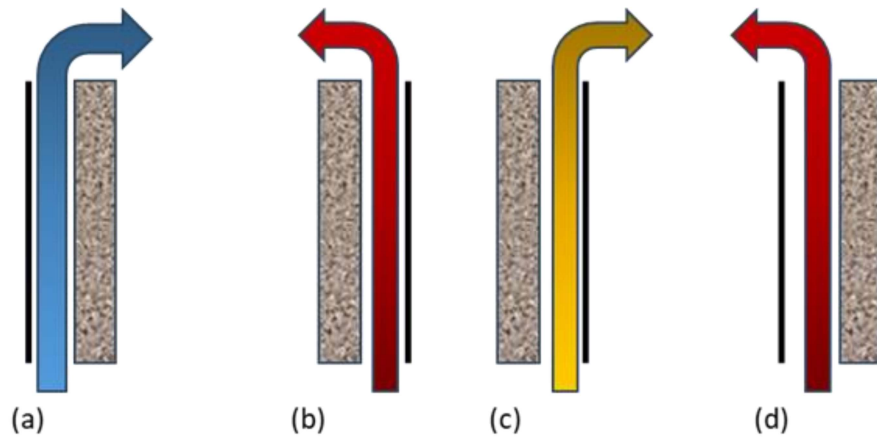


Fig. 1. Existing airflow window types: (a) supply mode, (b) exhaust mode, (c) indoor air curtain and (d) outdoor air curtain.[71]

Nourozi et al. [66] published a paper investigating the thermal performance of airflow windows in Scandinavian countries in collaboration with researchers from the Swedish Royal Institute of Technology. They present an innovative EAW's winter performance that utilizes low-grade energy, such as waste heat in a sealed air loop between the windowpanes. The purpose of using EAW is to utilize waste heat to maintain higher window-surface temperatures in winter. This technology converts conventional passive windows into an energy-active component. In addition, based on the literature review, it has a tangible effect on reducing building heating demand, improving indoor thermal comfort, and reducing peak heating demands. This paper is based majorly on numerical models and literature review. Taking TGW as a base, they found that the temperature difference between the outer windowpane and inner one would reach up to 25 °C based on indoor and outdoor conditions. The same value would be reached for the difference between air temperature at the inlet and outlet. Moreover, the variations in supply (injected) air temperature are the main factor affecting the U-value of the energy-active window that to maintain a low U-value, the supply air temperature to EAW must be above the indoor temperature.

2.4- Other related windows system technologies in buildings

Li and Tang [17] made a novel brand-new double-circulation water-flow window that combines sun shading, indoor cooling/heating, and solar thermal collector functions. They create their own simulation program and use to assess performance year-round. They found that window is effective at collecting solar thermal energy in cooling-dominant regions and uses low-grade geothermal energy to provide additional heating/cooling in winter and summer. The window can collect 21.25% of the total incident solar energy at a flow rate of 0.005 kg/s; this amount can be increased to 28.76% by using colored water with a higher solar absorptance. The window uses 174.27 and 64.76 kWh of geothermal energy per unit area per year for indoor cooling and heating. The current work presents a workable method for modeling and assessing the overall performance of an active window, which integrates the use of geothermal and solar energy in a single building envelop. Furthermore, rather than emphasizing the window component itself, the authors focused on beneficial indoor

heat gain/loss through windows, which favors the energy savings in air conditioning systems. The numerical model can be used in building energy simulation software to aid in the design of environmentally friendly structures.

Casini[16] made a comprehensive study to meet the urgent need to increase energy efficiency of new and existing buildings as well as the rising demand for environmental comfort, it is necessary to conduct a thorough analysis of the features and specifications of each building. His analysis focuses on technological solutions that can guarantee maximum thermal insulation as well as the ability to control solar radiation or produce electricity. A new class of extremely inventive glazing systems is approaching the market primarily by utilizing important supporting technologies like nanoparticles or smart materials, thanks to the enormous advances made in the field of materials science. One of these cutting-edge technologies, active dynamic glass, enables for considerable energy savings as well as improved thermal and visual comfort for occupants by adjusting the quantity of incoming near-infrared radiation and visible light. His article compares the operation, performances, and building application potential of active dynamic glazing technologies that are currently available or under development, such as electrochromic and gasochromics, as well as additional emerging technologies, such as nanocrystal in-glass composites, electrokinetic pixels, elastomer-deformation tunable windows, and liquid infill tunable windows, while also providing pertinent data to help readers understand the effects on energy.

Considering that buildings need energy produced by fossil fuels to meet their demand for artificial lighting, heating, and air conditioning. It is feasible to reduce this building's energy use by using modern, switchable smart windows that are energy efficient. Currently, electrochromic (EC), suspended particle device (SPD), and liquid crystal are the three types of electrically triggered switchable smart window systems (LC). While SPD and LC need an alternating current (AC) power supply, EC operates with a direct current (DC) power supply. These three window technologies' specifics (working principle, window characteristics, and potential for building energy savings) have been studied in this paper. Another desirable tactic is to power them with PV systems using highly insulated switchable smart windows. Smart windows, however, require stakeholder support, from

the government and building control code, in order to successfully enter the building industry[15].

Enhancing energy efficiency in the construction industry is achievable in both residential and tertiary buildings thanks to electrochromic technologies for smart windows. The ability to dynamically modulate a glazing's spectral characteristics throughout the visible and infrared ranges of wavelengths enables one to adjust the glazing's thermal and optical behavior to the constantly shifting environmental circumstances of the building's location. This makes it possible to control how much solar radiation gets inside the structure. The scientific literature is still exploring the numerous benefits that follow, which are numerous. In "cooling dominated" climates, especially, the reduction in energy consumption for summer air conditioning (and artificial lighting, too) becomes significant and reaches high percentages of savings compared to conventional transparent windows. On the other hand, the continuous adaptation of the optical properties of the glass to changing external conditions allows for the setting of appropriate management strategies for the smart window, in order to offer optimal

Beginning with an examination of the primary architectural designs of the devices already on the market, this review's objective is to critically evaluate the pertinent literature pertaining to the advantages obtained in terms of energy consumption and aesthetic comfort[45].

Tavares et al[46] made evaluation of energy performance electrochromic windows in Mediterranean climates considering renovating older buildings which crucial for boosting building energy indicators on a worldwide scale. This setting serves as the backdrop for the article, which focuses on potential energy savings associated with electrochromic (EC) windows, an intriguing new technology that may be used in place of shading mechanisms to reduce solar gain in structures situated in Mediterranean climates. A brief introduction to the EC windows technology is given, and the discussion of the glasses' optical property modifications according to the operating range follows. The ESP-r building simulation program models and uses the various control schemes and the dynamic behavior of EC windows. Examining various ambient characteristics (external dry bulb temperature, interior dry bulb temperature, and incoming radiation) as well as set points for the EC

control, the effect of EC windows on the energy requirements for heating and cooling is investigated. Through the analysis of the energy requirements for heating and cooling, a comparison of various window solutions (single, double-glazing, and electrochromic windows), the type of building, internal gains from occupancy, lighting, equipment, and the orientation of windows are taken into consideration for discussion. It is found that using the electrochromic on the west façade produces the most favorable outcomes for this climate. The findings indicate that there are no appreciable benefits to utilizing EC windows on the south façade.

Systems for active building envelopes are a novel type of enclosure that utilize solar energy to offset passive heat gains or losses from building envelopes. Photovoltaic cells are used in ABE systems to transform solar radiation energy into electrical energy. Several solid-state thermoelectric modules powered by this electrical energy are then employed to regulate the enclosure's heat flow[53], [56], [58]. Xu and Dessel [48] have created a prototype ABE window-system and an outside testing area in order to evaluate the viability of ABE systems in real-world applications. The temperatures, solar radiation, current, and voltage of the ABE system were measured using a testing device. Results from theoretical and experimental studies are shown and contrasted. Finally, the ABE window-performance systems were assessed.

CHAPTER 3

METHODOLOGY

In order to evaluate the performance of EAW, developing an experimental and simulation methodology is essential to measure energy-saving potential. Experiments on the pilot alternative window have been conducted in a well-controlled environment, while CFD and thermal simulation has been applied, and results has been compared for validation. Nonetheless, Computational Fluid Dynamics (CFD) has become a potent tool for engineers and architects to simulate building aerodynamics with a low margin of error, without difficulties of air tunnel experiments. CFD can help simulate building behavior under high-speed winds. The fire spread scenarios in buildings, the rate of infiltration of building envelope etc., when it comes to CFD application to building airtightness.

On the other hand, building envelope cracks and tightness relate to the energy consumption rate. Casado et al. [72] conducted a study to evaluate and highlight links between energy consumption and uncontrolled airflow in residential buildings in Spain. They use the blower test to assess over nine provinces with different environmental conditions. After analyzing data, they found that infiltration impacts the heating load's 2.4 to 19 kWh/(m².y). Nonetheless, when it comes to CFD, an application to measure thermal window performance, much research works, and numerical models are being developed to match European and international standards. Malvoni et al. [26] made CFD simulation on window performance according to UNI EN ISO 10077-2, and they used GAMBIT 2.2 and ANSYS FLUENT 14.5 CFD code to evaluate the thermal performance of wooden and aluminum frames. However, their study provides a CFD model able to predict evaluate windowpane with a low margin of error. The flowchart illustrating the methodology used in this study is shown in Figure 2.

First step of the methodology is to conduct a literature review on window and curtain wall systems and their performance and issues on hot climate in areas like Saudi Arabia, also investigate results and procedures done to study their thermal aerodynamical properties. Moreover, literature review was scoping on field of recovery system considering that EAW can be categorized as passive recovery system. On the other hand, literature review isn't limited scientific papers only, that real life data or manufacturer survey been created by making limited study on suppliers and manufactures of curtain wall system in Saudi Arabia, considering their opinion and comments in regard of technical detail, also for HVAC engineers and supplier in regard of recovery system, to create the concept of the proposed curtain wall/ window if any; secondary data was collected from governmental records in regard of rate of energy consumption and upcoming urban plans, laws, regulations related the topic.

Second part of the methodology will be conducting the CFD simulation and experiment, by specifying the air and setup in detail for both, simulation, and experiment. Nonetheless, variety of alternative will be tested and simulated, to study impact of different factors, such as air velocity, air pressure, air gap, air temperature, different outdoor temperature, with and without solar radiation ...etc. to get the best combination of alternative which would give the best performance in form of reduction of glass surface temperature.

Nonetheless, experiments and simulation were evaluated and to have solid results, and margin of error of both were calculated, moreover, results were validated with literature review to increase the reliability of the outcomes.

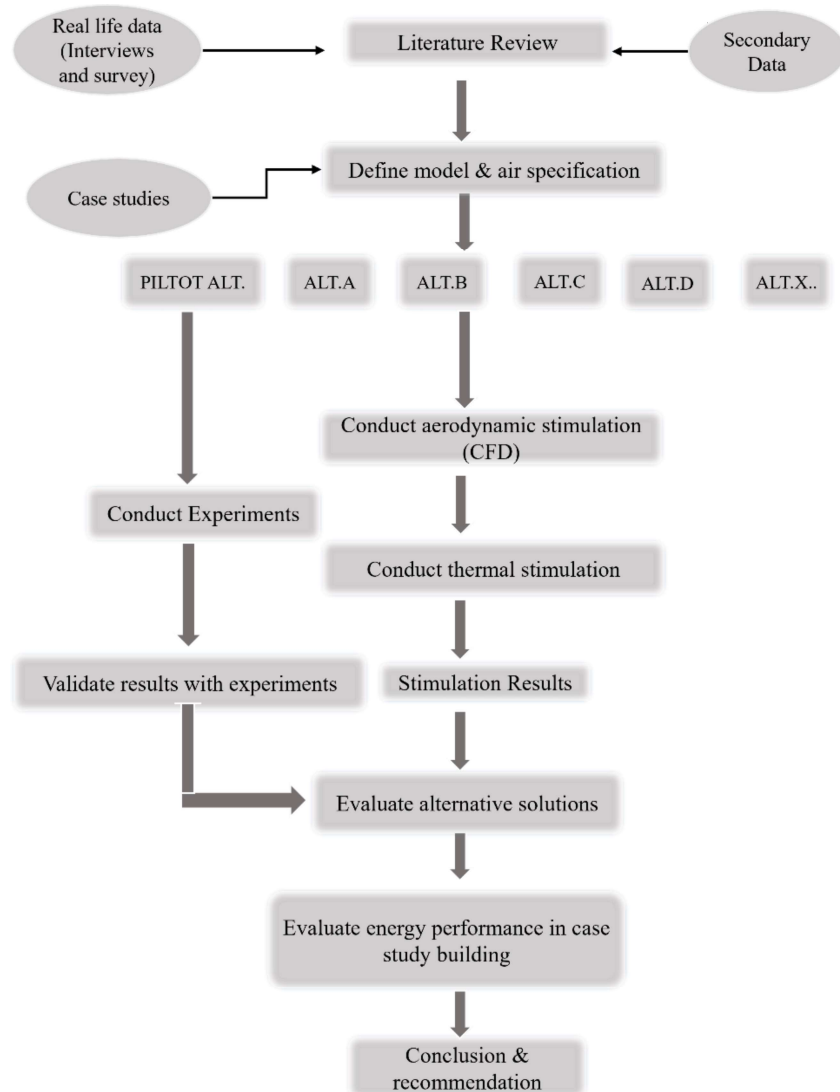


Fig. 2. Research Methodology for testing the theory and different alternatives (ALT)

3.1-Research Procedure

3.1.1- Experiment procedure

A reduced scale experimental model has been made in line with general requirements of American Architectural Manufacturers Association (AAMA), to measure the impact of moving air between glass pane, and investigate its impact on window thermal performance considering its surface temperature as a judging tool. To achieve that the following experimental procedures have been implemented:

- I. A detailed window model has been specified based on typical characteristics from the industry and literature.
- II. An air blower has been mounted at the top of the air gap to play the role of return system in the building, that there has been no return system in the building at all, considering that all the return air has been used for cooling the window/curtain.
- III. Thermocouples were installed to measure surface temperature of glass, as it will be the main evaluation factor for each alternative.
- IV. Several alternatives have been studied, such like but not limited to air velocity, air pressure, air gap, air temperature, different outdoor temperature, with and without solar radiation. For each factor tested all other variables were fixed.
- V. An experiment on one pilot alternative has been conducted to validate simulation results.

Nonetheless, due to novelty of this research, variant trials and models were made to get best results, however, any variation that may occur will be described individually in detail.

A scaled model has been tested within controlled environment, as illustrated in Figure 2.1, to simulate indoor and outdoor conditions, considering temperature, and air velocity. The experiment used forced air movement, considering average return air temperature, humidity, and velocity from HVAC system based on multiple case studies of high-rise buildings in Saudi Arabia during summer only, which is usually hot with extreme humidity reaching up to 80%. The glazing area is 1-meter width and 1- meter wide. A double clear glazing system with a thickness of 6 mm. There was one airflow inlet and one flow outlet, distributed along the entire window's frame. However, the supply air at a relatively low temperature was injected from the top while the sucking fan has been placed in the bottom; Figure 2.2 & 2.3 simplifies the working principle of EAW.

Moreover, thermal testing of certain window specimens can be confusing when dealing with researchers, engineers, architects, and others who retrofit or investigate buildings energy saving. There are two US testing procedures for windows to determine thermal performance. The American Architectural Manufacturers Association (AAMA) and the National Fenestration Rating Council (NFRC). U-Value describes thermal conductivity, the heat flow through the glazing, expressed in BTUs per hour per square foot per degree Fahrenheit temperature difference. The lower the U-value, the better. The U-value is calculated for the entire window, including the frame material and the glass. The test procedure includes a little airflow on the test specimen (15 mph). Therefore, an operable window with the same glass type as a fixed window will have a higher U-value rating.

An environmental room with a variety of designs has been created using 5cm foam to isolate heat with two aluminum foil layers to prevent radiation. The chamber representing outdoor condition will have 45°C Temperature (T) represents the thermal condition in Saudi Arabia at mid-summer, in hot, humid coastal cities like Dammam. On the other hand, the indoor chamber has $T=24^{\circ}\text{C}$.

A Temperature & Humidity Controller (THC) has been used to give the required thermal condition, which may change based on the performance of the window system and condensation rate. It is expected to eventually provide recommendations for heat and RH that suit such a system.

Air inlet temperature has been air exhausted from the HVAC system, which varies from 24c to 28c. The isothermal frame double clear glass windowpanes have been the experiment specimen. Thus, the frame impact on heat transmittance will not be considered due to huge factors, and variants could show in experiments or simulations.

Moreover, the THC will generate the necessary thermal condition in both chambers, as the rate of heat transmittance has been measured by on surface temperature sensor. The temperature gradient has been measured until it reaches a constant heat exchange rate between two glass panes. The RA flow rate will vary from $1\text{ m}^3/\text{min}$ to $1.1\text{ m}^3/\text{min}$ flow between them. That difference in temperature between two panes surfaces has been the main indicator of its performance in this study.

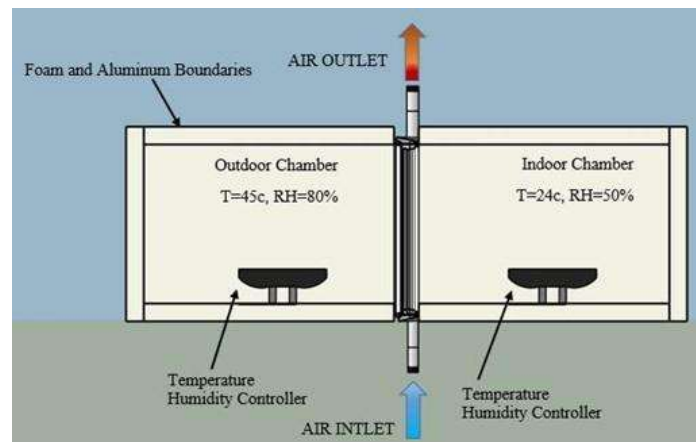


Fig. 2.1 Research Methodology for experiment which will vary based on alternatives (ALT)

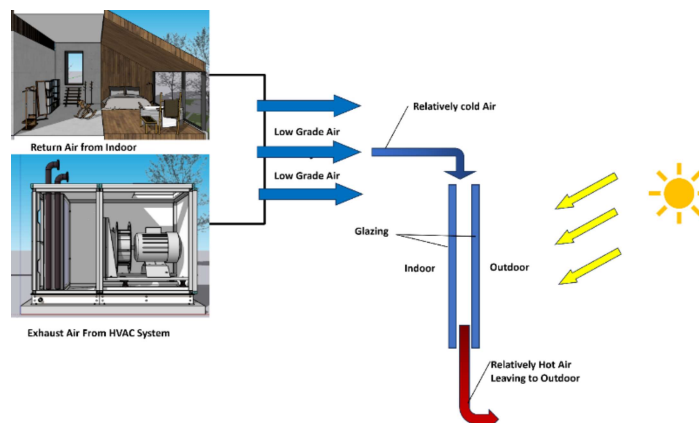


Fig. 2.2 The working principle of the EAW system

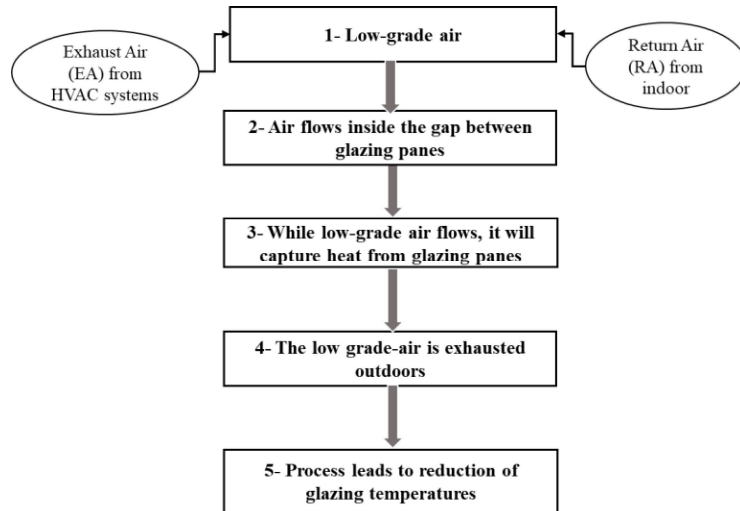


Fig. 2.3 The working principle of the EAW system

The first experimental model was made of 5cm foam, and consists of on dehumidifier and heater, attached with humidity controller and thermal controller as shown in figure 3. These controllers work by direct voltage inlet system, that when the sensor attached with it reaches the required temperature or humidity it stops the current/voltage from flowing to the electric device connected with it. It has high creditability, and it was used in variety of organizations, companies, and industries.

Nonetheless, the foam chamber was representing the outdoor temperature, with size of 1 cubic meter, while the indoor temperature was represented by the surrounding temperature, in other word the ambient environment where the experiment was conducted, that it has the ideal condition to represent the indoor temperature, with RH is 20% to 24% and temperature is 24.1 to 24.4 Celsius, which matches the AAMA requirements.

On the other hand, a fan that blows air perpendicularly toward glass with rate of 4m/s has been installed, to match the requirements of AAMA. The glass portion was in size of 1.1m x 1.1m, that the experimental area is 1 square meter, and the remaining 10 cm to frame the window and create the needed gap. The gap in this model has width of 2 cm for constructability reasons. When it comes to air filled in the air gap, it was inflated with rate of 0.0183 1.1 to 1.15 m³/ s and speed of 4m/s, with constant rate along the 1-hour time span. The surface of the window which represent the outdoor side, was heated to reach 50

°C, while the indoor temperature reached 43 to 44 °C. This process was kept for 1-hour to ensure that it reaches thermal steady state, however, it could go for more than 2 hours sometime to reach the steady state, which is determined by having negligible change in the indoor window glass pane. Then, the air was pumped within the air gap between glass panes, and the sensor attached with the indoor window to start recording the temperature difference. These measurements were recorded at three minutes intervals within until the temperature is constant and there is no tangible variation in temperature for 30 minutes' period. It normally takes only 30 to 45 minutes to reach the steady state, but in some rare cases it extends to 60 to 70 minutes, based on experiment condition and parameters. Nonetheless, humidity ratio in hot chamber that represents the outdoor condition was 15%, that AAMA recommend keeping it always under 30%.

Figures 5 and 6 show the temperature and humidity controllers. The temperature controller can work in range is -50~120 °C / -58~248 ° F with high accuracy: $\pm 1^{\circ}\text{C}$ (-50 ~ 70 ° C) / $\pm 1^{\circ}\text{F}$ (-50 to 160 ° F). Dual display window is displayed in a position to the measured temperature and set temperature simultaneously. Figures 6 & 7 show the setting and installation methods of the experimental setup and setting method with safe and reliable dual relay output humidity controller. Its plug-n-play designed, dual LED screens enabling more humanized. IHC-200 can control any 100–265-volt.



Fig. 3. Experiment model 01 while heat controller is working



Fig. 3.1 Experiment model 01



Fig. 4. Temperature and humidity controllers

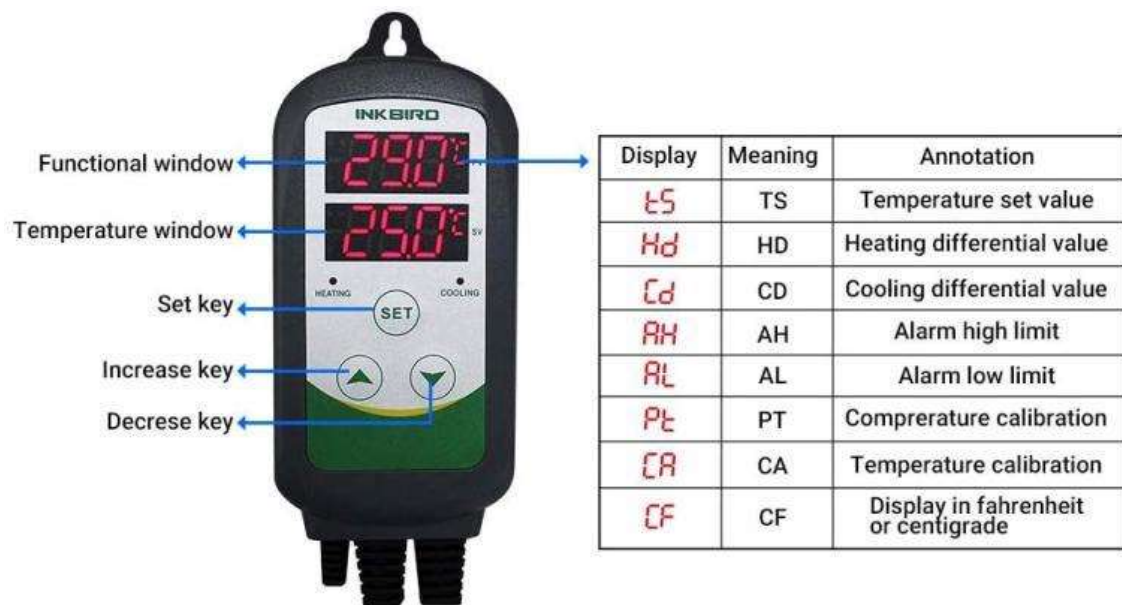


Fig. 5. Temperature controller setting method

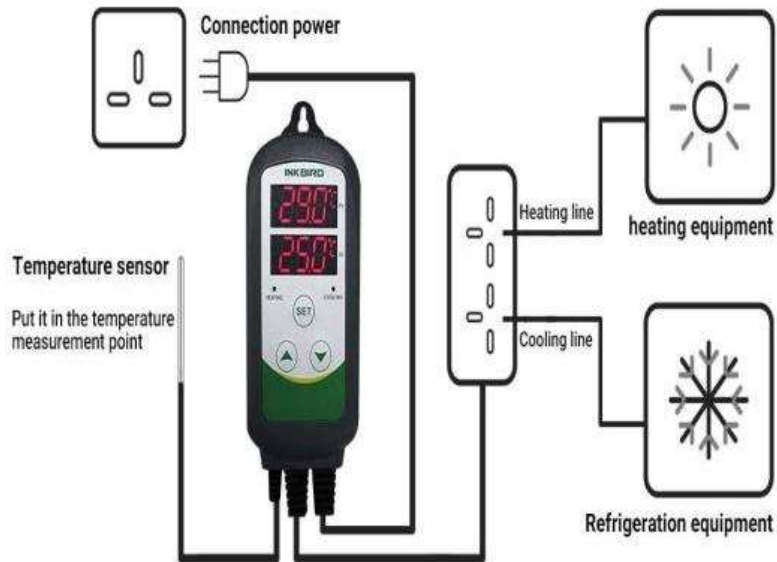


Fig. 6. Temperature controller installation method



Fig. 7. Humidity controller installing and setting method.

Reduced scale experiments will be discussed, and the difference between each trial and model will be described in detail. Moreover, results will be extracted and discussed, and based on each trial outcome, the next trial be sort of reaction toward it, weather to explain the reason behind and odd outcome to get a bitter result or investigate impact of variant value of certain factor. Table 1.1 shows all the experiments, models, and different trials; nonetheless, only the major experiments will be detailly discussed.

NO.	Model /Trial Name	Description	Results
1	Model 01 (Trial 01)	controlled outdoor environment, with 1mx1m, window size, 2cm air gap, outdoor temperature of 50 °C	6°C increment of inner window surface
2	Model 01 (Trial 02)	controlled outdoor environment, with 1mx1m, window size, 2cm air gap, outdoor temperature of 80 °C	5°C increment of inner window surface
3	Model 02 (Trial 01)	controlled indoor and outdoor environment, with .5mx0.5m, window size, 2cm air gap , outdoor temperature of 50 °C	6°C increment of inner window surface
4	Model 02 (Trial 02)	controlled indoor and outdoor environment, with .5mx0.5m, window size, 4cm air gap , outdoor temperature of 50 °C	3°C increment of inner window surface
5	Model 02 (Trial 03)	controlled indoor and outdoor environment, with .5mx0.5m, window size, 4cm air gap, fill from below , outdoor temperature of 50 °C	3°C increment of inner window surface
6	Model 02 (Trial 04)	controlled indoor and outdoor environment, with .5mx0.5m, window size, 4cm air gap, indirect heating , outdoor temperature of 50 °C	3°C increment of inner window surface
7	Model 02 (Trial 05)	controlled indoor and outdoor environment, with .5mx0.5m, window size, 4cm air gap, allowing surface temperature to cool up , outdoor temperature of 50 °C	3°C increment of inner window surface
8	Model 02 (Trial 06)	controlled indoor and outdoor environment, with .5mx0.5m, window size, 10cm air gap , outdoor temperature of 50 °C	2°C increment of inner window surface
9	Model 02 Alternative Experiments (Trial 01)	controlled indoor and outdoor environment, with .5mx0.5m, window size, 2 cm air gap, outdoor temperature of 50 °C, creating high- and low-pressure points	5°C increment of inner window surface

10	Model 02 Alternative Experiments (Trial 02)	controlled indoor and outdoor environment, with .5mx0.5m, window size, 2 cm air gap, outdoor temperature of 50 °C, Low air inlet temperature at 18°C	1°C increment of inner window surface
11	Model 02 Alternative Experiments (Trial 03)	controlled indoor and outdoor environment, with .5mx0.5m, window size, 2 cm air gap, outdoor temperature of 50 °C, No surface thermal control	2°C increment of inner window surface
12	Model 02 Alternative Experiments (Trial 04)	controlled indoor and outdoor environment, with .5mx0.5m, window size, 2 cm air gap, outdoor temperature of 50 °C, Air flowing from start of the heating	1°C reduction of inner window surface
13	Model 02 Alternative Experiments (Trial 05)	controlled indoor and outdoor environment, with .5mx0.5m, window size, 2 cm air gap, outdoor temperature of 50 °C, measuring heat loss with and without air flow	8°C difference of inner window surface comparing when is not flowing
14	Model 02A Alternative Experiments (Trial 06)	controlled indoor environment only , with .5mx0.5m, window size, 2 cm air gap, exposed to solar radiation, made on three consecutive days.	6°C increment of inner window surface
15	Model 02A Alternative Experiments (Trial 07)	controlled indoor and outdoor environment, with .5mx0.5m, window size, 2 cm air gap, different outdoor temperature	margin increment inner window surface temperature has inverse relation with outdoor temperature
16	Model 03 (Trial 01)	tighter setup , controlled outdoor environment, with 1mx0.6m window size , 2cm air gap, outdoor temperature of 45 °C, indoor temperature 20 °C.	2°C increment of inner window surface
17	Model 03 (Trial 02)	tighter setup , controlled outdoor environment, with 1mx0.6m window size , 2cm air gap, Variable outdoor temperature, indoor temperature 20 °C.	margin increment inner window surface temperature has inverse relation with outdoor temperature
18	Model 03 (Trial 03)	tighter setup , controlled outdoor environment, with 1mx0.6m window size , 2cm air gap, outdoor temperature of 45 °C, indoor temperature 20 °C, Variant Air Velocity	low the velocity led to lower surface temperature

The reduced scale model suffered from variety of issues, leads to have non-accurate outcomes, the reason behind this phenomenon will be discussed in the following chapter. Figure 8,9,10 shows the experimental model which has two controlled chambers to represent both indoor and outdoor environment. In addition, figure 11 shows another experimental model that aims to test the system in the presence of solar radiation. As figure 12 shows the interior glazing pane suffers from increasing its temperature after air starts flowing which is since flowing air is working as medium to increase heat transfer rate between outdoor glazing and indoor glazing as illustrated in figure 13.

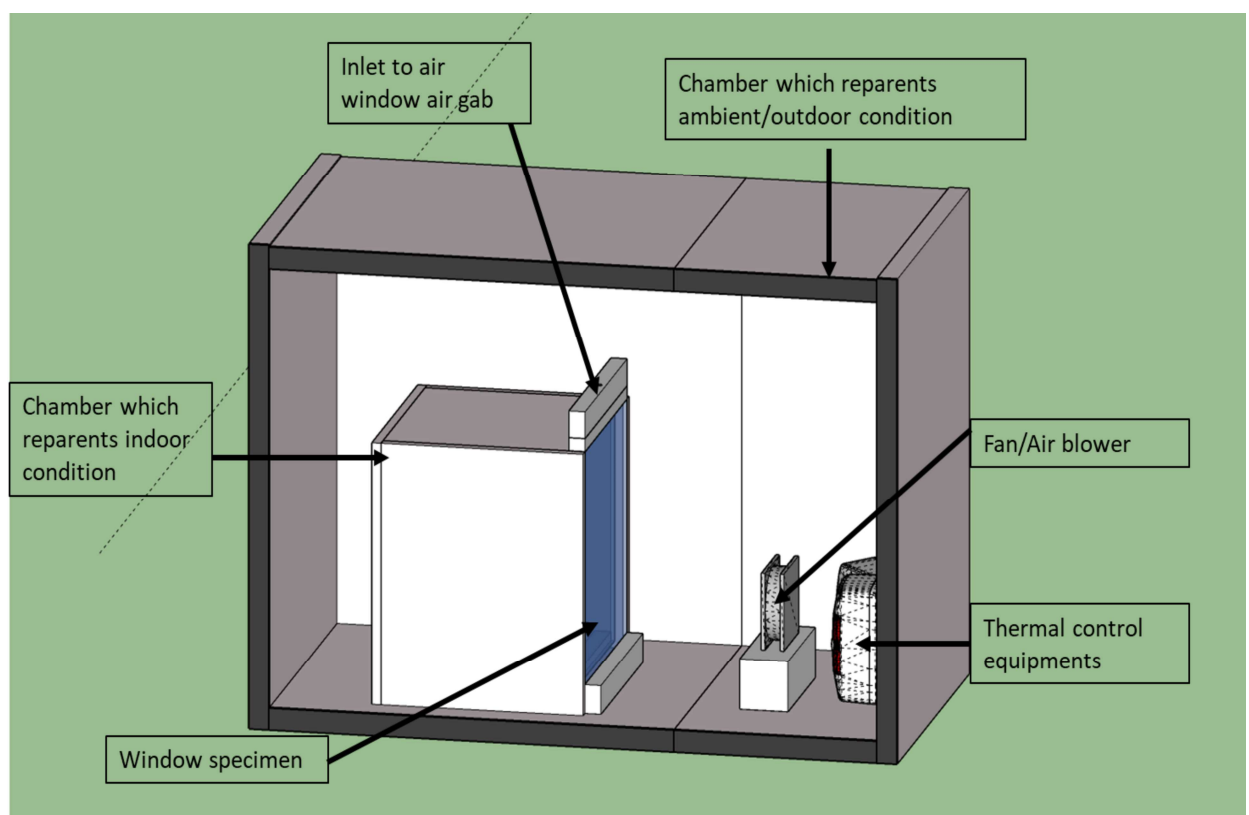


Fig 8. Experiment model 02 components illustration



Fig. 9. Experiment model internal view

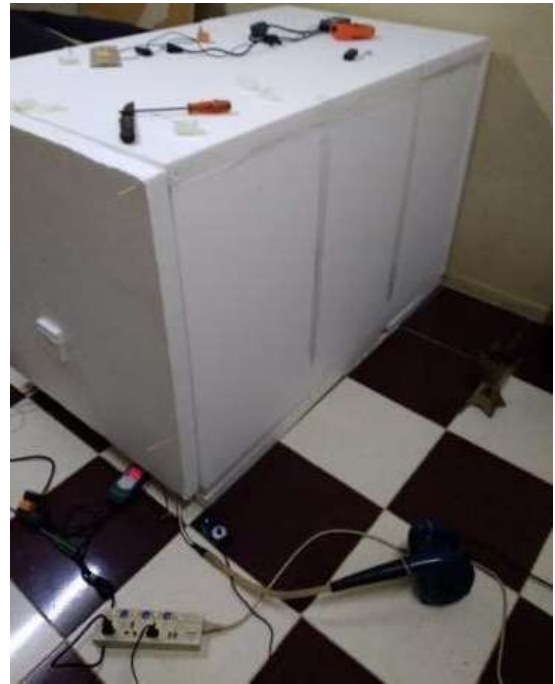


Fig. 10. Experiment model external view



Fig. 11. Outer glass Temp. reading



Fig.12 -Model 02 A solar radiation

3.1.2- The CFD Simulation procedure

A Computational Fluid Dynamic (CFD) simulation has been used to investigate the thermal characteristics of the window system and extract the amount of temperature variation of the surface. The CFD simulation tool can simulate the system thermally and aerodynamically. Nonetheless, when it came to thermal simulation, a wide range of scenarios could be test, with low margin of error, such as testing the system with different speed, pressure, indoor and outdoor temperature, and different locations and climates considering solar radiation and humidity. However, in this thesis, Ansys Fluent is being used to fulfil thesis objectives.

Ansys Fluent Workbench™ platform directly couples with CAD software and automatically extracts and meshes fluid volumes. It enables easy control operation via a small set of parameters. The yield is the high-quality meshes critical for both accurate and fast CFD simulation. CFD package includes solvers that accurately simulate behavior of the broad range of flows. Each solver is highly robust, well tested, validated and optimized for fast simulation time. Time tested and part of a single environment, the highly efficient solvers deliver both accuracies[73], [74], [75], [76].

As mentioned previously, this work will invest Ansys CFD Fluent capabilities to the optimum, they variant scenarios will be tested, like different climates, velocities, and type of glazing, therefore, each test conducted, its procedure will be mentioned in detail at chapter 5.

Based on fact that Ansys Fluent is used it this work, AmgX is default linear solver, on the other hand, dispersed turbulence model was used eliminating any mixture of the material components, with turbulent intensity of 5% and turbulent viscosity ratio of 10 as recommended values by the software. The model's mesh used was polygonal shape, and each model has 512000 cells, as it is the optimum available in student version. For inlet condition, it was defined as velocity inlet, with absolute reference frame; for outlet condition, it was defined as pressure outlet, with absolute reference either. Inner and outer temperature of the environment was specified in the software, while the glass surface temperature was designed as by system coupling, to vary with each single alternative.

Simulation convergence limits were set to 10000 which software mostly takes less than this to converge the solution.

EAW was tested by 4 different models with 18 alternative experiments to measure its thermal performance; yet the experiment suffers from lots of discrepancies due to material, tools and equipment used to conduct these experiments, and it was difficult reduce the margin of error with such financial and technological capabilities, hence, these experiments were conducted within variant of air inlet pressure, temperature, velocity and within variety of outdoor conditions and temperatures, with and without solar radiation. However, results used to contradict with literature review, the justification of such discrepancies will be discussed in the following chapters.

CHAPTER- 4

CFD SIMULATION PROCEDURE

4.1 Introduction

In this chapter, CFD simulation results will be presented and discussed; The thermal properties of the window system have been examined, and the amount of surface temperature variation has been extracted from CFD simulation. The system can be thermal and aerodynamic simulated with the help of the CFD simulation program. However, a large range of situations might be tested using thermal simulation, with a small margin of error, including testing the system at various speeds, pressures, indoor and outdoor temperatures, as well as different climates considering solar radiation and humidity. Ansys Fluent software program is employed in this thesis to achieve the set goals. Table 13 shows material specification of the simulation, and table 14 shows solver, boundary condition and meshing specification. On the other hand, a summary of all simulations with their description and results are listed in table 15. Simulation convergence considered achieved based on literature review, which states that scaled residuals reach limits of 10^{-6} for x, y, and z momentums, 10^{-5} for k, epsilon, and continuity[77].

Table.13. Simulation material specification

Foam	
Density	20 kg/m ³
Specific heat	1400 J/kg*K
Thermal conductivity	0.036 W/m K
Glass	
Density	2500 kg/m ³
Specific heat	792 J/kg*K
Thermal conductivity	0.8 W/m K
Aluminum	
Density	2710 kg/m ³
Specific heat	903 J/kg*K
Thermal conductivity	240 W/m K

Table.14. Meshing, boundary condition and solver specification

Meshing and solver specification	
Software	ANSYS FLUENT 2022 R1
Modeling software	SketchUp/AutoCAD 3D
Type of solver	AmgX linear solver/Pressure based
Turbulence model	dispersed turbulence model
Turbulence intensity	5%
Mesh characteristics	polygonal shape
number of cells	Based on sensitivity analysis
Simulation convergence limit	10000 iterations
Velocity formulation	absolute
Time	steady
Gravity	9.81 m/s ²
Initialization method	Standard Initialization
Initialization computed from	all zones
Time step method	Automatic
Length scale method	Conservative
Time scale factor	1
Verbosity	0
Inlet Specification	
Boundary conditions	velocity inlet
Velocity specification method	Magnitude, normal to boundary
Supersonic/Initial gauge pressure Pa	0
Turbulence intensity	5%
Turbulence specification method	Intensity and viscosity ratio
Turbulence viscosity ratio	10
Velocity magnitude	varies as per trial
Outlet Specification	
outlet boundary conditions	pressure outlet
Backflow reference frame	absolute
gauge pressure Pa	0
Pressure profile multiplier	1
Backflow direction specification method	normal to boundary
Backflow pressure specification	total pressure
Turbulence specification method	Intensity and viscosity ratio
Backflow Turbulence intensity	5%
Backflow Turbulent viscosity ratio	10
Target mass flow rate	Via system coupling
Average pressure specification	Via system coupling

Table.15. Summary of simulation results

NO.	CFD simulation	Description	Results
1	Simulation 01 (based on experimental model 02)	controlled indoor and outdoor environment, with .5mx0.5m window size, 2cm air gap, outdoor and indoor temperature of 45 °C and 24 °C respectively.	0.5°C increment of inner window surface
2	Simulation 02 (based on experimental model 02)	controlled indoor and outdoor environment, with .5mx0.5m window size, 2cm air gap, outdoor and indoor temperature of 45 °C and 24 °C. variant velocities.	0.1°C increment of inner window surface in range of 2 to 10 m/s
3	Simulation 03 (based on experimental model 02)	controlled indoor and outdoor environment, with .5mx0.5m window size, 2cm air gap, outdoor and indoor temperature of 45 °C and 24 °C. variant air gap.	0.4°C increment of inner window surface in range of 2 to 10 cm air gap
4	Simulation 04 (based on experimental model 02)	controlled indoor and outdoor environment, with .5mx0.5m window size, 2cm air gap, outdoor and indoor temperature of 45 °C and 24 °C. variant inlet air temperature	0.65°C reduction of inner window surface in range of 18 to 28 °C inlet air temperature
5	Simulation 05 (based on experimental model 02A)	controlled indoor and outdoor environment, with .5mx0.5m window size, 2cm air gap, Solar radiation considered , indoor temperature 24 °C	0.5°C increment of inner window surface
Validating/benchmarking results with experimental data from literature			
6	Simulation 06 based on Zhang experimental setup	Window size 85x550m, air gap 4cm air gap two channel, air fins inside gap, other values as per Zhang et al	results match literature with 3% error margin
Double Glazing Energy Active Window (DGEW)			
7	Simulation 07 based on Zhang experimental setup	window size 85x550m, air gap 4cm air gap two channel, air fins inside gap, other values as per Zhang et al. variant velocities.	1 to 1.5°C increment of inner window surface in range of 0.1 to 1.2 m/s

8	Simulation 08 based on Zhang experimental setup	window size 85x550m, air gap 4cm air gap two channel, air fins inside gap, other values as per Zhang et al. Air volume.	almost no increment of inner window surface temperature, in range of 0.01 to 1 kg/s
9	Simulation 09 based on Zhang experimental setup	window size 85x550m, air gap 4cm air gap two channel, air fins inside gap, other values as per Zhang et al. variant air gap.	1.0 °C reduction of inner window surface temperature, between 2cm to 4cm air gap; after 4 cm there is almost no variation
10	Simulation 10 based on Zhang experimental setup	window size 85x550m, air gap 4cm air gap two channel, air fins inside gap, other values as per Zhang et al. variant outdoor temperature.	System shows an acceptable result, where in range of outdoor temperature from 36 to 52 °C, only 1°C increment of inner window surface
Triple Glazing Energy Active Window (TGEW)			
11	Simulation 11 based on Zhang experimental setup	window size 85x550m, air gap 4cm air gap two channel, air fins inside gap, other values as per Zhang et al. variant velocities.	1 to 1.5°C increment of inner window surface in range of 0.1 to 1.2 m/s
12	Simulation 07 based on Zhang experimental setup	window size 85x550m, air gap 4cm air gap two channel, air fins inside gap, other values as per Zhang et al. variant air gap.	2.0 °C reduction of inner window surface temperature, between 2cm to 4cm air gap; after 4 cm there is almost no variation

Figure 14a show the procedure of CFD simulation, which start from identifying the material specs such as density and thermal conductivity, then specify meshing and solution specs based on available used software, afterwards a CFD simulation was conduct within literature review for validation. Nonetheless after having a verified model, simulations were conducted for all variables to evaluate the output based on solid bottom.

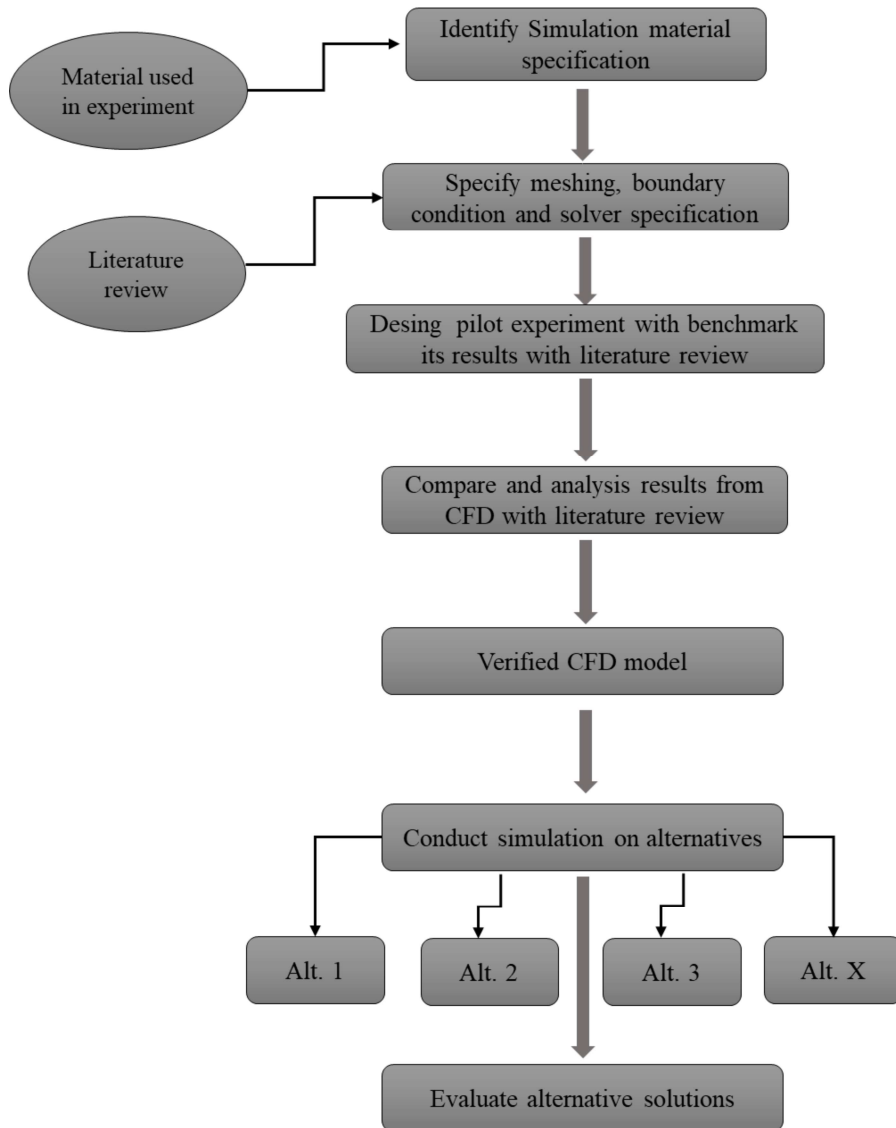


Figure 14a. CFD simulation procedure

4.2- CFD Model Development

CFD simulation was conducted to verify experiment results, Ansys Fluent 2022 R1 version was used to make the meshing, settings, simulation and extracting results. on the other hand, AutoCAD 3D & SketchUp2020 were used for the modeling. Nonetheless, the setup which was built to conduct the experiment was exactly modeled to have accurate results, noting that simulating areas, sizes, and fluid variable parameters were also per the pilot experiment.

The model was developed to represent the prototype engineering wise, which represented on its size, orientation, order, dimensions and thickness of the objects; where on the other hand, thermal properties of the material was represented by specifying the density of the materials, specific heat and thermal conductivity, which were taken from the materials' suppliers. Moreover, outdoor environment was design within the software in way where it represents the hot climate of Saudi Arabia.

The model is made to represent two types of windows which are basically DGEW and TGEW surrounded by two chambers, two represent outdoor environment and indoor environment. The two chambers were made of foam to represent the environmental envelope; the outdoor chamber was sat in way to generate/radiate heat in equivalent mode among entire windows surface, which was extremely difficult during experiment design and implantation, because the margin of the error would relatively high considering its results, air was inject inside the window gap to present return/exhaust air.

the air flowing properties were specified as per boundary condition driven from literature review and experiment condition. Air specifications play significant impact on model's boundary condition, which therefore play a fatal role while applying the governing equation, which would affect simulation convergence.

4.3- Discretization (meshing) Scheme:

The general goal of all CFD meshing techniques is to provide a point grid that can be utilized to solve the system of partial differential equations controlling the flow of fluid in a CFD simulation. As the example below -Figure 31- illustrates, the geometric mesh employed in a particular CFD issue can be rather intricate. In addition to having a variable density across the structure, the geometry made up of the mesh points—such as tessellations, tetrahedra, trapezoids, hexagons, etc.—can also change between different areas of the system[26], [78], [79]. Nonetheless, two important factors need to be considered during meshing process which are meshing design and meshing geometry, which will be detailly described in chapter 5. Simulation was conducted considering model uses 2cm gap and 45 °C outdoor temperatures as base, in other words, this experimental model was considered as validation model to conduct the CFD simulation on its basis. Figure 31 shows the meshing which is taken as 0.002m which is relatively high, and can affect the accuracy of the study, that it would reduce the required calculation per surface plane, however, it was taken in that element size due to limited allowed calculation per simulation for student version package, yet Ansys 2022 was used to do meshing sensitivity analysis, do determine element size with low margin of difference.

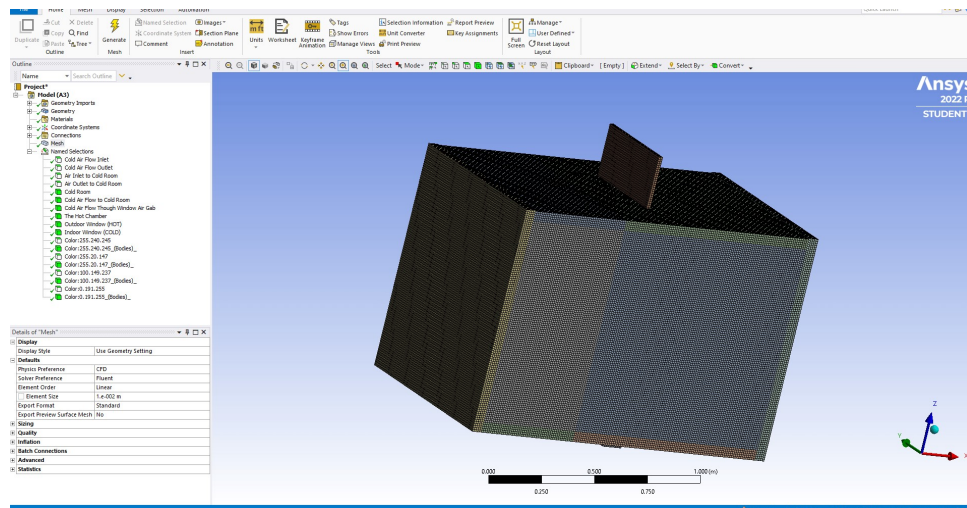


Fig. 31 CFD model Meshing

4.4- Boundary conditions of CFD simulation:

In the field of CFD, getting reliable results requires accurate data to simulate the environment/surrounding conditions as accurate as possible; nonetheless, getting these types of results required mainly on several key factors such as matching real environment's boundary conditions. The importance of the boundary conditions are sourced from it identifies the type of the reaction happens between the simulated body and its surrounding[54], [79]. However, in the simulation conducted, four types of boundary conditions were taken based on type of the case and software used; the four boundaries were as follows:

1. Velocity Inlets: The velocity at which fluid enters the domain is known, and the pressure is calculated.
2. Pressure Inlets: The total pressure is specified based on experiment conditions or from literature review based on experiment parameters, and the velocity is calculated. This type was mainly used in this simulation because it is essential in buoyancy-driven flow problems, which is required due to study air behavior in air gap.
3. Pressure Outlets: The total pressure is specified, and the velocity is calculated.
4. Wall Boundaries: Impermeable walls ensure no flow through them. At walls, a no-slip condition is applied, meaning the tangential velocity of the fluid at the wall is the same as the fluid velocity[80], [81], [82].

Boundary conditions of CFD simulation were coming basically from air parameters, properties of air inlet which based on temperature and speed, that energy equation were activated to make the software able to predict and calculate heat transfer between model components as shown in figure 32 which highlight air inlet properties.

4.5- Governing Equations

The governing differential equations of fluid dynamics which is the basis for modern computer modeling is shown in equations 2,3,4,5,6 and 7. The governing differential conditions of liquid elements frame the premise for advanced computer modeling, known blandly as computational fluid dynamics, or CFD. Until the 1960s and 1970s, arrangements to the conditions of liquid flow were ordinarily based on approximations and disentanglements that planned tractable for explanatory strategies for differential conditions[80], [83]. When effective computational assets got to be accessible, numerical arrangement methods were formulated and common reason CFD codes created to supply common arrangements for viable issues Nowadays, CFD recreation (and huge computer control) is unavoidable. As a result, CFD has presently gotten to be inserted as portion of the examination workflow for engineers and researchers. Portion of the reason of this course is to uncover this presently common shape of liquid flow examination utilizing the CFD computer program Ansys Familiar[73], [74], [75].

Navier-Stokes conditions are the governing conditions of Computational Fluid Dynamics [75], [76], [80], [81], [82], [84]. Figures 34 and 35 illustrate material properties which were taken as per standards, to have close results from the experiments. Figure 36 shows air inlet properties which are made to match experiment measurements when it comes to velocity magnitude and the amount of temperature inserted and seen in figure 37. Measurements show that inlet air velocity is 4 m/s with temperature of 25 °C which was reflected in the simulation at air inlet properties.

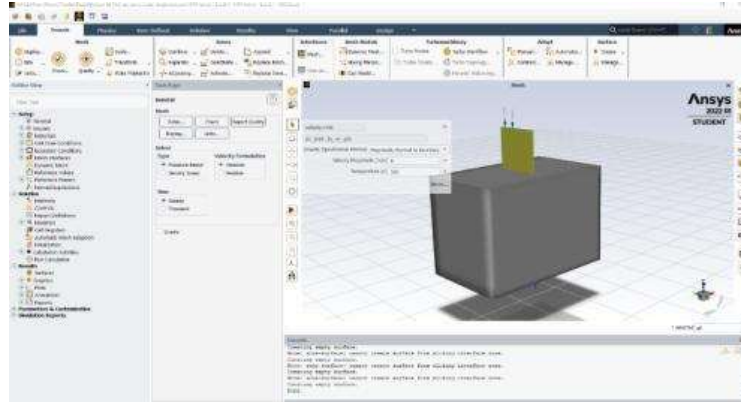


Fig. 32 Air inlet properties

$$\begin{aligned}
 \text{Continuity} \quad & \frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i} (\rho u_i) = 0 \quad \longrightarrow \quad \text{Eq.2} \\
 \text{Momentum} \quad & \frac{\partial}{\partial t} (\rho u_i) + \frac{\partial}{\partial x_j} (\rho u_i u_j) = -\frac{\partial P}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} \quad \longrightarrow \quad \text{Eq.3} \\
 \text{Energy} \quad & \frac{\partial}{\partial t} (\rho h_{\text{tot}}) + \frac{\partial}{\partial x_j} (\rho h_{\text{tot}} u_j) = \frac{\partial P}{\partial t} + \frac{\partial}{\partial x_j} (u_j \tau_{ij} + \lambda \frac{\partial T}{\partial x_j}) \quad \longrightarrow \quad \text{Eq.4}
 \end{aligned}$$

$$\text{where} \quad \tau_{ij} = \mu \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} + \frac{2}{3} \delta_{ij} \frac{\partial u_k}{\partial x_k} \right) \quad h_{\text{tot}} = h + \frac{1}{2} u_i^2$$

SST k-omega Governing Equations

Turbulence Kinetic Energy

$$\frac{\partial k}{\partial t} + U_j \frac{\partial k}{\partial x_j} = P_k - \beta^* k \omega + \frac{\partial}{\partial x_j} \left[(\nu + \sigma_k \nu_T) \frac{\partial k}{\partial x_j} \right] \quad \longrightarrow \quad \text{Eq.5}$$

Specific Dissipation Rate

$$\frac{\partial \omega}{\partial t} + U_j \frac{\partial \omega}{\partial x_j} = \alpha S^2 - \beta \omega^2 + \frac{\partial}{\partial x_j} \left[(\nu + \sigma_\omega \nu_T) \frac{\partial \omega}{\partial x_j} \right] + 2(1 - F_1) \sigma_{\omega 2} \frac{1}{\omega} \frac{\partial k}{\partial x_i} \frac{\partial \omega}{\partial x_i} \quad \longrightarrow \quad \text{Eq.6}$$

F1 (Blending Function)

$$F_1 = \tanh \left\{ \min \left[\max \left(\frac{\sqrt{k}}{\beta^* \omega y}, \frac{500 \nu}{y^2 \omega} \right), \frac{4 \sigma_{\omega 2} k}{C D_{kw} y^2} \right] \right\}^4 \quad \longrightarrow \quad \text{Eq.7}$$

Create/Edit Materials

Name: foam

Material Type: solid

Order Materials by: ☒ Name ☐ Chemical Formula

Chemical Formula: foam

Fluent Solid Materials: foam

Mixture: none

Fluent Database...
GRANTA MDS Database...
User-Defined Database...

Properties

Density [kg/m³]: constant Edit...

Cp (Specific Heat) [J/(kg K)]: constant Edit...

Thermal Conductivity [W/(m K)]: constant Edit...

Change/Create Delete Close Help

Fig. 34 Material properties 01

Create/Edit Materials

Name: glass

Material Type: solid

Order Materials by: ☒ Name ☐ Chemical Formula

Chemical Formula: gl

Fluent Solid Materials: glass (gl)

Mixture: none

Fluent Database...
GRANTA MDS Database...
User-Defined Database...

Properties

Density [kg/m³]: constant Edit...

Cp (Specific Heat) [J/(kg K)]: constant Edit...

Thermal Conductivity [W/(m K)]: constant Edit...

Change/Create Delete Close Help

Fig. 35 Material properties 02

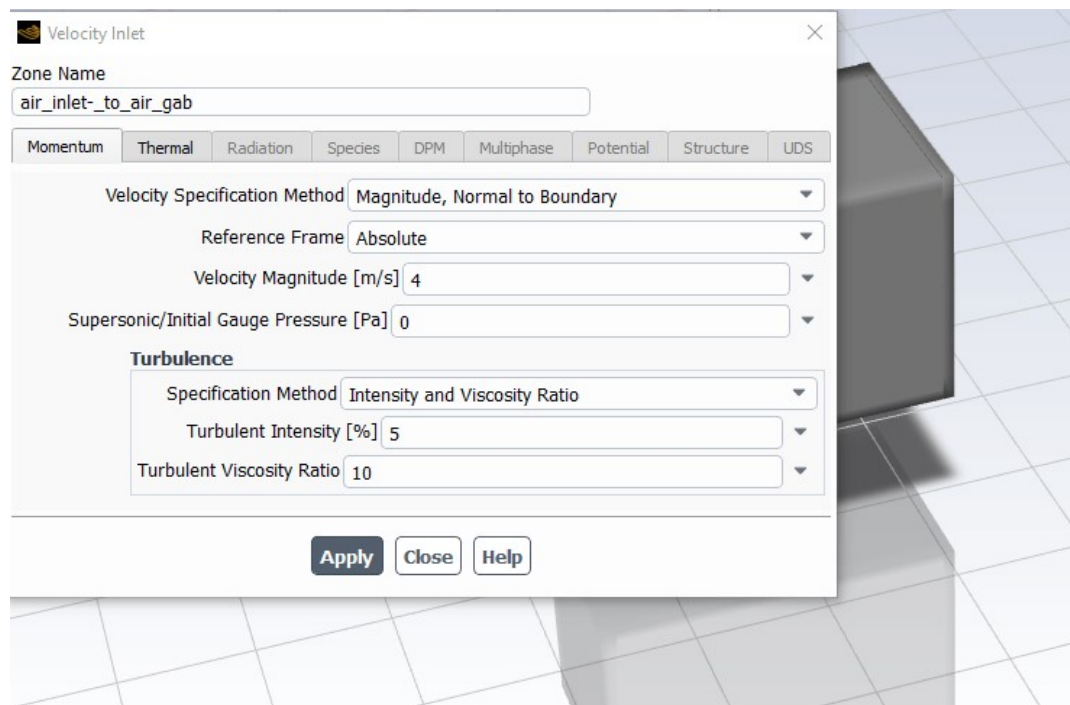


Fig. 36 Air inlet properties



Fig. 37 Air inlet velocity reading

Figure 38 show iteration for a steady simulation. The number of iterations per time steps indicate how many times the flow equations has been solved per time step before moving on to the next time step. Generally, in this case the number of iterations was take as 10000. However, it may increase or decrease this number depending on application. In the residuals plot, it can be noticed a saw-tooth pattern, which indicates the iterations per time step. The residual curve will start from a high at 1st iteration, keep dropping if everything is fine until 2000th iteration. This completes the first-time step and then the residual will rise again and drop for the next 2000 iterations and so on.

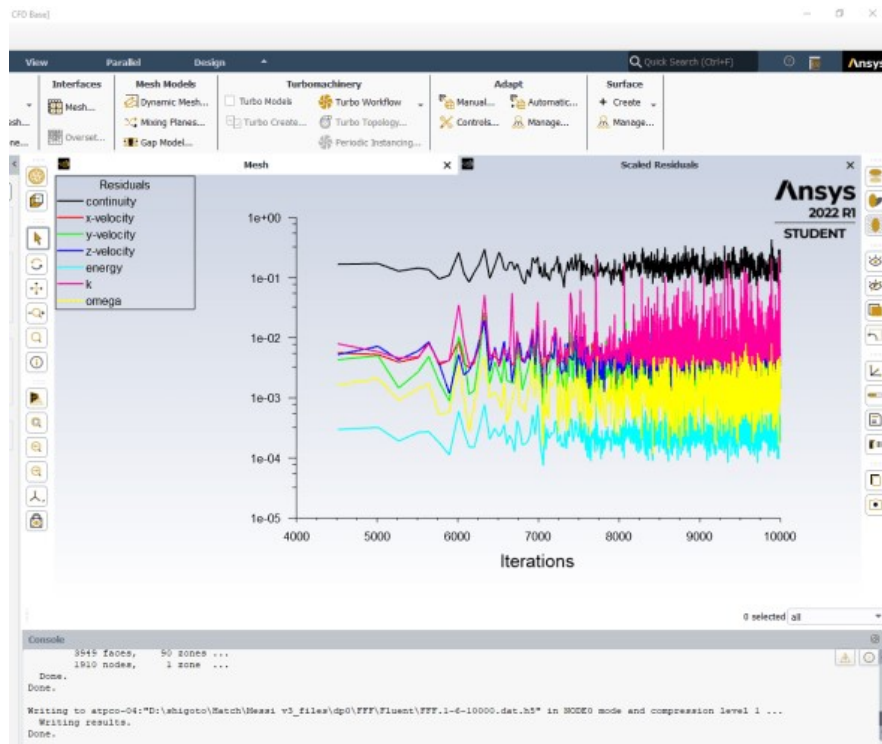


Fig. 38 Simulation iteration

4.6- Turbulence model in CFD simulations:

CFD strategy in view of the Reynolds Arrived at the midpoint of Navier-Stokes (RANS) approach is as yet thought to be as the most well-known choppy displaying approach in auto enterprises because of its satisfactory precision and reasonable computational expense for anticipating streams including complex calculations. This famous utilization of RANS endures despite the verifiable truth that, for car streams, RANS choppy models frequently neglect to describe the related stream field appropriately [75]. It is even a fact that on a more regular basis, the RANS approach neglects to foresee right indispensable streamlined amounts like lift, drag, or second coefficients, and thus, they are utilized to evaluate the general size and course of a pattern. Also, in any event, for such purposes, prominent conflicts for the most part exist between results anticipated by various RANS models. Because of quick advances in PC innovation, expanding notoriety has been found in the utilization of the mixture Disengaged Vortex Reenactment (DES), which mixes the RANS approach with Enormous Whirlpool Reproduction (LES). The DES philosophy showed a high capability of being more precise and useful than the RANS approaches. [75], [76], [78],

In RANS approaches, the whole choppy range is approximated through a bunch of transport conditions to settle the time-found the middle value of mean stream field. These conditions were laid out during the beyond a very long while in view of experimentation, numerical examination, and actual thinking of the key systems saw in sanctioned streams. RANS models have delighted in surprising outcome in different modern applications [73], [74], [75]. Be that as it may, the powerlessness of RANS models to foresee complex isolated streams accurately has roused analysts to create and apply higher request models in modern applications. One promising model is the DES approach. DES is a mixture displaying approach that consolidates the best of both RANS and LES: a RANS recreation in the thickness overwhelmed limit layers and a LES in the shaky isolated locales [73], [74], [75].

4.7- Simulation convergence

One of the main problems in using CFD software is convergence. The study of fluid mechanics involves non-linear processes and phenomena that are inherently unstable, such as turbulence. Because CFD software aims to represent/simulate these environmental reactions and processes, it has many of the same problems as the processes it is meant to depict. As a result, there is no assurance that a problem will have a steady-state "converged" solution. The majority of computational fluid dynamics issues are non-linear, and the methods for solving them employ an iterative process to gradually improve a solution until "convergence" is attained [80], [81], [82]. In many research articles, convergence can signify many things. *‘More formally, in mathematics, convergence describes limiting behaviour, particularly of an infinite sequence or series toward some limit. To assert convergence is to claim the existence of a limit, which may be itself unknown. For any fixed standard of accuracy, you can always be sure to be within it, provided you have gone far enough’* [80].”

As this definition makes clear, but you want to be close enough to the solution to meet the required accuracy level. Thus, convergence does need to be linked to a specific degree of precision being required. This criterion is contingent on the intended use of the solution. In addition, the degree of residuals—that is, the degree to which discretized equations are unsatisfied—are frequently used to quantify convergence rather than solution error. Because of this, the user needs to be aware of this when choosing which convergence criterion to apply when evaluating a solution [80], [81].

When it comes to the case studied in this paper, simulation convergence considered achieved based on literature review, which states that scaled residuals reach limits of 10^{-6} for x, y, and z momentums, 10^{-5} for k, epsilon, and continuity [77].

4.8- Simulation post-processing

Post-Processing is crucial stage in correctly deriving the appropriate conclusions from the models and simulation, presenting the findings to users, and guaranteeing the optimal prototype/model design is post-processing of computational fluid dynamics (CF; considering that CFD simulations frequently produce enormous output files, it might be difficult to effectively construct visual aids[78], [85].

Design choices necessitate optimization research, which calls for a high volume of separate CFD simulations. I've used numerous well-known CFD visualization tools in a variety of industries over the years, and my experience has led me to understand some best practices that should always be followed[85].

CFD simulations don't end with the fluid flow prediction. Post-processing that provides users with full insight into the outcomes of their fluid simulation is necessary in order to represent the benefits of the simulation. ANSYS CFD-Post, was used as post-processor that It has quiet manageable graphics that ANSYS CFD-Post generates to demonstrate the flow in any desired level of detail are limited in their ingenuity by the current and user-friendly interface which can easily notice in figure 38b . ANSYS CFD-Post gives all the tools needed to create perceptive solution visualizations, including 3D pictures that can be viewed by everyone with the freely distributable 3D viewer, from vector plots and streamlines to vortex cores and flow animations.

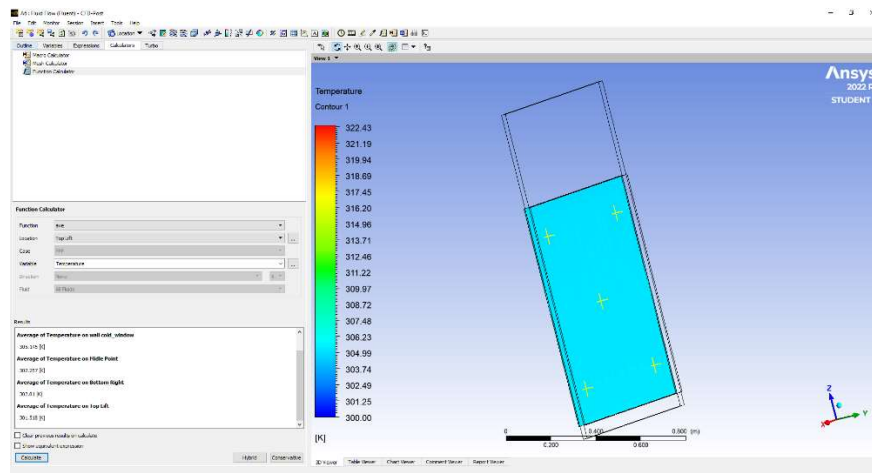


Fig.38b ANSYS CFD-Post

CHAPTER- 5

CFD SIMULATION RESULTS

In This chapter CFD simulation results will be detailly discuss and validated these outcomes with experimental model described from previous chapter or from literature review. Figure 39 shows the first output from the simulation results, which is a general view of temperature distribution on both chambers. Figure 39 shows that the temperature of the chamber wall would reach range of 39 to 42 degree, which is in the acceptable difference domain of the experiment model, which is temperature reaches 42 °C as shown in figure 39.

On the other hand, a primary result of the simulation can be represented by figure 40, which shows how surface temperature of the inner window which reach 33.85 °C, and it can be notice the relative uniformity of temperature among window, nonetheless, these results will be discussed in detail in the fallowing sections.

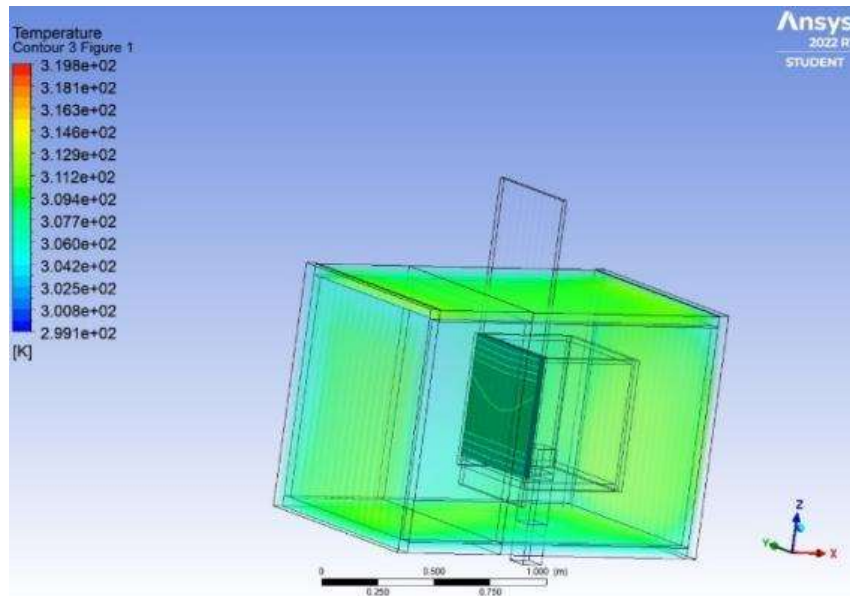


Fig. 39 Heat distribution among the chambers

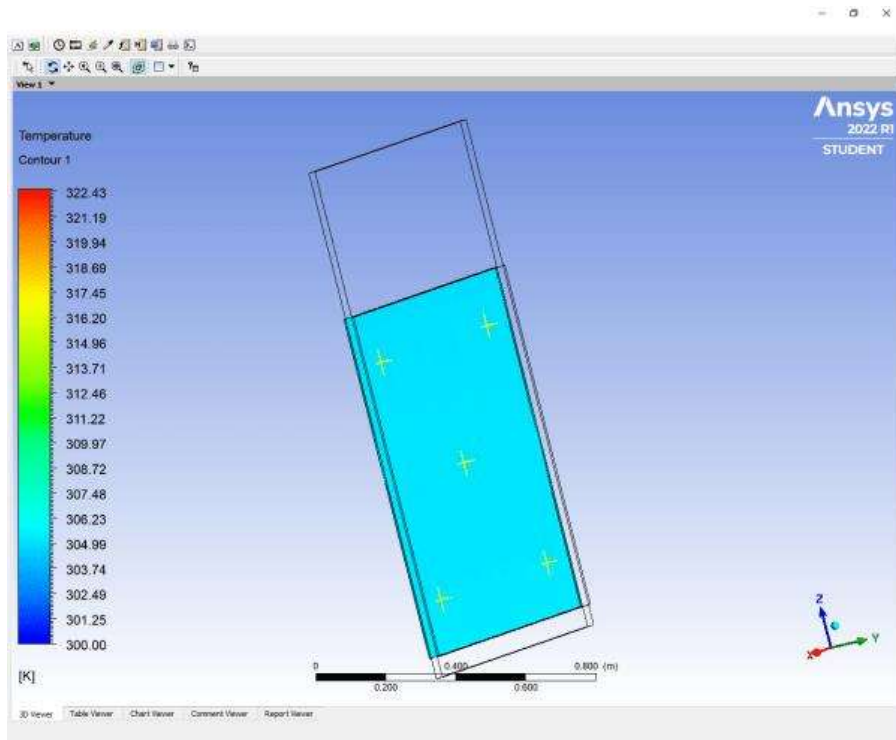
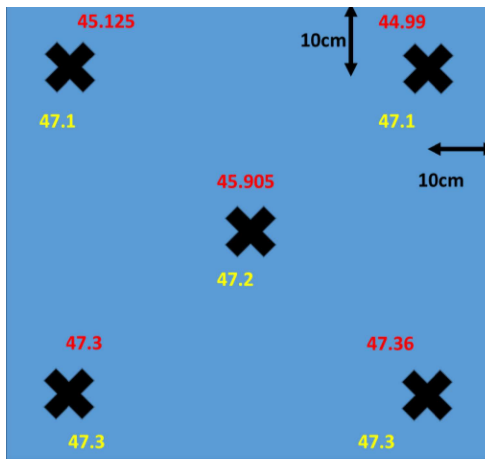


Fig. 40 Heat distribution among indoor glass

Figure 41 shows the amount of indoor window glass panes. It illustrates that the average temperature of window after air flowing inside air gap could reach 32.17 °C, where the initial set temperature for the window is 32°C. In other words, CFD simulation proves that such concept would increase the surface temperature of the inner glass even if the amount is very low. Nonetheless, comparing CFD result with experiment result would show 6°C difference, that in experimental model temperature reach 38.1°C. However, such a difference could be due to span of experiment time, that the software makes the calculation until there is no variation in temperature at all, which it would take up to 6 hours, where the experiment with time span of two hours only, nonetheless, figure 42 shows the comparison between experiment and simulation for five points, having one in the middle and four at 10cm offset from edge. Figure 43 shows the rate of temperature decreased when air flow in between window glass panes, that it reduced from 50 °C to 48.2 °C. Figure 41 and 43 respectively as visual representation of the results, which shows that inner glass pane increased by a very low margin, where the outer glass pane temperature decreases, which in line with general view of experiment, despite its high margin of difference between the simulation and the experiment, which could reach 14%.



Fig.41 comparing experiment and simulation



- Yellow for experiment results.
- Red for stimulation results.

Fig.42 comparing experiment and simulation

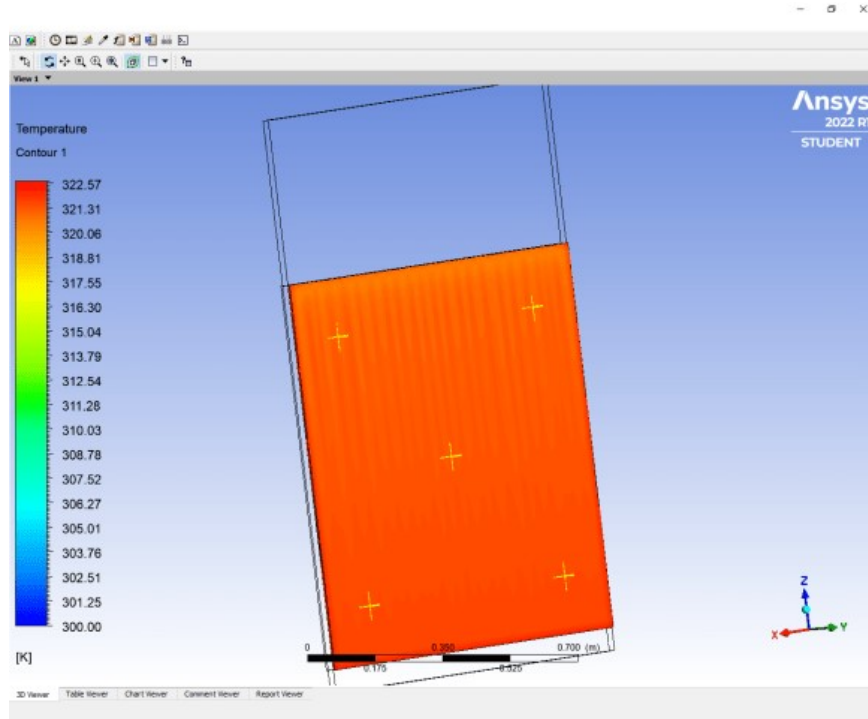
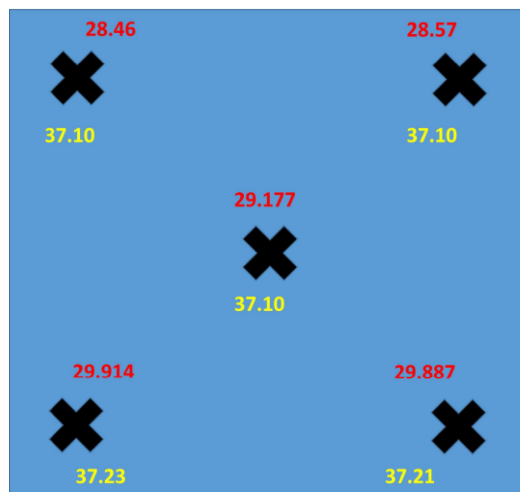


Fig. 43 Heat distribution on outdoor glass



- Yellow for experiment results.
- Red for stimulation results.

Fig.44 comparing experiment and simulation.

Table 14 and 16.1 represent previous figures, which illustrate the values of experimental and simulation results, hence tables are highlighting the differences between them and percentages from; table 16 compares outdoor glazing temperature for the experimental setup and CFD simulation, it can be noticed that margin of difference is very low that it doesn't reach 5%.

On the other hand, Table 14.1 comparing outcomes of the experimental setup with CFD simulation, which shows high margin of difference, could reach up to 27%, it also shows differences between two results reaches 10 °C, which is totally out of the acceptable margin of error. Table 16.1 clearly highlights that there is a critical issue in regard of the experimental outcomes, that this high margin of error/difference can't be justified.

Table.16. Experiment and simulation results for outdoor glazing

Comparison of experiment and simulation results for outdoor glazing			
Point	Experiment	Simulation	Difference %
A	47.4	45.125	4.917589841
B	47.1	44.99	4.582473667
C (Middle Point)	47.2	45.909	2.773093901
D	47.3	47.3	0
E	47.3	47.36	-0.126769491

Table.16.1. Experiment and simulation results for outdoor glazing

Comparison of experiment and simulation results for indoor glazing			
Point	Experiment	Simulation	Difference %
A	37.1	28.46	26.35753508
B	37.1	28.57	25.97837673
C (Middle Point)	37.1	29.177	23.90874662
D	37.23	29.914	21.7919695
E	37.21	29.887	21.82809962

5.1- Simulation of alternatives:

Different alternatives were simulated based on air velocity, air temperature, and air gap. Moreover, in these simulations a good replication of the experimental model properties was made within then virtual CFD simulation to provide reliable and more accurate results. This was achieved by locating the position of the experiment latitude and longitude, and specifying the date and time of simulation, which in turn would provide accurate solar calculations and therefore considering solar radiation in the results outcome to be compared to trial-06 results, which was conducted considering sun radiation.

Figures 45 and 46 show the setting of relevant solar properties within the CFD software for Dhahran, using average solar radiation of 1423 W/m^2 as constant value for direct irradiation and 200 W/m^2 as diffused solar irradiation. Date of simulation was chosen to be 3 of May that it is the hottest day in year in Saudi Arabia and the study area.

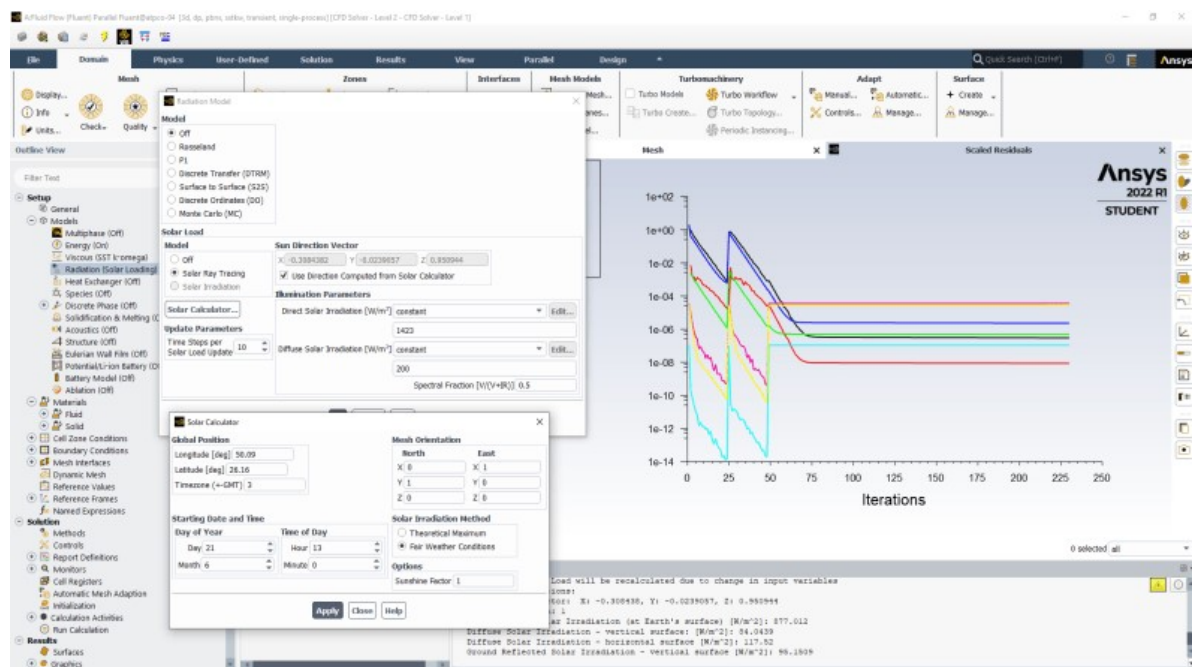


Fig. 45 Solar calculation at May

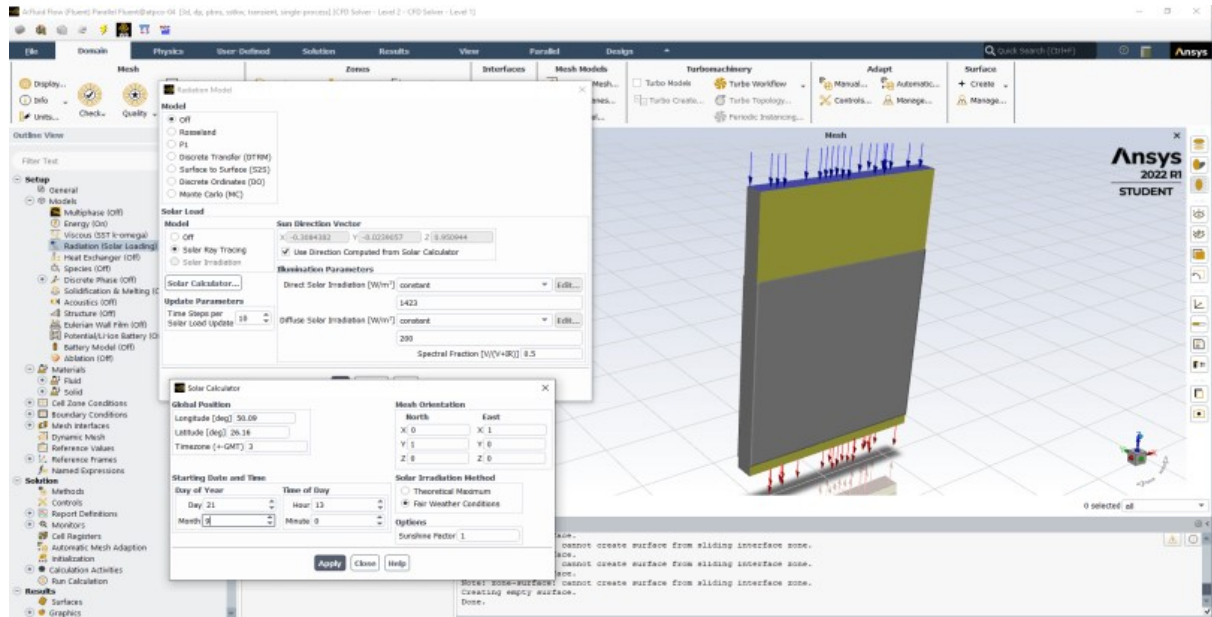


Fig. 46 Solar calculation at month of May

Table 17 shows the results of the CFD simulation which doesn't provide a notable variation for the experiment results. When it comes to velocity, it can be noticed that it decreases the surface temperature of the outer pane by $1.3\text{ }^{\circ}\text{C}$ in domain of 2 to 10 m/s, on the other hand, the temperature of inner glass pane increases by $0.063\text{ }^{\circ}\text{C}$ in same domain of air velocity. When it comes to air gap it can be noticed that it decreases the surface temperature of the outer pane by $0.5\text{ }^{\circ}\text{C}$ in domain of 2 to 10 cm gap between windowpanes. On the other hand, the inner glass pane temperature increases by $0.4\text{ }^{\circ}\text{C}$ in same range of air gap.

Air temperature plays a limited role as previous variables, it can be noticed that it decreases the surface temperature of the outer pane by $0.683\text{ }^{\circ}\text{C}$ in domain of 18 to $28\text{ }^{\circ}\text{C}$ as temperature of air flowing between windowpanes. On the other hand, the inner temperature glass pane its temperature increases by $0.646\text{ }^{\circ}\text{C}$ between 18 to $28\text{ }^{\circ}\text{C}$, that low temperature of air flowing, would decrease the temperature of the inner glass, but it would increase the temperature of the outer one. However, the relation between air flow temperature and surface temperature decreasing is not encouraging at all, that it requires lot of energy to reduce air temperature without a notable change or reduction in the window surface temperature, that reducing air temperature by $10\text{ }^{\circ}\text{C}$ would reduce inner surface window

Table.17. Result of CFD simulation for three variables/alternatives

Constant values: 2cm Gap, T=26 C		
Air Velocity	Outer glass surface temperature	Inner glass surface temperature
2	49.5	33.35
4	48.85	33.37
6	49.087	33.39
8	48.981	33.394
10	48.2	33.413
Constant values: V=4m/s, T=26 C		
Air Gap	Outer glass surface temperature	Inner glass surface temperature
2	49.5	33.35
4	49.03	33.705
6	49.005	33.73
8	49.003	33.747
10	49.002	33.759
Constant values: 2cm Gap, V=4m/s		
Air Temperature	Outer glass surface temperature	Inner glass surface temperature
18	48.32	34.296
20	48.993	33.648
24	48.998	33.648
26	49.087	33.649
28	49.003	33.65

by 0.6 °C only. It is worth mentioning that the listed temperatures in table 17 as well as figure 47,48,49 are average temperature amount on the glass surface.

For the three consecutives figures 47,48 and 49 can represent and summarize table17, they show relative inconsistent non well described relation between the alternatives and window thermal performance represented in the inner, however, the phenomenon of increasing inner glazing surface temperature reduced significantly; that when using alternatives that in favor of reducing surface temperature, especially return air temperature which is reducing down to 18 °C that it is able to make reduction of 2°C in surface window temperature. Yet, these results require to be bench marked with literature and make a plan to develop its performance, to increase the margin surface glazing reduction in its temperature.

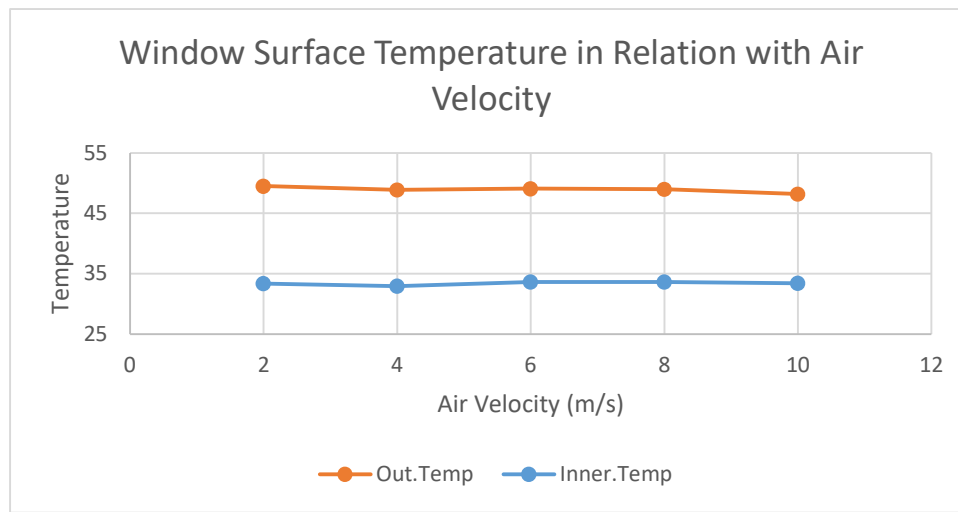


Fig. 47 CFD results for alternatives.

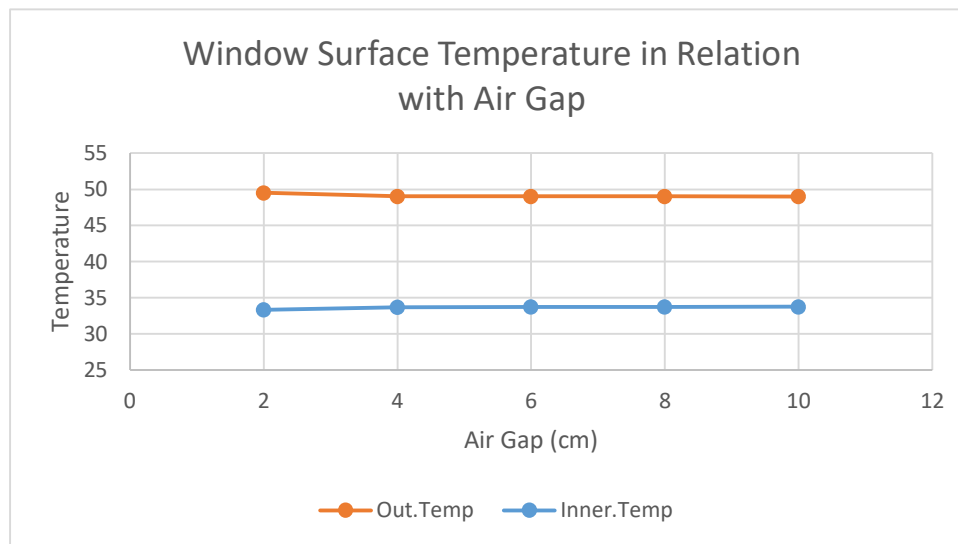


Fig. 48 CFD results for alternatives.

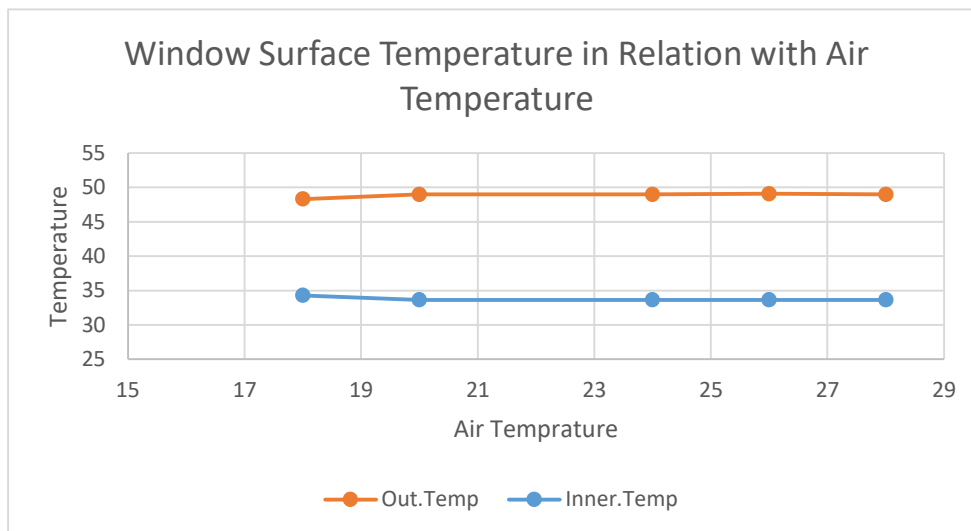


Fig. 49 CFD results for alternatives.

5.2- Validating/benchmarking results with experimental data from literature:

The experiment and simulation both show that there is tendency of this window system to increase its surface temperature rather than reduce it, therefore, a CFD simulation has been used to provide as deeper investigation through this dilemma. Hence, the thing that initiate the uncertainty of the previous results that it is contradicting with literature review published with same area, Zhang et al. [69] made a study discussing the same topic considering cold climate; they made experimental setup and compare with numerical model, their setup has better environmental control, technologies, and abilities than the one provided in this work.

However, the exact setup has been modeled in the CFD, and the results founded has been compared with the one made by Zhang et al and determine the margin of error between them, then the same simulation condition was applied to the proposed alternatives to test its reliability and even could have positive results proving that such a system could reduce

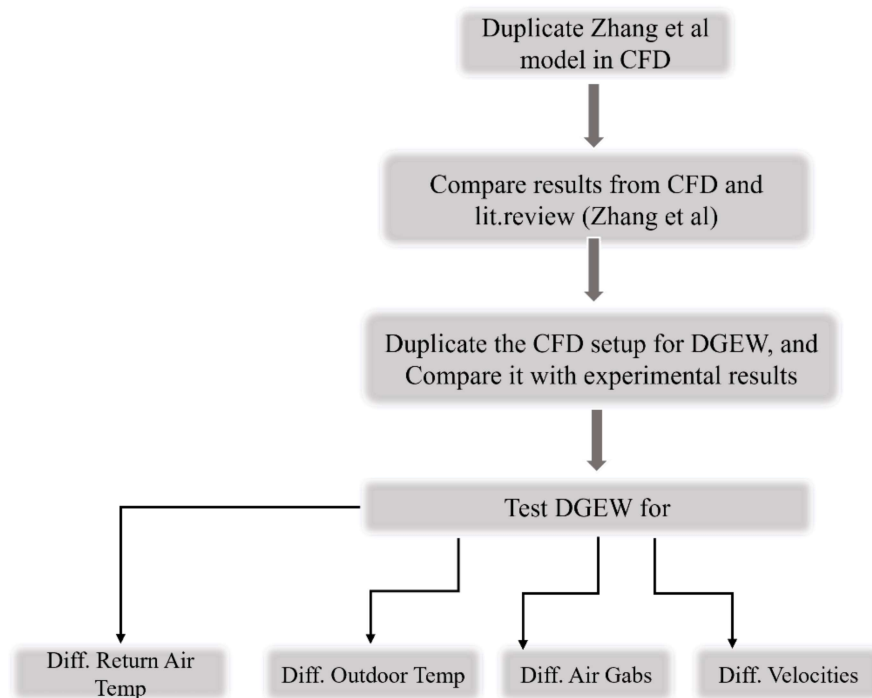


Fig. 50 Validating CFD with experimental data from literature

the temperature of the inner glazing comparing to normal glazing system in hot climate of gulf countries and Saudi Arabia; figure 50 summarize the benchmarking process .

Figure 51 shows triple glazing energy active window (TGEW) modeling and its component as per Zhang et al which is made of 3 glass panes, aluminum fins, and two chambers, considering the following the parameter mentioned in table 16.

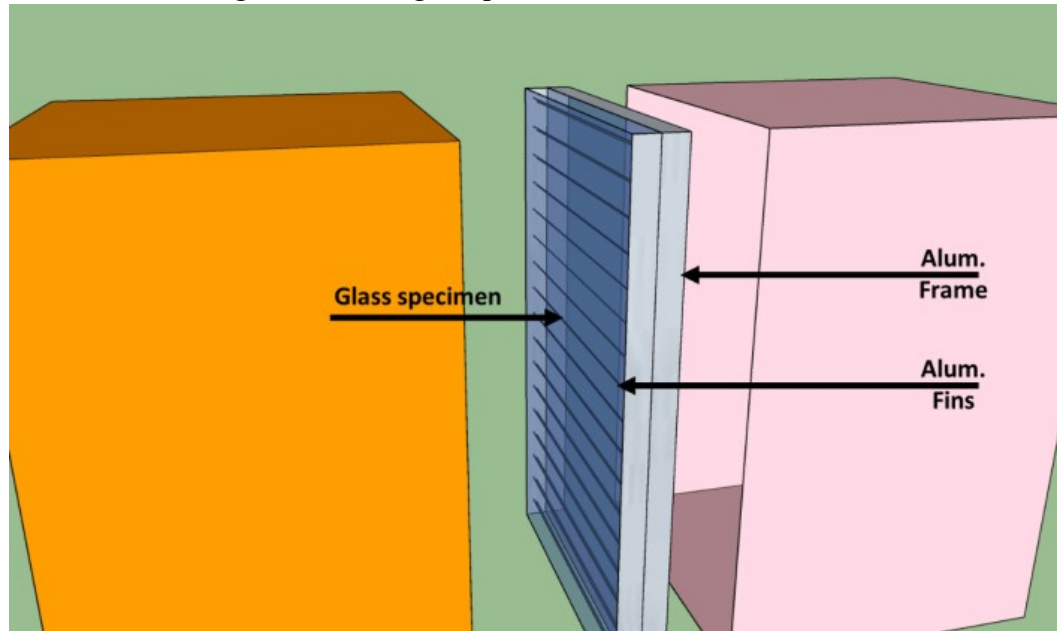


Fig. 51 TGEW model as per Zhang et al model

Table.16. CFD simulation parameter as per Zhang et al experimental setup

Variable	Value
Window Size	850 (L) mm x 550 (W) mm
Single Cell Size	1550 (L) mm X 850 (W) mm X 2000 (H)mm
Air Gap	40mm Two Air Channel
Aluminum fins	45 °C slanted
Flowing rate inside air gap	0.234 m/s
Indoor Temperature	24 C
Outdoor Temperature	Varies with day and solar irradiance
Air flow Temperature	Higher that indoor temperature

5.2.1- Meshing sensitivity analysis:

In this section, the model was subjected to a variety of meshing/element sizes and different number of nodes for both DGEW and TGEW. Meshing sensitivity analysis is one of the main requirements to increase the reliability of the results; therefore, it would give a better understanding of spatial discrepancies errors, and into which limit meshi is affecting the results.

Using low size of meshing would definitely give a better result, yet it is not practical at all, that using a very fine meshing/small size would consume tremendous amount of time to converge, yet to provide or extract results for long list of alternatives; therefor, applying meshing sensitivity would able users to use a higher mesh/element size without affecting the results. The size of the mesh will be increased gradually, and their results will be

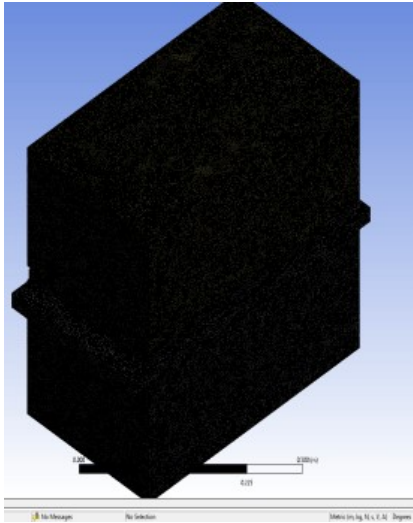


Fig. 52 A

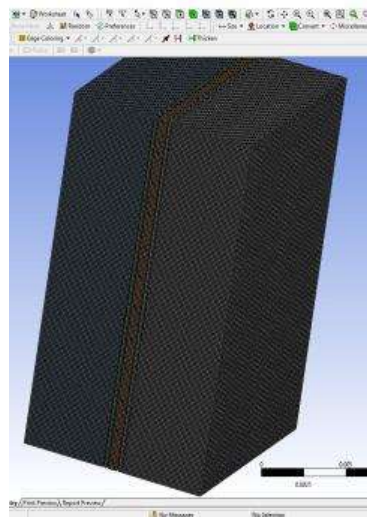


Fig. 52 B

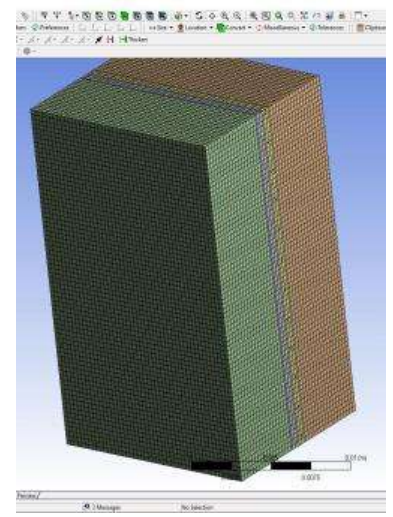


Fig. 52 C

compared with the outcome of the finer meshing, until the difference in result becomes notable. Figure 52 show variety of meshing sizes.

Figure 53A&b shows convergence critical for all meshing sensitivity analysis and validation study, that all the scaled residuals should go below 10^{-6} , which is more than what is required which is 10^{-5} according to literature review.

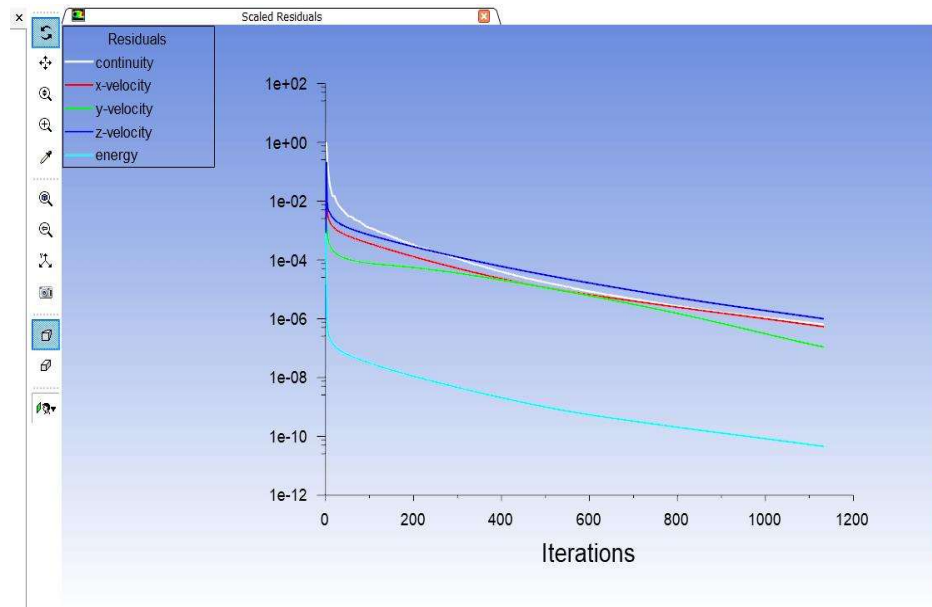


Fig. 53 A- scaled residual for TGEW

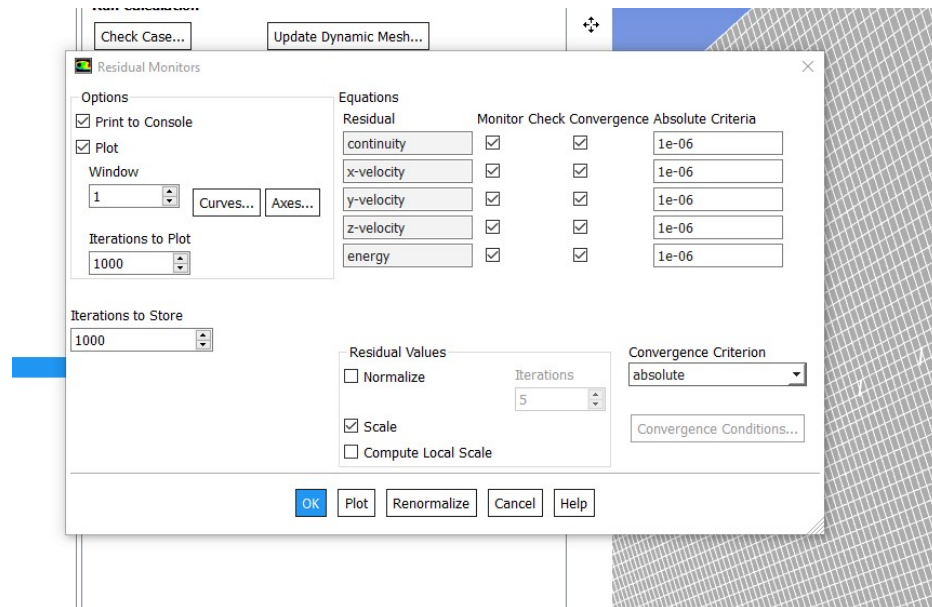


Fig. 53 B- Convergence criteria for validation and meshing sensitivity study

Table 17, illustrate Mesh independence test conducted on TGEW to ensure the results are not sensitivity grid elements size nor nodes, element sizes in range of 3×10^{-4} to 1×10^{-4} , and number of nodes in domain of 3.8 million to 170 thousand, it can be noticed that the margin of difference is less than 0.5% and higher than 0.01%. This sensitivity analysis illustrates the impact of the grids size on the outcomes of the study.

Table.17. TGEW meshing sensitivity analysis.

TGEW Meshing Sensitivity Analysis						
Element Size	Number of Nodes	Number of Elements	Outdoor Glazing Temp.	Mid. Glazing Temp.	Indoor Glazing Temp.	Parentage of Difference (Inner Glazing)
0.0003	170496	139308	34.479	31.18	29.846	0.083693214
0.00025	234157	200547	34.528	31.205	29.871	0.053534982
0.0002	514182	446880	34.604	31.391	29.887	0.026760328
0.00015	1151688	1033416	34.657	31.415	29.895	0.419706206
0.000125	1974336	1804656	34.782	31.561	30.021	0.016652235
0.0001	3838161	3573360	34.917	31.563	30.026	

Furthermore, same grid sensitivity analysis was conducted on DGEW, table 1, illustrates Meshing impact on DEW results, element sizes in range of 35×10^{-4} to 1×10^{-4} , and number of nodes in domain of 3.5 million to 102 thousand, it can be noticed that the margin of difference is in range of 3% to 0.05%, it can be observed that system fail to converge at 3×10^{-4} .

Table.18. DGEW meshing sensitivity analysis.

DGEW Meshing Sensitivity Analysis					
Element Size	Number of Nodes	Number of Elements	Outdoor Glazing Temp.	Indoor Glazing Temp.	Percentage of Difference (Inner Glazing)
0.00035	102705	102705	No Convergence	No Convergence	
0.0003	152976	129156	33.909	30.91	3.10177706
0.0002	467748	416640	33.96	30.95	0.226683938
0.00015	1069908	979848	34.011	30.88	-0.058256198
0.000125	1836702	1707776	34.042	30.898	0.13178931
0.000115	2310309	2158912	34.086	30.857	0.084329794
0.0001	3562788	3361680	34.127	30.831	

As an outcome e of this analysis, we can notice that using 0.00015 as element size would give relatively accurate outcomes, without going to extreme fine meshing, which would

increase converge time. Thus, striking a balance between meshing reliability and computational power is critically required to ensure successful study and accurate results.

5.2.2- Validation model:

The validation is required to ensure that study outcomes are free of any errors, moreover, to see if it is in line with previous literature and instigate the reason behind it differ if any; Figure 54 show the condition where the measurements were made in Wuhan according to Zhang's et al study; The areas where temperatures is more stable were stable were selected, which is at time without solar radiation (at night), so solar radiation component in this

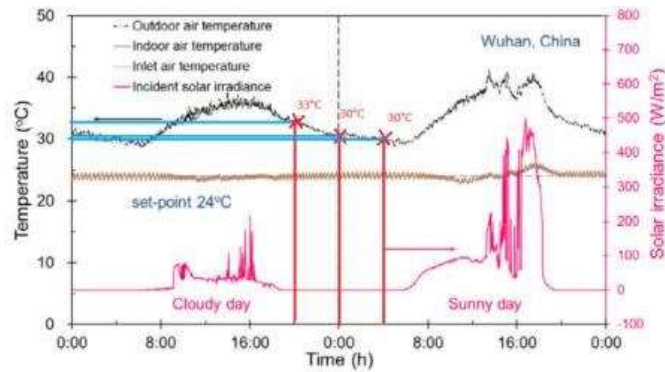


Fig. 54 Measured input parameters used

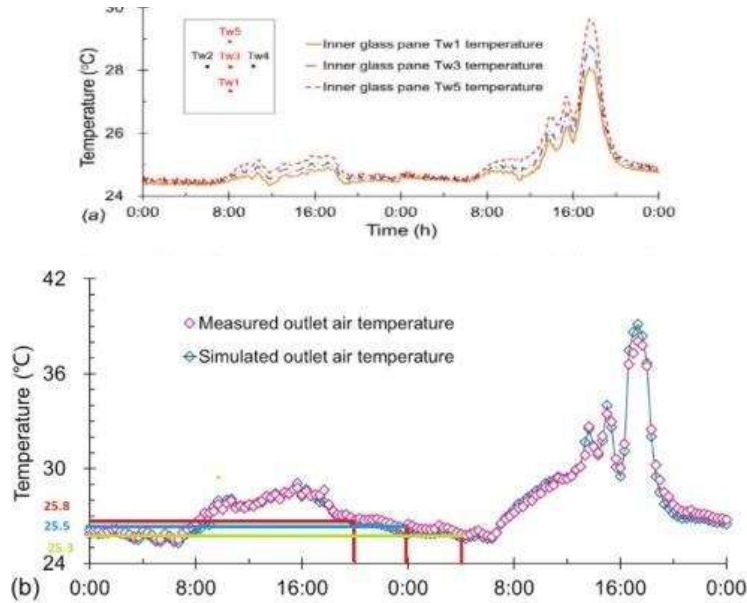


Figure 55 a. Measured indoor window temperature. b. Measured outlet temperature.

validation study is exclude, that temperature were measured at 4M, 12AM, and 8PM, at temperatures of 33°C, 30.2, 30 °C respectively. Figure 55 shows the results of Zhang's experimental setup, it shows the result in form of inner glazing surface temperature and out air temperature.

Table 19 summarizes outcomes of the validation study using inner glazing temperature as comparison criteria, however, figure 56 a,b and c provide graphical representation of table 19. In general, these graphs show that difference between Zhang's experimental result and CFD results is in range of 3% to 6%, which is within acceptable margin according to literature review [77] [78] [79]. Figure 56a shows inner window temperature at three middle points distributed vertically. At the constant part of the curve all three points are in the range of 24.5 °C - 24.75°C. Figure b shows the reading for the three points for measured outlet air temperature. It shows that the outlet has temperatures of 25.8 °C, 25.5 °C, 25.3 °C.

Table.18. DGEW meshing sensitivity analysis.

Outdoor Temp. 33°C			
	Inner Glazing Temp. Zhang at al	Inner Glazing Temp. CFD	Percentage of difference (%)
Tw5 (top point)	24.73	26.282	5.905%
Tw3 (Middle point)	24.58	26.096	5.809%
Tw1 (bottom point)	24.53	26.096	6.001%
Outdoor Temp. 30.2°C			
	Inner Glazing Temp. Zhang at al	Inner Glazing Temp. CFD	Percentage of difference (%)
Tw5 (top point)	24.66	25.588	3.627%
Tw3 (Middle point)	24.58	25.582	3.917%
Tw1 (bottom point)	24.5	25.52	3.997%
Outdoor Temp. 30°C			
	Inner Glazing Temp. Zhang at al	Inner Glazing Temp. CFD	Percentage of difference (%)
Tw5 (top point)	24.54	25.583	4.077%
Tw3 (Middle point)	24.52	25.544	4.009%
Tw1 (bottom point)	24.5	25.54	4.072%

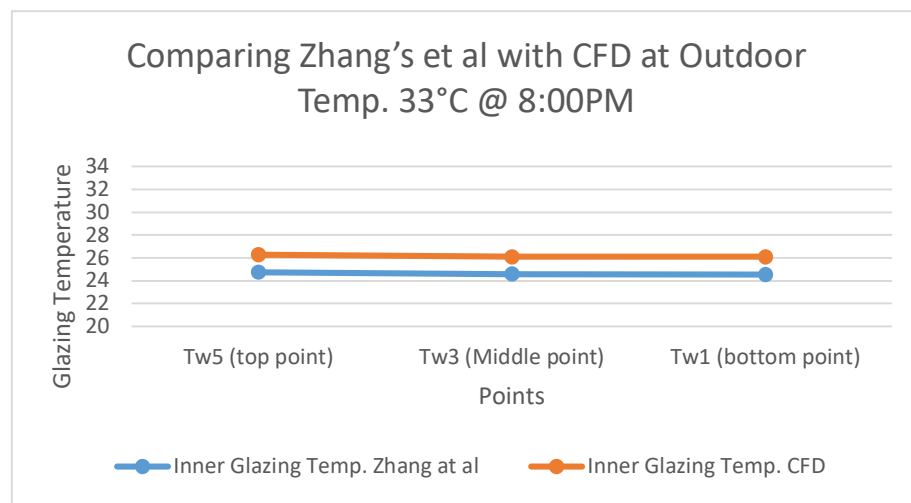


Figure 56 a. CFD and Zhang's experimental results at 33-degree outdoor temperature

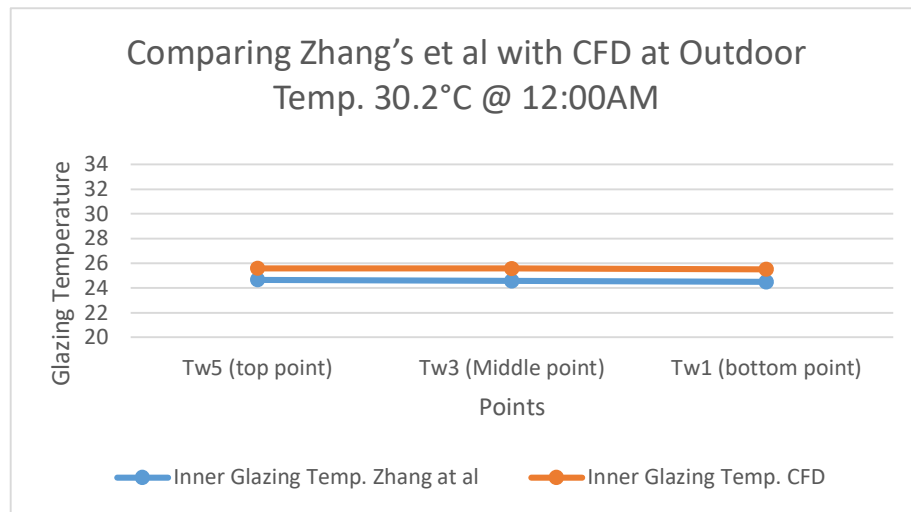


Figure 56 b. CFD and Zhang's experimental results at 30.2-degree outdoor temperature

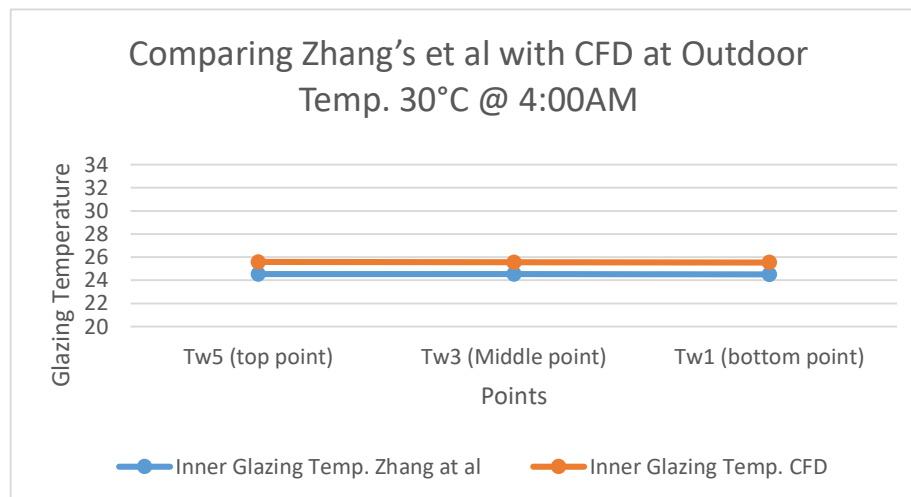


Figure 56 c. CFD and Zhang's experimental results at 30-degree outdoor temperature

Figure 57 compares and validates CFD results with literature review (Zhang's experiment) by using air outlet temperature. Table 19 shows the reading for the three different outdoor temperatures for measured outlet air temperature; While comparing experimental results from Zhang with CFD model, the difference recorded was in a range of 8.5 to 10 %, which is within acceptable margin of error.

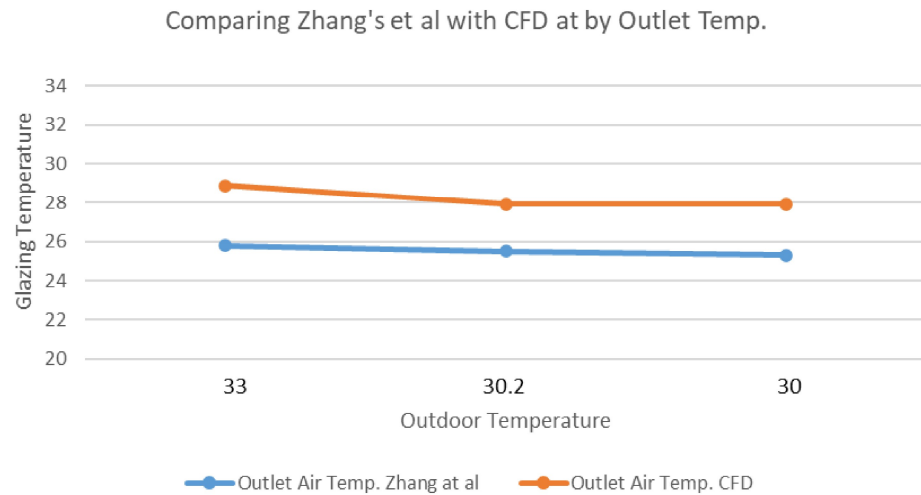


Figure 57. CFD and Zhang's experimental results at 30-degree outdoor temperature

Table.18. DGEW meshing sensitivity analysis.

Outdoor Temp.	Outlet Air Temp. Zhang at al	Outlet Air Temp. CFD	Percentage of difference (%)
33	25.8	28.893	10.705%
30.2	25.5	27.915	8.651%
30	25.3	27.903	9.329%

As a general output from the validation study, we can reach a conclusion that CFD model is reliable and in line with experimental results in literature, by margin of error within the acceptable range of 10%, thus, the subsequent simulation will be conducted confidently.

5.2.3- DGEW in hot climate of Saudi Arabia

After validating the CFD results as per the experimental setup described in literature, CFD simulation was used for all the subsequent studies for Double Glazing Energy Active Window (DGEW) & Triple Glazing Energy Active Window (TGEW). All related studies were conducted in the hot environment of Saudi Arabia to develop design guideline able to predict surface window/curtain temperature. Both DGEW and TGEW have been tested using the factors mentioned in figure 50 which are air velocity, air mass volume, RA temperature air gap, and outdoor air temperature. On the other hand, table 18 shows the justification behind domain of simulation for each variant.

Table18. Justification of selected simulation domain/ranges

Variant	selected ranges	Justification of the selected ranges
Air Velocity	0.234 m/s - 0.634 m/s	Zhang et al set their air inlet velocity to be 0.234m/s, therefore an increment of 0.1m/s was added with required domain
Air gap	2cm-10cm	12mm gab is the conventional type of window , yet while conducting the experiments, gap of less than 2cm isn't practical at all to inlet air, therefore, 2cm was selected to be the minimum gap, while other gap alternatives where in increment of 2cm
Air mass volume	3 kg/s - 13kg/s	going below 3kg/s would reflect on very low velocity (0.17m/s), which its effect can't be noticed
Return air temperature	24°C - 34°C	indoor temperature typical is 24°C, therefore it was selected to be starting point of simulation, yet it extremely rare for RA temperature increase higher than 34°C
Outdoor temperature	36°C - 52°C	this study intended to be in hot climate of Saudi Arabia, so the minimum expected temperature in the summer in Dharan climate would be 36°C and it can reach 48°C or 50 in extreme cases

Figure 54 illustrates the impact of air velocity on DGEW on surface glazing temperature of the windowpanes. it shows that velocity of air flowing inside the gap would reduce the temperature of the outer glazing by 2 °C whereas it wouldn't make a notable impact on inner glazing temperature. Moreover, it wouldn't give solid and direct relation to notice, despite the wide range of velocities been tested. Nonetheless, it seems that velocity makes higher and more tangible impact on outer pane than the effect of difference of the temperature start to appear. Note that in the previous chapter the impact of third law of thermodynamics was very clear in experimental field, where air was cooling the outer pane in clearer and higher rate; that the implication of the figure54 represents into certain extent that the heat is being transferred to inner pane with variant pace depending on the velocity.

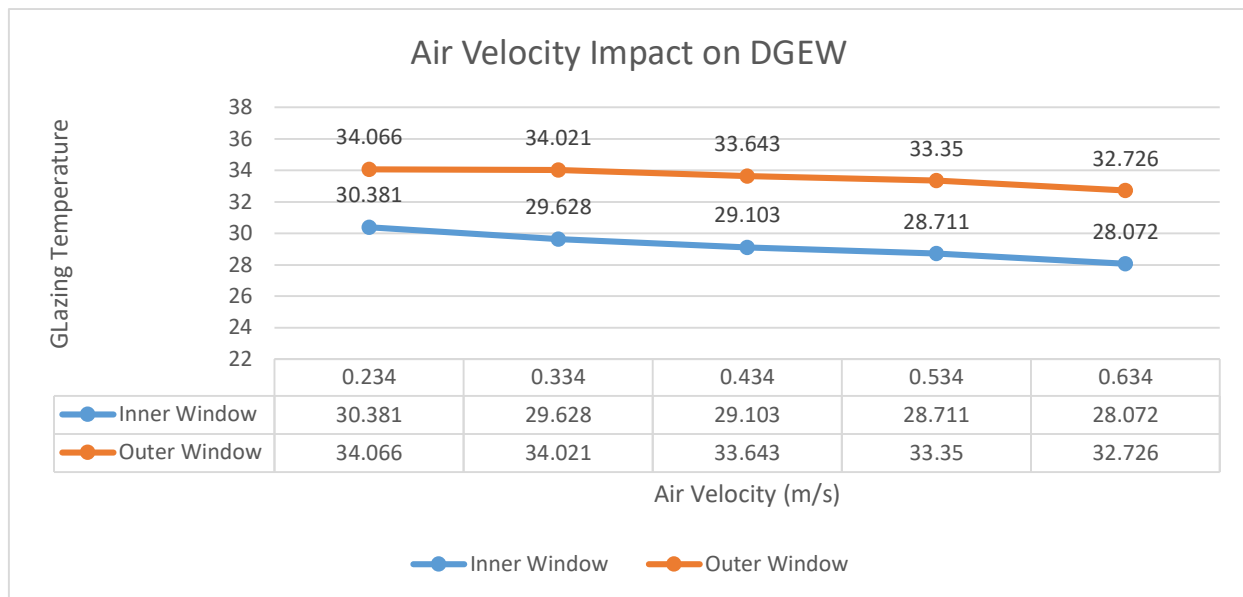


Fig. 54 Velocity impact on glazing temperature for DGEW

Figure 55 illustrates the contour of the temperature for the inner glazing at different velocities in domain of 0.343m/s to 0.543m/s consecutively from left to right; it can be notice that the lower operation of the inner glazing has lower temperature than middle and upper portion by 3°C to 4°C. moreover, as more the velocity increase the cold lower portion area keep increasing vertically, which is expected outcome from increasing the velocity. On the other hand, increasing the velocity may result of less contours, which may translate of tense variation of temperature along the glazing vertically, which can't be noticed in

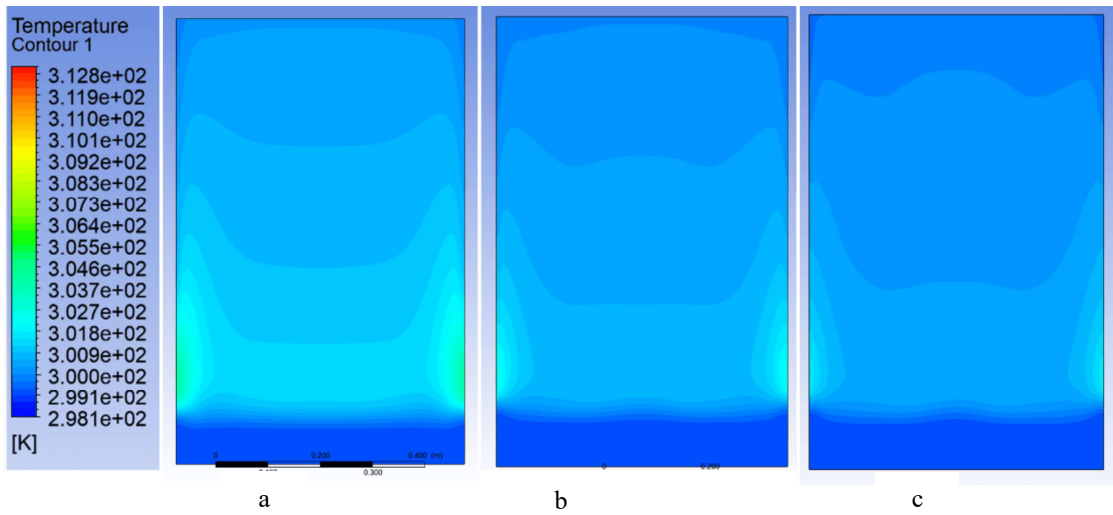


Fig. 55 Contour variation for inner glazing for A. $V=0.343\text{m/s}$, B. $V=0.434\text{m/s}$, C. $V=0.534\text{m/s}$

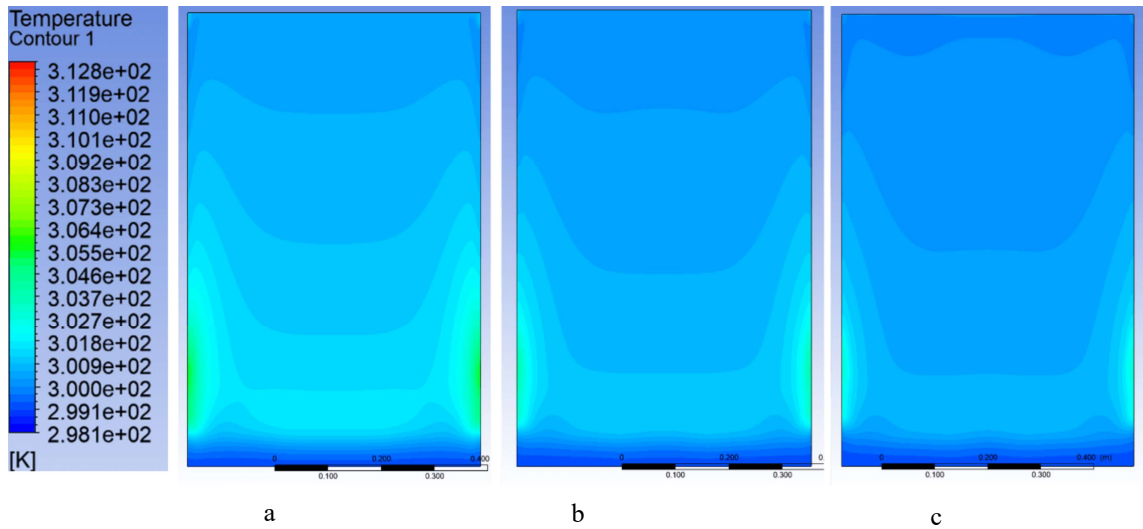


Fig. 56 Contour variation for outer glazing for A. $V=0.343\text{m/s}$, B. $V=0.434\text{m/s}$, C. $V=0.534\text{m/s}$

figure 55a, that contours seem smoother however, the same effect can be noticed in figure 56 which represents the outer glazing.

Figure 57 illustrates impact of air gap on DGEW on surface glazing temperature of the windowpanes, it shows that increasing the air gap from 2 to 4 cm would give 2 °C reduction in temperature for the inner glazing pane, where it would remain constant for the remaining air gap, which are between 4 to 8 cm. On the other hand, the temperature of the outer glass pane would remain constant without any notable variation. However, these results are aligned with main guideline of glazing and cavity system design in literature or standards such as ASHRAE, which says that window systems which contain cavity always tend to have optimum limit where the increasing space of the gap would be feasible thermally. On the other hand, it can be noticed that the phenomena of heat transferring from the outer pane to the inner pane even removed in this trial that after 4 cm air ability to transfer heat between glazing pane start getting less and barely noticed.

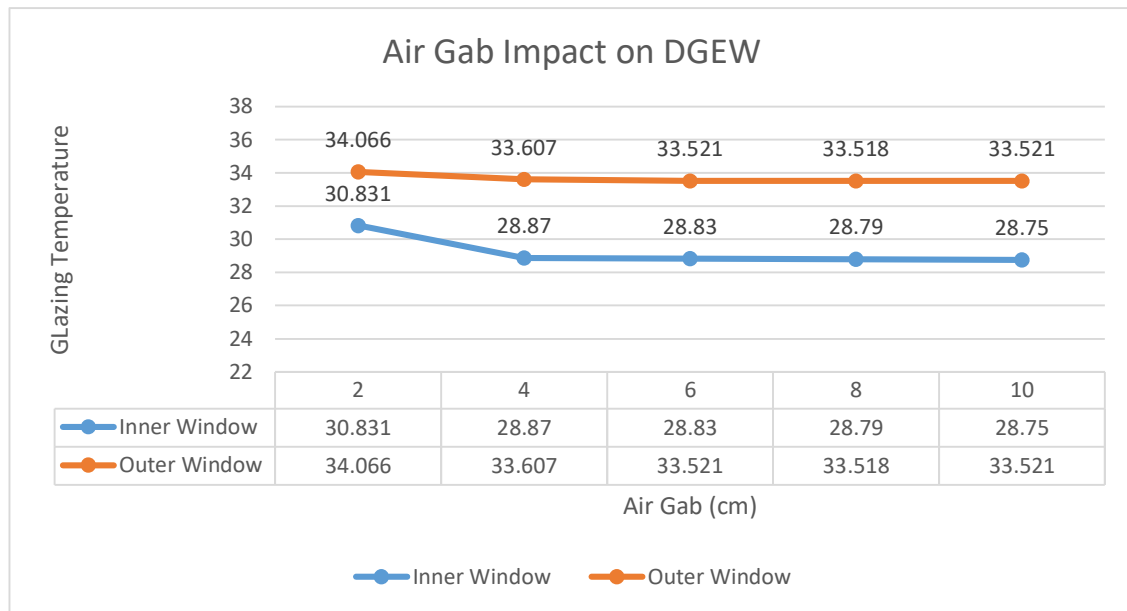


Fig. 57 Air gap impact on glazing temperature for DGEW

Figure 58 illustrates impact of air volume on DGEW surface glazing temperature of the windowpanes, it shows that increasing the amount of air flowing inside the gap would make a notable reduction of inner glazing by 4 degrees, and do the same with the outer pane; it would give rate of reduction in span of increasing the volume from 3 kg/s to 13 kg/s. Such a figure could give perspective on the required air volume in order to get tangible reduction of the inner glass pane temperature; the importance of such output that give a higher range of application for such a system -assuming its feasibility- won't be restricted to big space or rooms where air volume could be available, that relatively small amount of air would be enough; moreover, the rest of air could be retreated and cooled down.

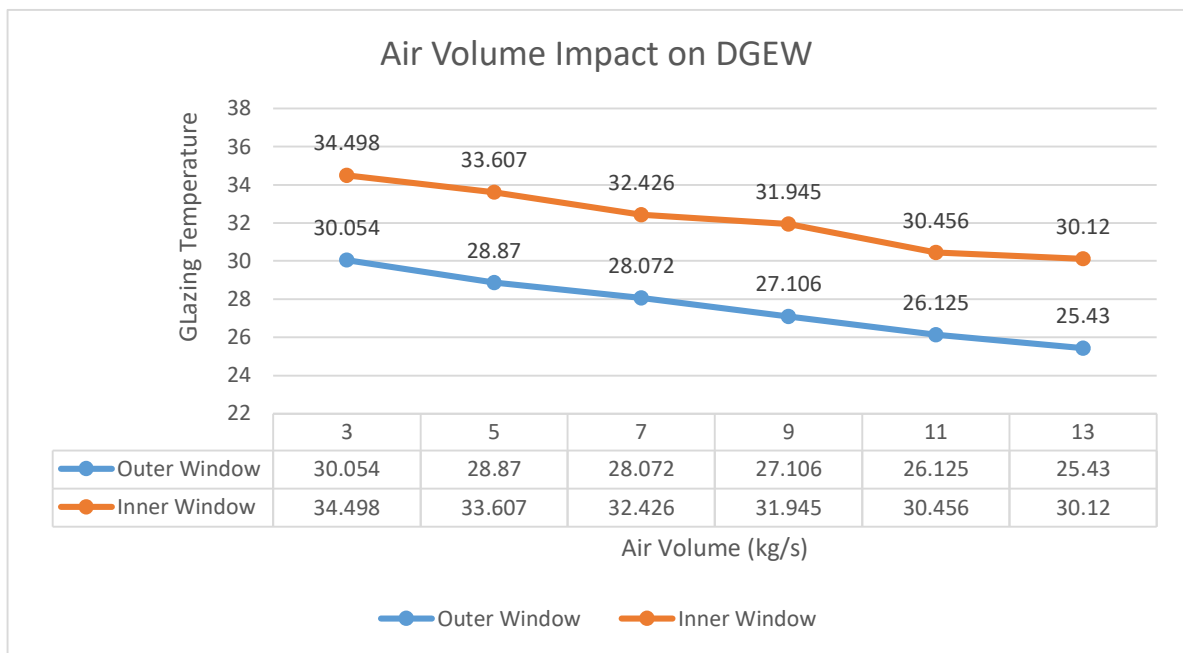


Fig. 58 Air volume impact on glazing temperature for DGEW

Figure 58 illustrates the impact of RA temperature on inner glazing temperature for DGEW, it can be noticed that in span of temperature between 24 °C to 34 °C inner glazing temperature increased by almost 2°Cm where the outer pane increased by almost same amount. In addition, it can be noticed that DGEW system is not very sensitive toward changes in RA temperature, that between 24°C to 28 °C there is only increment by 0.3 °C, which considered a very positive outcomes, that even if the RA is relatively high DGEW could perform effectively well. On the other hand, figure 59 illustrate the impact of RA temperature visually by show temperature contour on the inner glazing.

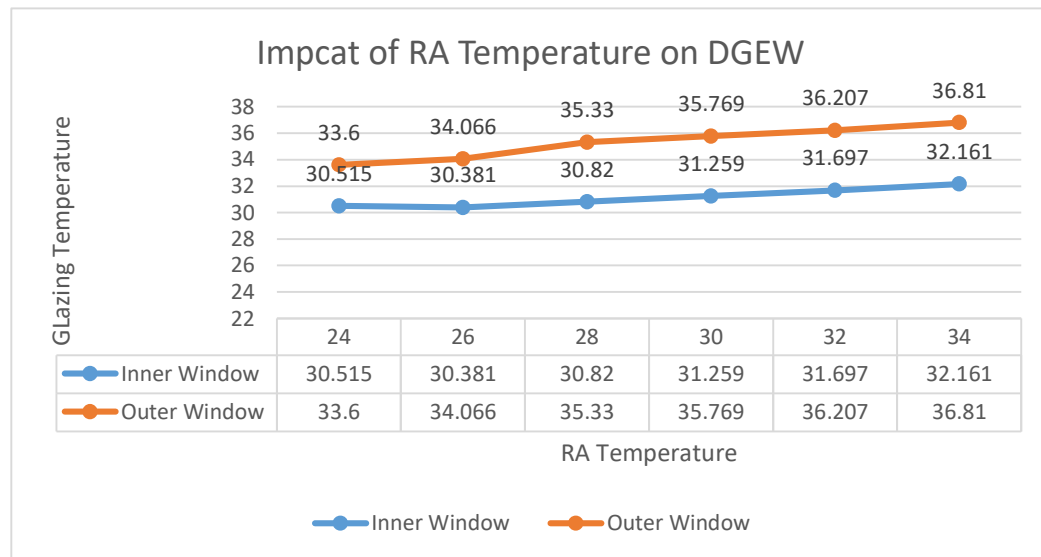


Fig. 58 Return Air temperature impact on glazing temperature for DGEW

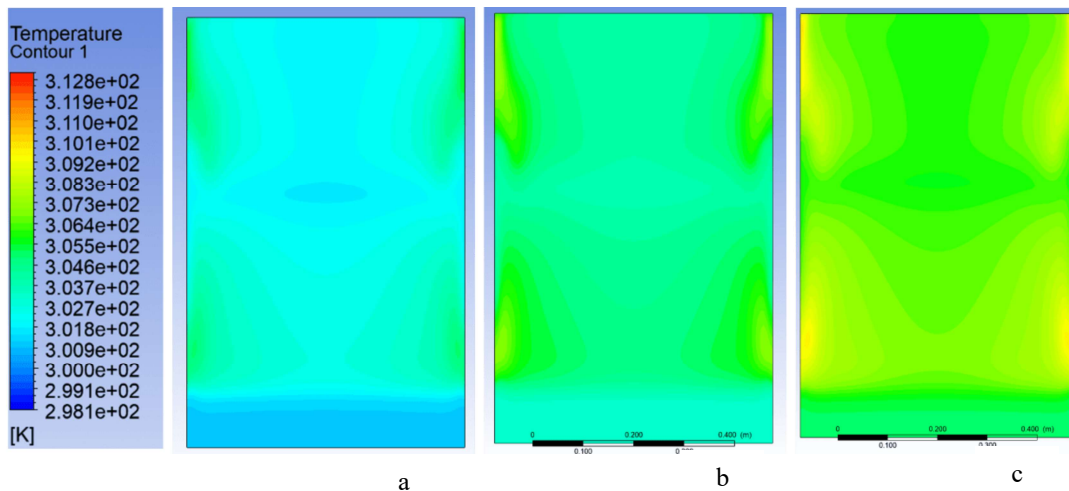


Fig. 59 Contour variation for inner glazing for A. RA=28°C, B. V=30°C, C. V=32°C

Figure 60 illustrates impact of air volume on DGEW on surface glazing temperature of the windowpanes and compares it with normal double-glazing system, the figure shows that outer glass pane increases gradually with outdoor temperature, which is very expected, nonetheless, inner glazing pane increases by rate of 1 degree in span of 18-degree variation, from 36 °C to 52 °C. on the other hand, normal double-glazing system have lower outer glazing temperature and higher inner glazing temperature, however, they are very close in value and increase within the same rate, where in DGEW they have totally different tendencies. Nonetheless, despite following the Zhang's model, yet, the DGEW has higher tendency to cool the outer glazing comparing to the inner one, on the other hand, comparing its performance with DGW, that at 52°C outdoor, inner glazing has 2°C rate of reduction, while the outer one has around 3°C.

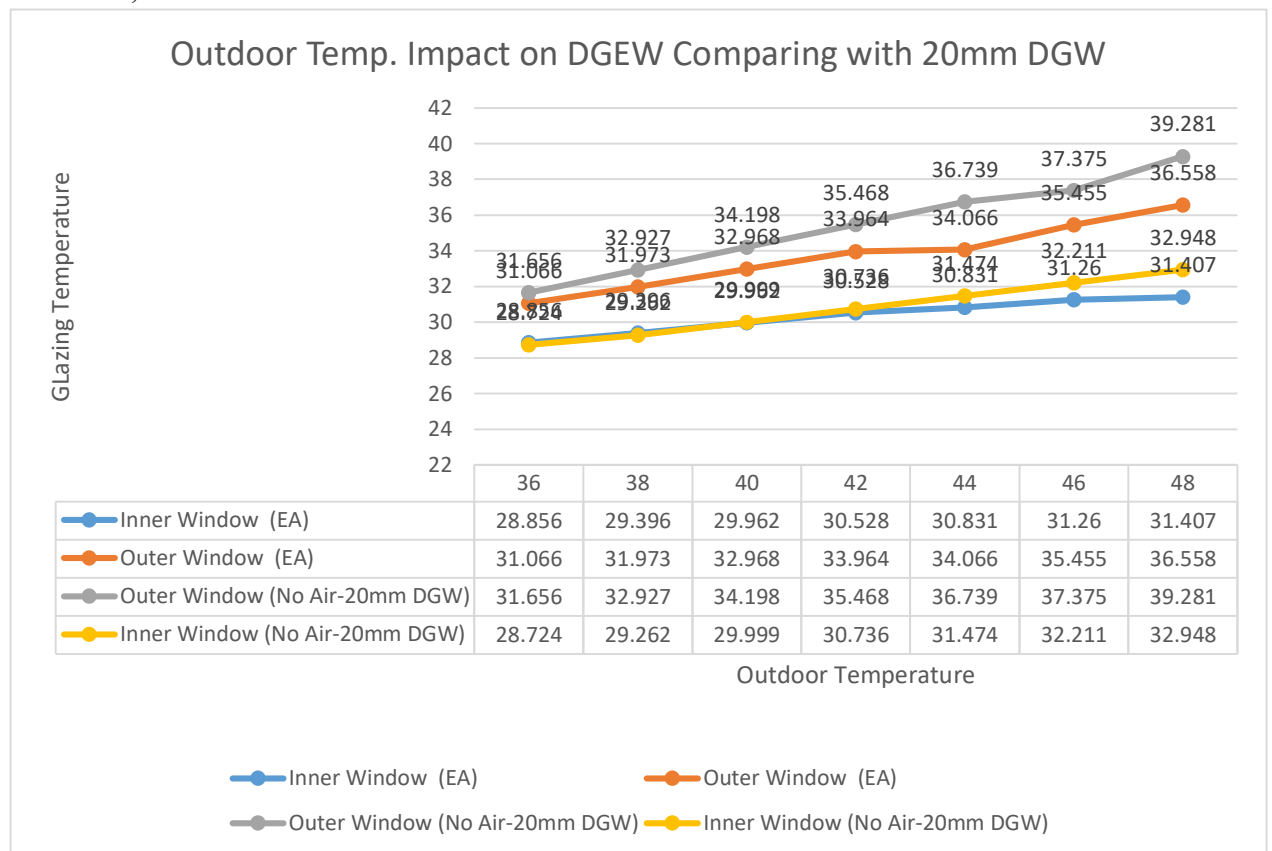


Fig. 60 Outdoor temp. impact on glazing temperature for DGEW

Based on the simulation results which is conducted in high outdoor temperature to replicate the condition of Saudi Arabia and city like Dharan; based on these outcomes, a general guideline can be created for DGEW, to get the best condition for Dharan and Saudi Arabia, which is to have 2cm air gap, 13kg/s of air volume or 0.634 m/s velocity of air inlet, and within out wide range of outdoor temperature up to 52 °C. These results can provide the required level of heat transfer reduction and fulfill the required aim of using such a system in buildings, especially in Saudi environment and in type of building like skyscape enveloped with curtain walls. Figure 61 compares the performance of DGEW with conventional type window with 12mm air gab (DGW) on standard set testing condition which is a combination of figure 62 & 63 which are comparing the outer glazing and inner glazing respectively; figure 61 illustrate that inner glazing temperature reduced by 2°C comparing with DGW, and this reduction could reach 4.5°C when inlet air velocity is 0.634 m/s, however, one way to reduce the inner glazing even more in comparison to DGW, is to increase the air volume or air mass volume to 13kg/s which could reduce the inner glazing to 26.125°C which is equal to 7°C reduction comparing with DGW in the sample outdoor condition.

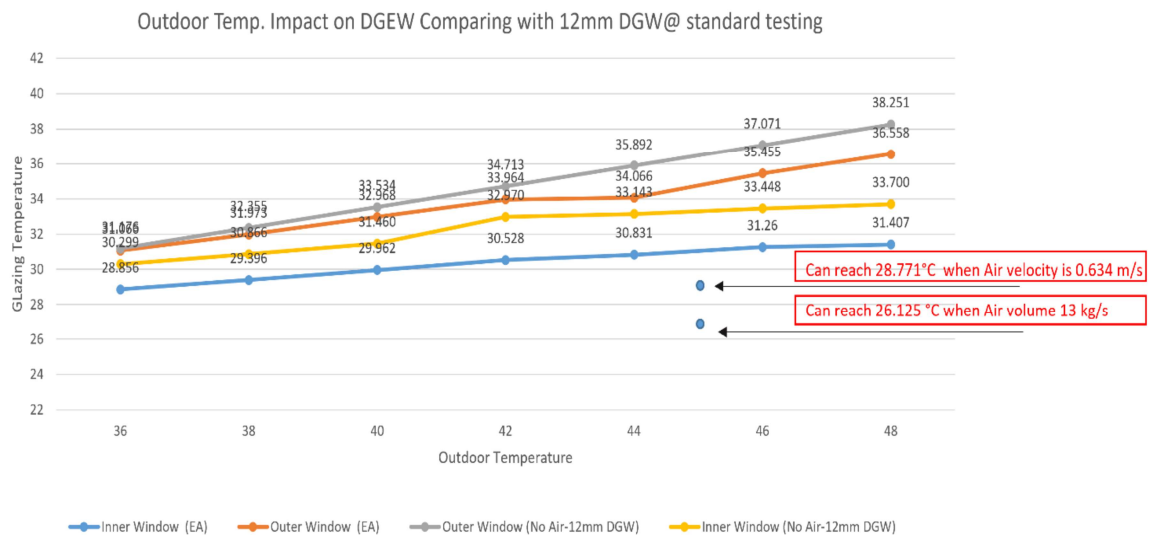


Fig. 61 Outdoor temp. impact on inner and outer glazing temperature for DGEW comparing with 12mm DGW

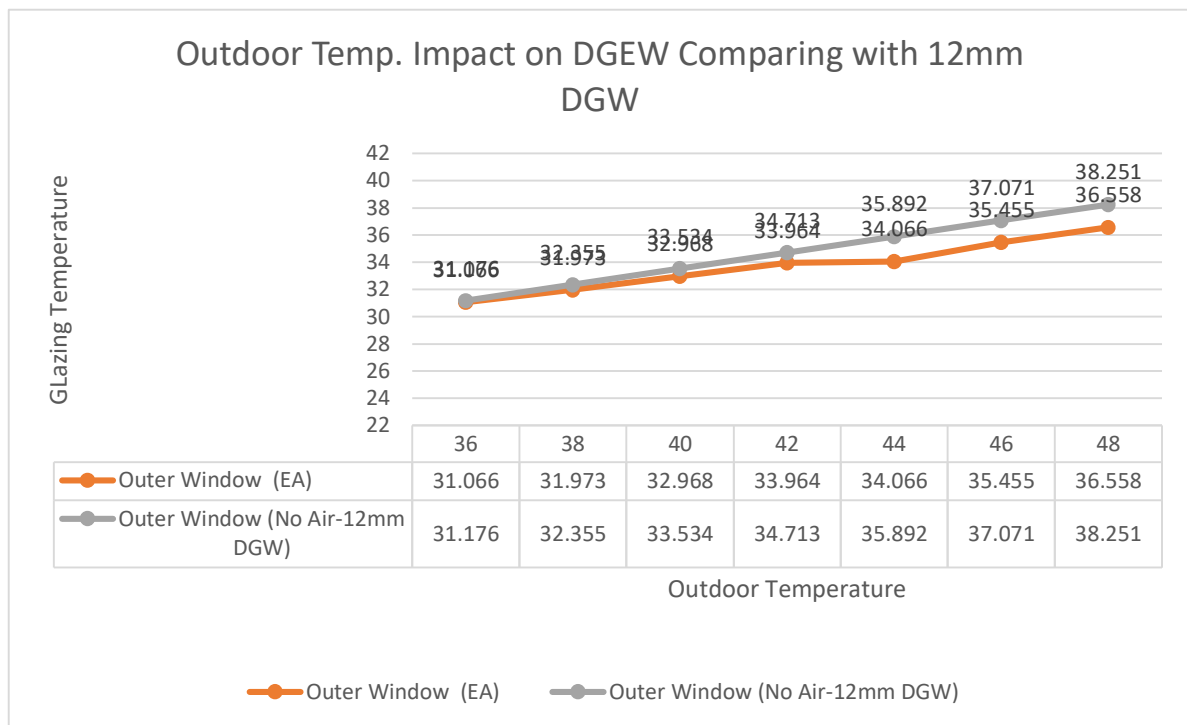


Fig. 62 Outdoor temp. impact on outer glazing temperature for DGEW comparing with 12mm DGW

Figure 64 and 65 shows the relation between air gap and velocity; in other words, it was made to see if air gap impact is related to the distance between glazing pane it is effect on conductive heat transfer between them, or it is related with amount of air, which is represented in term of inlet air velocity, that the higher the velocity of air would result in higher amount of air volume or air particles. Hence, figure 64 shows the relation of the inner glazing temperature with different gab with different velocities at the standard sat condition mentioned earlier; it can be noticed, 2cm air gap have the high inner glazing temperature while the 10cm have the lower temperature and the gaps between tend in that rate respectively as expected, nonetheless, increasing the air gab and increasing the velocity in range 0.234m/s to 0.343m/s would make relatively high steep reduction of inner glazing surface temperature; that while for 2cm to 6 cm gap the reduction within the same velocity range is around 2°C, for the 8cm and 10cm the reduction is around 4°C, which is quit controversial considering the previous results.

On the other hand, figure 65 illustrates the same for the outer glazing, which shows more predictable behavior in comparison with the inner glazing, that outer glazing shows minor reduction in relation with air gap size and velocity, that it varies in the range of 33.5°C and 31°C; nonetheless, it can be noticed that increasing inlet air velocity doesn't make much of difference for the outer pane surface temperature; which can be explained due to lack of ability of the glazing and air flow to transference the heat to the inner glazing.

It is important to note that there is no certainty that the amount of air volume or inlet air velocity set for the simulation/experiment can be considered adequate for the air gap, that the proportion of the volumetric air required to get the best thermal performance is not yet well covered in the literature.

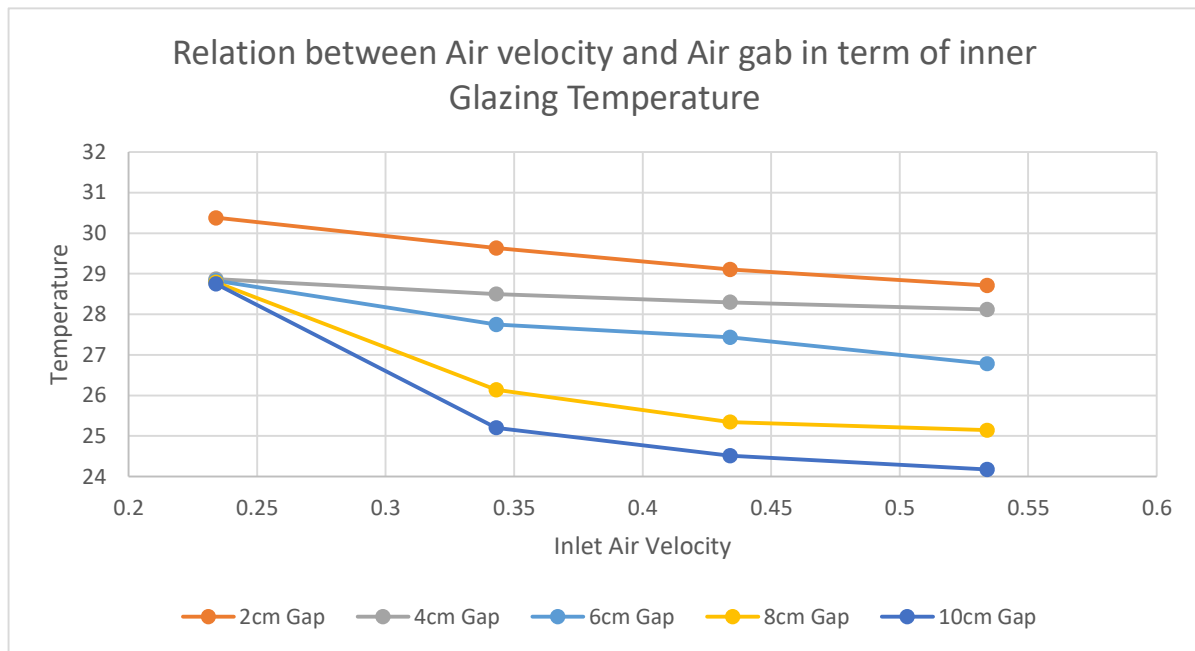


Fig. 63 Outdoor temp. impact on inner glazing temperature for DGEW comparing with 12mm DGW

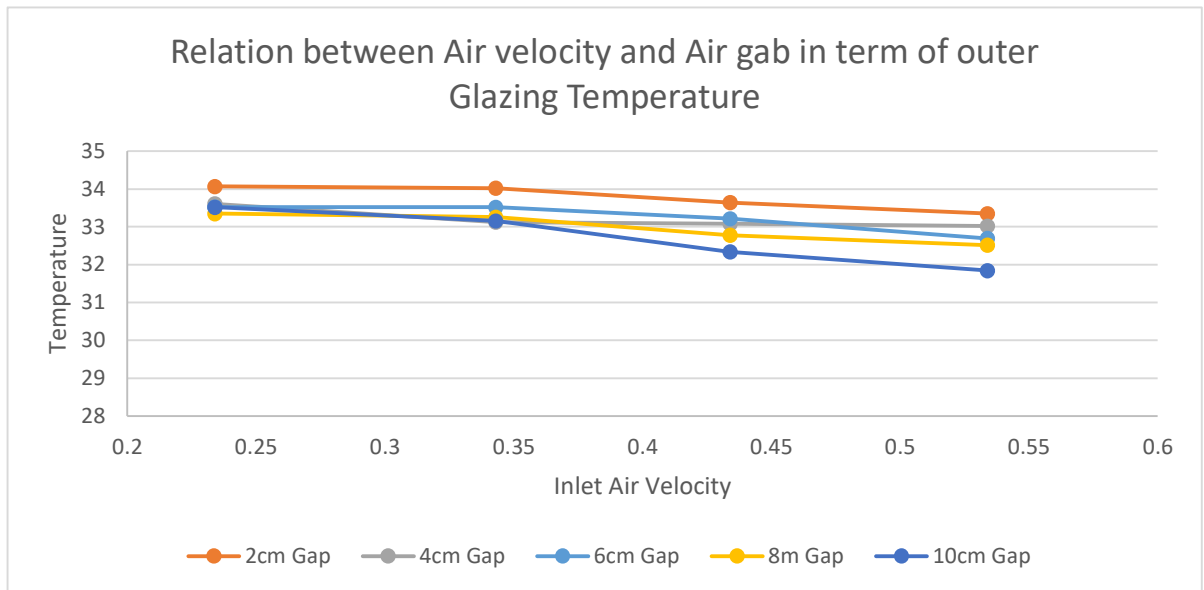


Fig. 64 Relation between Air velocity and Air gab in term of inner Glazing Temperature

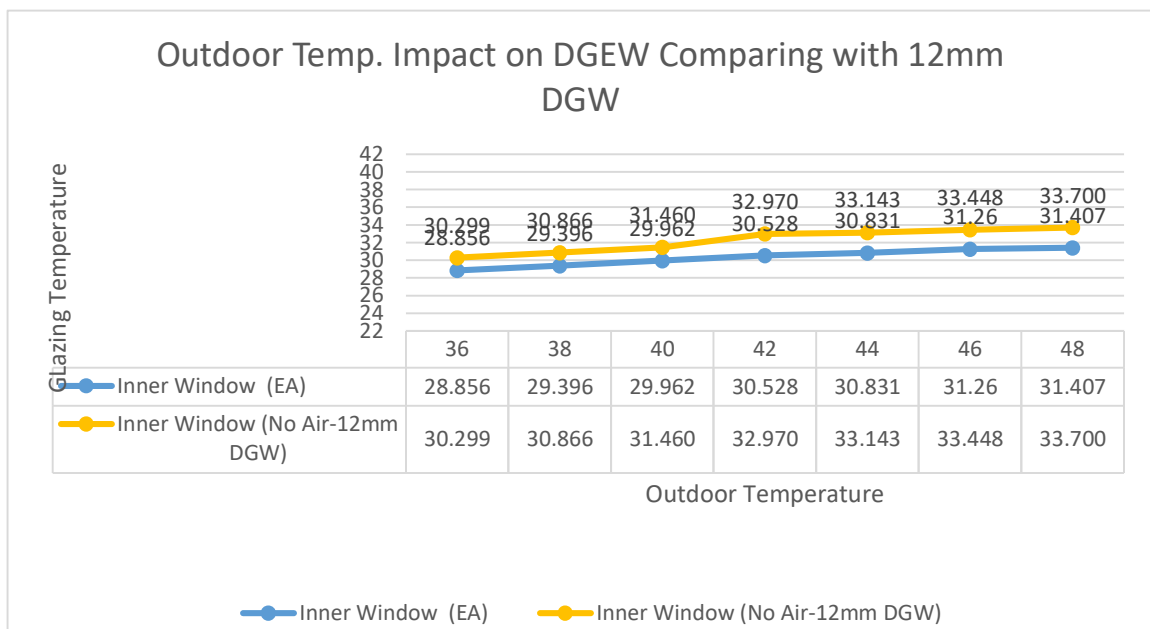


Fig. 65 Relation between Air velocity and Air gab in term of outer Glazing Temperature

Table 19 summarizes all the previous results with percentage of difference, to give a more general view of the thermal performance of DGEW.

Table.19. summary of DGEW performance with percentage of differences

Air Gap Rate of increment/reduction				
Air Gab	Outer Window	Inner Window	Outer Window Rate of reduction %	Outer Window Rate of reduction %
2	34.066	30.831	1.347384489	6.360481334
4	33.607	28.87	0.255899069	0.13855213
6	33.521	28.83	0.008949614	0.138744364
8	33.518	28.79	-0.008950415	0.138937131
10	33.521	28.75		
Air Volume Rate of increment/reduction				
Air Volume	Outer Window	Inner Window	Outer Window Rate of reduction %	Outer Window Rate of reduction %
3	34.498	30.054	2.582758421	3.939575431
5	33.607	28.87	3.514148838	2.764114998
7	32.426	28.072	1.483377537	3.441151325
9	31.945	27.106	4.661136328	3.619124917
11	30.456	26.125	1.10323089	2.660287081
13	30.12	25.43		
Air velocity Rate of increment/reduction				
Outdoor Temp.	Outer Window (EA)	Inner Window (EA)	Outer Window Rate of reduction %	Outer Window Rate of reduction %
36	31.066	28.856	-2.919590549	-1.871361242
38	31.973	29.396	-3.112000751	-1.925432032
40	32.968	29.962	-3.021111381	-1.889059475
42	33.964	30.528	-0.300317984	-0.992531447
44	34.066	30.831	-4.077379205	-1.391456651
46	35.455	31.26	-3.110985757	-0.47024952
48	36.558	31.407		
Return Air Rate of increment/reduction				
Return air Temp.	Outer Window	Inner Window	Outer Window Rate of reduction %	Outer Window Rate of reduction %
24	33.6	30.515	-1.386904762	0.439128298
26	34.066	30.381	-3.710444431	-1.444982061
28	35.33	30.82	-1.242570054	-1.42439974
30	35.769	31.259	-1.224524029	-1.401196455
32	36.207	31.697	-1.665423813	-1.463860933
34	36.81	32.161		

5.2.4- TGEW in hot climate of Saudi Arabia

In this part TGEW performance has been tested in environmental conditions of Saudi Arabia, where the outdoor temperature and other simulation parameter are matching with previous CFD setup made for DGEW, noting that air has been flowing between outer and mid glazing pane, which is the summer mode design by Zhang et al [69].

Figure 66 indicate the impact of air velocity on glazing temperature of TGEW; the glazing surface for the three glass panes is represent in graph 59, which indicate that air velocity won't make a notable impact on glass surface temperature in the three of the windowpanes, hence there is no tangible or direct relation can be detected on the impact of velocity on glass temperature, that it keep getting frequent up down without a solid relation, nonetheless, inner glazing pane have sort of solid direct relation between air velocity and its temperature that it reduces in span of 1 degree in range of 1 m/s increment in velocity. The indoor average temperature remains below 25 degrees. But the system works better when the air velocity is low. This is probably due to the reduction of turbulence which usually increases heat transfer by convection.

Figure 67 shows the impact of air gap between the three glass panes; it shows that increasing the air gap from 2 to 4 cm would give 2 °C reduction in temperature for the inner glazing pane, where it would remain constant for the remining air gap, which are between 4 to 8 cm. On the other hand, temperature of the outer and mid glass pane would increase gradually by 6°C while increasing the air gap, which occur mainly due to the fact of its inability to transfer its gain heat to inner glazing pane, therefore, surface temperature remains constant within air gap equal or less than 4cm. In other words, in terms of air gap thickness, the larger the thickness is better, however, it there is no feasibility in increasing

gap's width more than 4cm as figure 64 indicates, therefore, air gap lower or equal to 4cm is recommended for related application in this study.

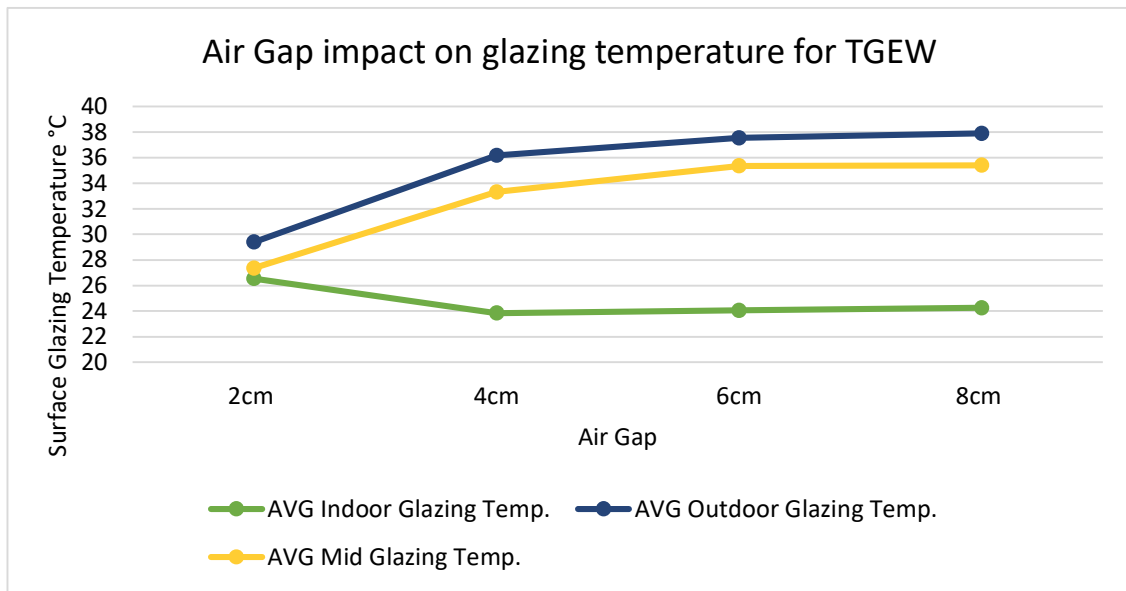


Fig. 66 Impact of air velocity on glazing Temp for TGEW

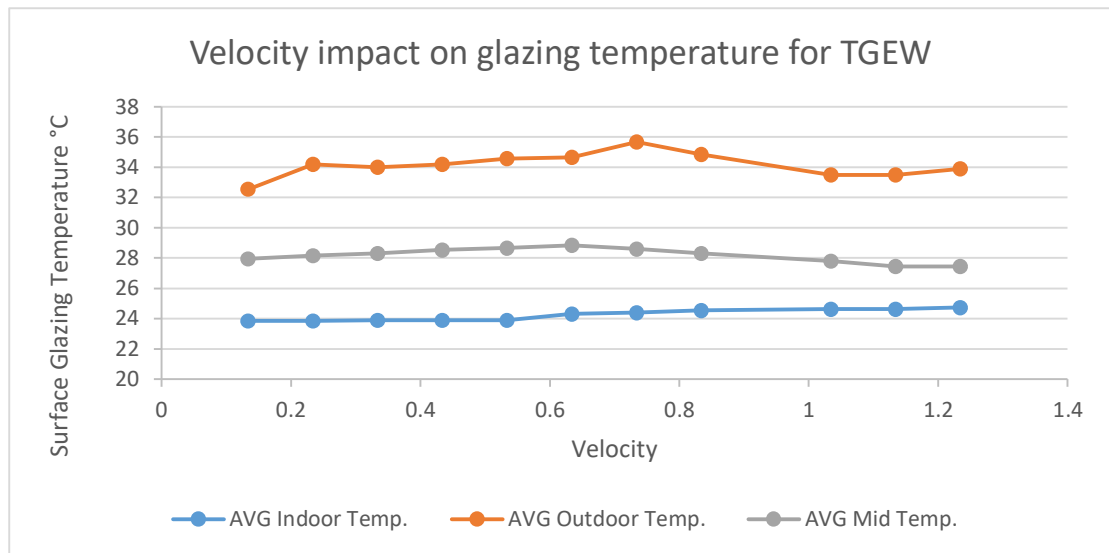


Fig. 67 Air gap impact on glazing temperature for TGEW

5.3- EAW experiment implementation guideline in hot climate of Saudi Arabia:

In this part, a testing guideline is presented to direct researchers to avoid mistakes made in previously mentioned experiments in hot climates, and present lesson learned.

AAMA testing procedure was followed precisely while conducting experiments, except for the required size, which is more than 3m^2 ; nonetheless, it seems that this standard fits the conventional type of windows but is not efficient at all when testing EAW or any type of air flow windows. AAMA considers Window's U-value while conducting the experiments or extracting results, while in EAW or air flow window must measure by efficient U-value (U_{eff}), that heat which is been transmitted through glass panes has been mixed or joined with air floating inside the gap, which increase the uncertainty of U-value measurements. Therefore, presenting the concept of U_{eff} which is based on surface temperature of windowpanes is critical when conducting experiments on these types of windows.

It is recommended to make specified standard of experiments, dedicated for EAW, and how to measure all its related values, such as U-value, R-value, heat flux etc. While conducting the literature review there wasn't a single published paper describing testing procedure of EAW or air flow windows in general, which is considered as a huge research gap. Nonetheless, a general guideline is describing all necessary points related experimental procedure required, to avoid mistakes which could increase uncertainty of the results; the guideline is presented as follows:

- 1- To measure the sole impact of air flow window or EAW specifically its recommended to neutralize as many factors as possible, one way to do that is avoid making the experiments under solar radiation.
- 2- It is recommended to have two chambers, to replicate both environments (hot & cold), to ensure the consistency of temperatures of the windows surfaces.
- 3- Heating the chamber which represents the outdoor should be by providing heated air, not by allocating the heat source inside the chamber, to avoid the effect of radiant heat.

- 4- Heating the outdoor shouldn't be generated by any type of radiation, that it would harm the experiment outcomes severely, that radiation don't get affected by air flowing inside the gap, because radiation don't need medium to travel through, which in results, would give negative results always.
- 5- As mentioned previously, it seems that AAMA isn't useful for EAW, one example of that, AAMA state that chamber temperature is determined by surface temperature of the window, by allocating temperature controller on window surface; this would cause that glass wouldn't have opportunity of cooling up, that wherever its temperature would decreased, the thermal controller will send signal to thermal controller to starting heating the window to keep its set temperature. It recommended to have several temperature sensors, and the thermal controller make the heater work when the average of their reading go below the set temperature by 2 to 4 °C. this thermal gap, would give the window allowance to cool up and create an adequate ability to absorb the heat.
- 6- The function of heat transfer between outdoor and indoor can't be separated for the properties of air flowing inside the gap, especially velocity, which is based on the previous experiments and simulations make notable impact on thermal EAW performance, therefore, tight air velocity measurement should be made at air inlet and outlet and along entire window section, not conducted in the experiment made in chapter 3, where velocity is measured and determined at the inlet only.
- 7- A one pilot experiment required to be made for long hours, say 8 hours, to determine expected time range where the system reach equilibrium or steady state. Therefore, all other experiments were done with high certainty that the system reached the equilibrium state.
- 8- Evaluation of the system is recommended to be based on surface temperature solely, or at least to be the main criteria of thermal performance evaluation, that any other criteria like U-value, R-value, or heat flux would be extremely difficult to be measured in precise scientific way, that the behavior of air flowing and its attitude between glass panes play critical role in measurements of these values. Moreover, air itself takes some of the heat while it is traveling through the window

section by high relative speed and pressure, in other words, the amount of heat removed or gained by the system is difficult to be tracked with casual tool and instruments.

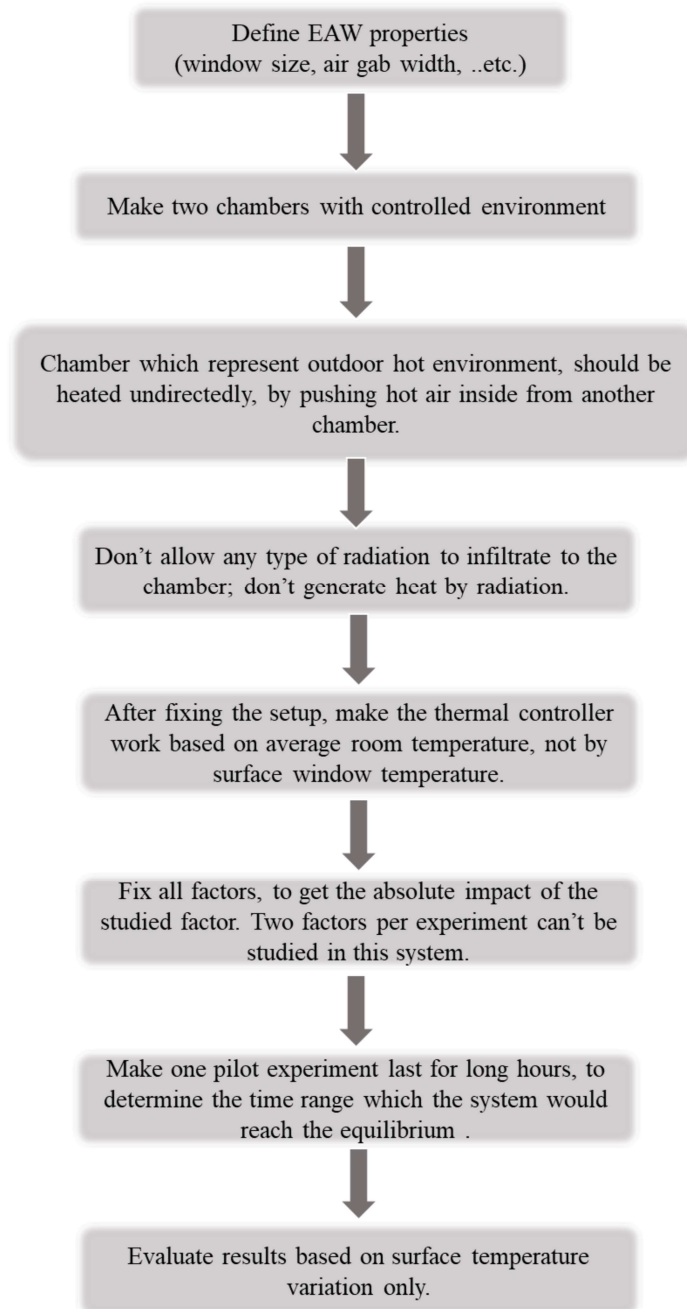


Figure 65 summarize and illustrate the previous points in systematic steps, to make it easier

Fig. 65 experiment implementation guideline in hot climate of Saudi Arabia

for researchers to flow:

5.4- EAW prediction guideline in hot climate of Saudi Arabia:

This section presents the prediction guideline to provide a procedure to forecast the expected results, with factors in range of hot climate of Saudi Arabia, based on the previous simulation results. In respect to all factors that have been tested, outer glass pane is always the surface which show highest pace of variability in DGEW and TGEW. Nonetheless, this guideline will present its recommendations based on impact of such factor on reducing the inner glazing temperature only; needless to say, reducing inner glazing temperature would make it closer to indoor temperature, therefore, less heat transfer between indoor environment and glass portion, moreover, cooler inner pane would reduce its amount of radiation.

DGEW shows good outcomes when installing aluminum fins, that these fins uniforms the air movement inside the gap, and prevent most of heat transfer between inner and outer glass panes, by preventing the horizontal convention which was the main reason of getting negative result during experiment process; that when inflating air inside the gap turbulence effect used to move heat from the outer pane to the inner one, which result rapid decrease in the outer one and rising the inner one.

On the other hand, air fins may disturb visual quality of the window/curtain system, that is why it is recommended to study the angle of the fins, which give the best thermal performance and visual quality, nonetheless, these fins can be an advantage when it came to reaction of window with solar radiation, that it would be able to break its direct rays; in this paper angle of 45 degree was used as per Zhang et al . Figure 68 shows how fins inclination toward outer pane make air flow faster near to inner pane and prevent air to be attached with outer hot pane; this type of design would result in preventing air to behave as medium to transfer heat between both panes. Figure 65 shows that velocity near to inner pane is around 0.24 m/s where is almost zero at the outer pane, which result in cooling the inner one, which is the required outcome.

Figure 69 show air flow between glass panes without aluminum fins, that velocity tend to be more unformal, which allows air the behave as medium for heat to be transferred from the outer to inner pane, hence figure shows that 0.13 m/s is the average velocity, which is

half the velocity when there are aluminum fins: in other words, not using fins would reduce the velocity of air flowing, while using fins would at least keep the velocity and air momentum; keeping high velocity would increase air capability to reduce glazing

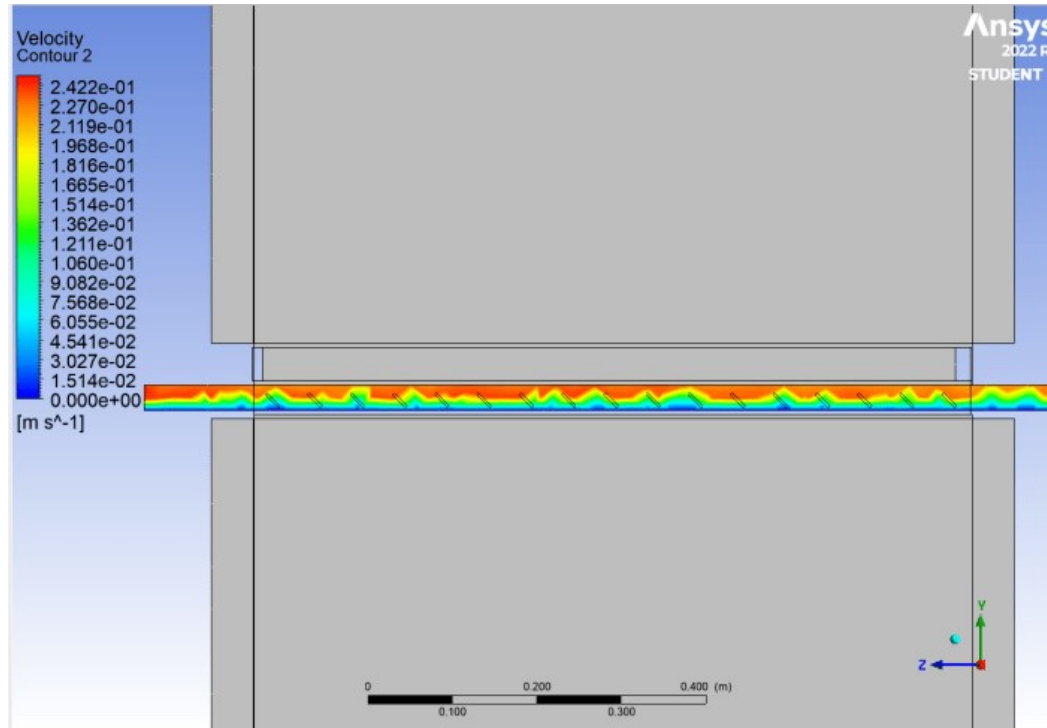


Fig. 68 Air velocity distribution with air fins inside the gap

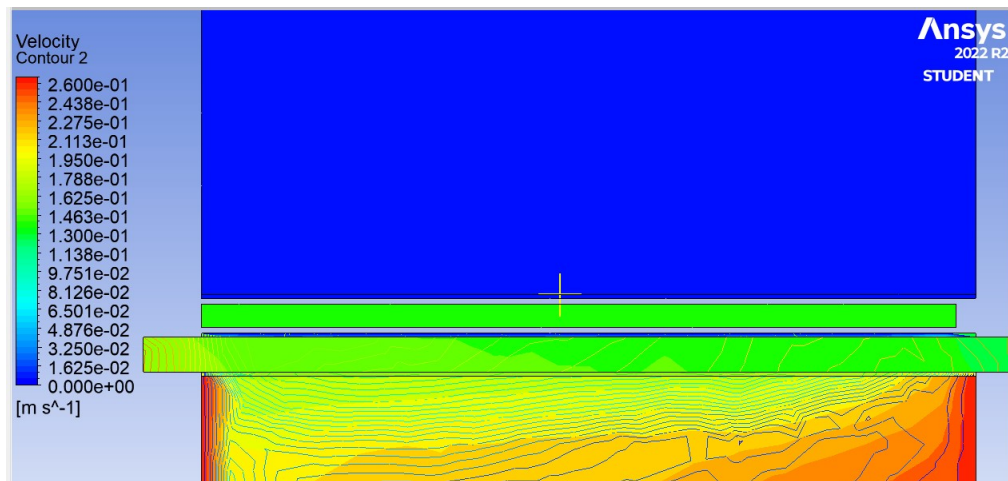


Fig. 69 Air velocity distribution without air fins inside the gap

temperature, taking in consideration that inlet velocity was around 0.2 m/s, When it comes to velocity, it is preferred to keep within the range of 0.5m/s-0.6m/s, that in this domain there is notable 4°C to 5°C when comparing with conventional type of windows. On the other hand, 4 cm air gap is good air gap for windows, that comparing to 2cm gap, it has ability to reduce the temperature of the inner pane by 2 °C, that it would reduce heat transfer between inner and outer pane; playing with such factor has almost no impact outer glass pane. However, going above 4 cm gap wouldn't have any impact on inner or outer pane, even increasing gap width from 2 to 4 cm need further study on its feasibility that increasing air gap by 2cm for only 2°C reduction doesn't sound attracting, in other words, does reduction of 2 °C of inner surface temperature would reduce energy consumption by value which could cover the increment of the initial cost of windows system of 4cm frame? Without answering this question, flowing 2cm air gap would be a good alternative than 4cm.

Volume of air give almost the same outcomes of velocity, that it has strong impact on the outer pane and the inner pane, having mentioned that, amount of air volume has the strongest impact among all other factors, that it gives more than 4°C reduction in span of 3kg/s to 13kg/s, and reduction of 7°C when comparing with conventional type of window.

When it comes to outdoor environment where EAW have to work in term of outdoor temperatures, it can be noticed that DGEW at 36 °C outdoor temperature, difference between inner and outer glass pane is 2°C, and this temperature gap keep increasing by constant pace, until it reach 6°C, that inner glazing reach 28 °C while outer one is 34°C at outdoor temperature of 52°C which is quite extreme, nonetheless, when considering average temperature of summer in Dharan, Saudi Arabia which is 40°C to 45°C, difference between two glass pane become between 4 °C to 5°C; hence the difference between glass pane come from the outer pane, that inner pane remain almost constant among all temperature tested, where outer pane is increasing gradually and provide 7°C rise among tested temperatures.

Table.20. Design guideline for EAW in hot climate of Saudi Arabia

Optimum conditions for EAW in hot climate of Saudi Arabia	
Factor	Recommended Value
velocity	0.6 m/s
Air gap	4 cm
Air volume	13 kg/s
Other components	Air Fins; to prevent air flowing from transferring heat form outer to inner pane, and to enhance convective heat transferer between glass panes

Table 19 gives and summarizes the best required velocity, air gap and volume of air for EAW to operate in hot climate and get lower inner surface temperature as performance evaluation tool.

Table.21. Design guideline for EAW in hot climate of Saudi Arabia

Variant	Rate of increment /reduction of inner glazing temperature
Air Velocity	each increment in air inlet velocity of 0.1 m/s results on reduction of inner glazing by 0.17°C
Air gap	increasing air gap by 1cm results of 0.98°C reduction of inner glazing until 4cm, after 4cm increasing the give no tangible impact
Air mass volume	increasing air volume by 1kg/s cause 0.46°C reduction of inner glazing temperature
Return air temperature	increasing RA temperature by 1c results of reducing inner glazing by 0.16 °C
Outdoor temperature	each 1°C increment of outdoor temperature results in 0.16 increment of inner glazing temperature

In addition, results of DGEW can be summarized in the form of relation between unit increment of the studied variant criteria with glazing surface temperature. Table 20 shows the rate of glazing temperature in relation to air velocity, air mass volume, air gap, outdoor temperature, and RA temperature. It can be noticed from table 21 that air gab has the most tangible impact on reducing inner glazing temperature that increasing the gap by 1cm

would reduce the inner glazing temperature by 1 °C, where air mass volume had the second strongest impact on the thermal performance of DGEW, that increase the air volume by 1kg/s resulting in reduction of almost 0.5°C.

However, such an outcome would help project stakeholders to fulfill Saudi Building Code (SBC) requirement when it came to glazing requirements, hence, SBC doesn't discuss energy regulation related to High rise buildings in term of energy conservation requirements. Nonetheless, taking the extremist condition discussed in SBC which is 50%Window to Wall Ratio (WWR) and 0 Projection Facto (PF); as mentioned in table 21 U-Factor of 0.4 is required, which EAW would help to achieve. Considering heat flex out of simulation is 2.2 W/m² and 6°C difference an effective U-value of 0.367 W/m²°C based on equation 2. Such an output would help engineers and designers to reach the required value without increasing the window specifications. On the other hand, DGEW as system would cut the amount of heat gain by 1.211W which can be calculated by equation 3, considering the area of the simulated and experimentally tested window which has area of 0.46m².

$$U - value = \frac{Q}{\Delta T} \dots \dots Eq2$$

$$Heat\ Gain = U \times \Delta T \times A \dots \dots Eq3$$

Table.21. Window required U-value as per SBC.

DESIGN BY ACCEPTABLE PRACTICE FOR COMMERCIAL BUILDINGS

TABLE 6.2.2(10) (Continued)

WINDOW AND GLAZED DOOR AREA GREATER THAN 40 % BUT NOT GREATER THAN 50% OF ABOVE-GRADE WALL AREA

Element	Condition / Value	
Skylights (U-factor)	1	
Slab or below-grade wall (R-value)	R-0	
Windows and Glass doors	Solar Heat Gain Factor (SHGC)	U-factor
PF < 0.25	0.4	3.975
0.25 ≤ PF < 0.50	0.5	3.975
PF ≥ 0.50	0.7	3.975
Roof assemblies (R-value)	Insulation between framing	Continuous insulation
All-wood joist/truss	R-4.403	R-3.346
Metal joist/truss	R-4.403	R-3.522
Concrete slab or deck	NA	R-3.346
Metal purlin with thermal block	R-5.284	R-3.522
Metal purlin without thermal block	X	R-3.522
Floors over outdoor air or unconditioned space (R-value)	Insulation between framing	Continuous insulation
All-wood joist/truss	R-1.937	R-1.233
Metal joist/truss	R-1.937	R-1.409
Concrete slab or deck	NA	R-1.233

Chapter-6

Conclusion and recommendation

Building envelope plays a vital role in reducing energy consumption in buildings, which reflect on its life cycle cost, however, considering hot climate like Saudi Arabia, decreasing the level of heat transfer becomes a necessity. Using Energy Active Window (EAW) adapts window insulation technology to reuse low-grade air from the HVAC system. This technology makes the temperature at the internal surface of the window close to the indoor air temperature, which would decrease heat transfer between indoor and outdoor. The system uses two basic concepts related to window thermal design: firstly, moving air has a higher ability to reduce surface temperature than stagnant air; secondly, air resistivity has an inverse relationship with its temperature.

EAW was tested by 4 different models with 18 alternative experiments to measure its thermal performance, which shows that temperature of the inner window would increase not decrease, which would be an additional heat source, therefore, would create an extra load on the indoor environment. Nonetheless, flowing air inside the window gap would decrease the temperature of the outer glass panes, as a result, it could reduce the irradiation, therefore reduce inner window temperature.

However, when making CFD simulation based on the experimental model reference to the literature, DGEW and TGEW show a positive window. A reduction of 4 °C in hot climate where outdoor temperature is 45 °C and could go down to 6 °C when the outdoor temperature reaches 52 °C and could go even to 7 when there is when air volume reaches 13kg/s when comparing it with conventional type of windows.

These contradicting results may imply that there is a high margin of error in the experimental models made, that their results are contradicting with literature, so, it is important to make complete professional and high technological setup to be able to validate CFD results with experiment, which is out of the capability of the researcher at this time technologically, and financially. However, assuming the CFD results are the right one, and based on its calibration with literature review, such a reduction of 4 °C in surface

temperature of glazing would make a tangible impact of energy performance on buildings, especially if it's enveloped with curtain walls like office or high-rise buildings. Hence, such a relatively new topic need be heavily tested and studied to be able to have a solid judgement on its performance, that this work focuses on air flowing impact only without considering other engineering and technical perspectives, like how window system will suck return air from the room.

Nonetheless, here are list of factors that may cause high margin of error on the experimental setup, leading to conflict with literature and CFD simulation:

- 1- The heater generates a relatively high amount of radiation, which would create direct impact on inner pane surface temperature, that for most of the models, chamber was representing the outdoor temperature.
- 2- Thermal controller works whenever glass pane reduced lower than the set temperature which don't give the system opportunity to cool up, that in the experiment it is extremely hard to make window system determine by coupling.
- 3- Low ability to control air flowing inside the glass, that parameters like quantity of air and its pressure requires special type of equipment to control it.
- 4- Heat flux measurement was required to have solid analysis behind such phenomena like inner pane increasing of its temperature.
- 5- An annual range study to evaluate the system performance under solar radiation for longer span of time.
- 6- Increase the experiment duration more than two hours to insure there is no variation of temperature may occur, and to insure also, the system reaches steady state, hence, it is fact in physics that thermal energy is transferred from hot bodies to cold bodies, not vice versa by convection; however, the probability that system doesn't reach equilibrium is high.

6.1-Recommendation for future work:

Based on the highlighted findings in this study, several recommendations for future work were raised to extend the limitation associated with this study. Following is a brief description of future research work:

- 1- It is extremely important to have full model installed in building in real life condition, to provide absolute result, that there are always factor which could impact the performance of the window system, and these factors most of the time can't be determined or be known without experiment.
- 2- A clear systematic approach of how to test EAW thermally regardless to the climatic regions is critically essential, to be able to have a solid ground to compare between alternatives or other design solutions.
- 3- Impact of window dimensions, and ratio between its length and width is required to be studied, to provide the optimum dimensions.
- 4- More research is required to investigate the impact of such a concept other than thermal performance; it could be useful from other perspectives like reducing noise or longwave radiation.
- 5- Provide a tight experimental model able to investigate condensation risk factor, without impacting heat measurements accuracy.

Reference

- [1] S. W. Tong, W. P. Goh, X. Huang, and C. Jiang, “A review of transparent-reflective switchable glass technologies for building facades,” *Renewable and Sustainable Energy Reviews*, vol. 152. Elsevier Ltd, Dec. 01, 2021. doi: 10.1016/j.rser.2021.111615.
- [2] Y. Luo, L. Zhang, Z. Liu, Y. Wang, J. Wu, and X. Wang, “Dynamic heat transfer modeling and parametric study of thermoelectric radiant cooling and heating panel system,” *Energy Convers Manag*, vol. 124, pp. 504–516, Sep. 2016, doi: 10.1016/j.enconman.2016.07.055.
- [3] Y. Luo, L. Zhang, Z. Liu, J. Wu, Y. Zhang, and Z. Wu, “Numerical evaluation on energy saving potential of a solar photovoltaic thermoelectric radiant wall system in cooling dominant climates,” *Energy*, vol. 142, pp. 384–399, Jan. 2018, doi: 10.1016/j.energy.2017.10.050.
- [4] M. Ibañez-Puy, J. Bermejo-Busto, C. Martín-Gómez, M. Vidaurre-Arbizu, and J. A. Sacristán-Fernández, “Thermoelectric cooling heating unit performance under real conditions,” *Appl Energy*, vol. 200, pp. 303–314, 2017, doi: 10.1016/j.apenergy.2017.05.020.
- [5] D. Jung *et al.*, “Inorganic gel and liquid crystal based smart window using silica sol-gel process,” *Solar Energy Materials and Solar Cells*, vol. 159, pp. 488–495, Jan. 2017, doi: 10.1016/j.solmat.2016.10.001.
- [6] F. Goia, M. Perino, and V. Serra, “Improving thermal comfort conditions by means of PCM glazing systems,” *Energy Build*, vol. 60, pp. 442–452, 2013, doi: 10.1016/j.enbuild.2013.01.029.
- [7] S. D. Rezaei, S. Shannigrahi, and S. Ramakrishna, “A review of conventional, advanced, and smart glazing technologies and materials for improving indoor environment,” *Solar Energy Materials and Solar Cells*, vol. 159, pp. 26–51, Jan. 2017, doi: 10.1016/j.solmat.2016.08.026.
- [8] L. Long and H. Ye, “Discussion of the performance improvement of thermochromic smart glazing applied in passive buildings,” *Solar Energy*, vol. 107, pp. 236–244, 2014, doi: 10.1016/j.solener.2014.05.014.
- [9] N. L. Sbar, L. Podbelski, H. M. Yang, and B. Pease, “Electrochromic dynamic windows for office buildings,” *International Journal of Sustainable Built Environment*, vol. 1, no. 1, pp. 125–139, 2012, doi: 10.1016/j.ijbsbe.2012.09.001.

- [10] S. Cao, S. Zhang, T. Zhang, Q. Yao, and J. Y. Lee, "A Visible Light-Near-Infrared Dual-Band Smart Window with Internal Energy Storage," *Joule*, vol. 3, no. 4, pp. 1152–1162, Apr. 2019, doi: 10.1016/j.joule.2018.12.010.
- [11] M. Yazdanian and J. H. Klems, "Measurement of the Exterior Convective Film Coefficient for Windows in Low-Rise Buildings.pdf."
- [12] Bauer, "(12) United States Patent," vol. 1, no. 12, 2011.
- [13] Y. S. Byon and J. W. Jeong, "Phase change material-integrated thermoelectric energy harvesting block as an independent power source for sensors in buildings," *Renewable and Sustainable Energy Reviews*, vol. 128, Aug. 2020, doi: 10.1016/j.rser.2020.109921.
- [14] F. Goia, M. Zinzi, E. Carnielo, and V. Serra, "Spectral and angular solar properties of a PCM-filled double glazing unit," *Energy Build*, vol. 87, pp. 302–312, Jan. 2015, doi: 10.1016/j.enbuild.2014.11.019.
- [15] S. Nundy, A. Mesloub, B. M. Alsolami, and A. Ghosh, "Electrically actuated visible and near-infrared regulating switchable smart window for energy positive building: A review," *Journal of Cleaner Production*, vol. 301. Elsevier Ltd, Jun. 10, 2021. doi: 10.1016/j.jclepro.2021.126854.
- [16] M. Casini, "Active dynamic windows for buildings: A review," *Renewable Energy*, vol. 119. Elsevier Ltd, pp. 923–934, Apr. 01, 2018. doi: 10.1016/j.renene.2017.12.049.
- [17] C. Li and H. Tang, "Evaluation on year-round performance of double-circulation water-flow window," *Renew Energy*, vol. 150, pp. 176–190, May 2020, doi: 10.1016/j.renene.2019.12.153.
- [18] "2020،" ماو علا 2015-2018 قيلعت ءابر هكلل ينكسلا كلاهتسلال ثدح اذام للاخ قيديو عسلا قبيير علا ةكلملا يف ؟ م "
- [19] "2020،" قيلعت يعانصلا عاطقلا يف ةقاطلا كلاهتسا قيديو عسلا قبيير علا ةكلملا يف "
- [20] M. Majzoub and A. Eweda, "Probability of winning the tender when proposing using bim strategy: A case study in saudi arabia," *Buildings*, vol. 11, no. 7, 2021, doi: 10.3390/buildings11070306.
- [21] R. Zevenhoven, R. Erlund, and T. M. Tveit, "Energy efficiency of exhaust air heat recovery while controlling building air humidity: A case study," *Energy Convers Manag*, vol. 195, no. June, pp. 1238–1243, 2019, doi: 10.1016/j.enconman.2019.05.058.
- [22] A. Rackes and M. S. Waring, "Modeling impacts of dynamic ventilation strategies on indoor air quality of offices in six US cities," *Build Environ*, vol. 60, pp. 243–253, 2013, doi: 10.1016/j.buildenv.2012.10.013.

- [23] S. As'ad, Mukahar, and M. Sukiman, "Investigation on wall crack damage and its proposed repair method," *Procedia Eng*, vol. 54, pp. 165–175, 2013, doi: 10.1016/j.proeng.2013.03.016.
- [24] M. Limb, "A review of International ventilation, airtightness, thermal insulation and indoor air quality criteria," *Air Infiltration and Ventilation Center*. ..., p. 203, 2001, [Online]. Available: http://www.inive.org/Ibase_search/search-detail-airbase-001.asp?ID=16247
- [25] R. Sherman, Max H. Chan, "Building Airtightness: Research and Practice," no. July, pp. 35–43, 2004.
- [26] A. Li, W. Zhang, and M. Gao, "Field test and CFD modeling for flow characteristics in central cooking exhaust shaft of a high-rise residential building," *Energy Build*, vol. 147, pp. 210–223, 2017, doi: 10.1016/j.enbuild.2017.04.056.
- [27] S. Sriram, K. Hema, and N. Karthiga Shenbagam, "HVAC Design and Operation for Green Buildings," *Lecture Notes in Mechanical Engineering*, no. June 2001, pp. 687–694, 2021, doi: 10.1007/978-981-15-8025-3_66.
- [28] P. V. Dorizas, M. N. Assimakopoulos, C. Helmis, and M. Santamouris, "An integrated evaluation study of the ventilation rate, the exposure and the indoor air quality in naturally ventilated classrooms in the Mediterranean region during spring," *Science of the Total Environment*, vol. 502, pp. 557–570, 2015, doi: 10.1016/j.scitotenv.2014.09.060.
- [29] P. Lotfabadi, "High-rise buildings and environmental factors," *Renewable and Sustainable Energy Reviews*, vol. 38, pp. 285–295, 2014, doi: 10.1016/j.rser.2014.05.024.
- [30] S. Barth, H. Memarian, and C. Park, "Solar Control Window Films — A Historical and Technological Perspective," 2000.
- [31] M. Saeli, C. Piccirillo, I. P. Parkin, R. Binions, and I. Ridley, "Optimisation of Thermochromic Thin Films on Glass; Design of Intelligent Windows," *Advances in Science and Technology*, vol. 75, pp. 79–90, 2010, doi: 10.4028/www.scientific.net/ast.75.79.
- [32] L. Boman, J. Meade, C. Stoessel, R. W. S. Technologies, and P. Alto, "Impact of Thin Film Coatings on the Performance of Highly Energy-Efficient Windows," pp. 452–456, 2011.
- [33] K. Iqbal, A. Maqsood, M. Mujahid, and M. H. Asghar, "Characterization and Preparation of Anti-Reflection," pp. 327–337, 2012.
- [34] "b30b569b44c78116cbecbab12b23380.pdf."

- [35] F. Containing and A. N. Airlayer, “(12) Patent Application Publication (10) Pub. No.: US 2011/0010994 A1,” vol. 1, no. 19, 2011.
- [36] A. N. Y. Samaan, S. M. Wasim, A. E. Hill, D. G. Akmour, and R. D. Tomlinson, “Preparation and Properties of CuInS₂ Thin Films Deposited by RF Sputtering,” *Physica Status Solidi (a)*, vol. 96, no. 1, pp. 317–324, 1986, doi: 10.1002/pssa.2210960139.
- [37] T. O. N. The, O. Of, and T. Interpolymer, “S Tudies on the F Ilm M Orphology of Pmaa and Its I Nterpolymer a Dducts,” vol. 2, no. 2007, pp. 111–118, 2020.
- [38] F. Goia, M. Perino, and V. Serra, “Improving thermal comfort conditions by means of PCM glazing systems,” *Energy Build*, vol. 60, pp. 442–452, 2013, doi: 10.1016/j.enbuild.2013.01.029.
- [39] Y. Khetib, A. A. Alotaibi, A. H. Alshahri, M. Rawa, G. Cheraghian, and M. Sharifpur, “Impact of phase change material on the amount of emission in the double-glazed window frame for different window angles,” *J Energy Storage*, vol. 44, Dec. 2021, doi: 10.1016/j.est.2021.103320.
- [40] F. Goia, M. Zinzi, E. Carnielo, and V. Serra, “Characterization of the optical properties of a PCM glazing system,” in *Energy Procedia*, 2012, vol. 30, pp. 428–437. doi: 10.1016/j.egypro.2012.11.051.
- [41] J. Han, L. Lu, and H. Yang, “Numerical evaluation of the mixed convective heat transfer in a double-pane window integrated with see-through a-Si PV cells with low-e coatings,” *Appl Energy*, vol. 87, no. 11, pp. 3431–3437, 2010, doi: 10.1016/j.apenergy.2010.05.025.
- [42] C. Liu, Y. Wu, D. Li, Y. Zhou, Z. Wang, and X. Liu, “Effect of PCM thickness and melting temperature on thermal performance of double glazing units,” *Journal of Building Engineering*, vol. 11, pp. 87–95, May 2017, doi: 10.1016/j.jobbe.2017.04.005.
- [43] B. L. Gowreesunker, S. B. Stankovic, S. A. Tassou, and P. A. Kyriacou, “Experimental and numerical investigations of the optical and thermal aspects of a PCM-glazed unit,” *Energy Build*, vol. 61, pp. 239–249, 2013, doi: 10.1016/j.enbuild.2013.02.032.
- [44] F. Goia, L. Bianco, Y. Cascone, M. Perino, and V. Serra, “Experimental analysis of an advanced dynamic glazing prototype integrating PCM and thermotropic layers,” in *Energy Procedia*, 2014, vol. 48, pp. 1272–1281. doi: 10.1016/j.egypro.2014.02.144.
- [45] S. Grynning, F. Goia, E. Rognvik, and B. Time, “Possibilities for characterization of a PCM window system using large scale measurements,” *International Journal of Sustainable Built Environment*, vol. 2, no. 1, pp. 56–64, 2013, doi: 10.1016/j.ijsbe.2013.09.003.

- [46] A. Cannavale, U. Ayr, F. Fiorito, and F. Martellotta, "Smart electrochromic windows to enhance building energy efficiency and visual comfort," *Energies (Basel)*, vol. 13, no. 6, 2020, doi: 10.3390/en13061449.
- [47] P. F. Tavares, A. R. Gaspar, A. G. Martins, and F. Frontini, "Evaluation of electrochromic windows impact in the energy performance of buildings in mediterranean climates," *Energy Policy*, vol. 67, pp. 68–81, Apr. 2014, doi: 10.1016/j.enpol.2013.07.038.
- [48] S. D. Rezaei, S. Shannigrahi, and S. Ramakrishna, "A review of conventional, advanced, and smart glazing technologies and materials for improving indoor environment," *Solar Energy Materials and Solar Cells*, vol. 159, pp. 26–51, Jan. 2017, doi: 10.1016/j.solmat.2016.08.026.
- [49] X. Xu and S. van Dessel, "Evaluation of a prototype active building envelope window-system," *Energy Build*, vol. 40, no. 2, pp. 168–174, 2008, doi: 10.1016/j.enbuild.2007.02.027.
- [50] F. E. Boafo, J. H. Kim, J. G. Ahn, S. M. Kim, and J. T. Kim, "Slim curtain wall spandrel integrated with vacuum insulation panel: A state-of-the-art review and future opportunities," *Journal of Building Engineering*, vol. 42. Elsevier Ltd, Oct. 01, 2021. doi: 10.1016/j.job.2021.102445.
- [51] A. Piccolo and F. Simone, "Performance requirements for electrochromic smart window," *Journal of Building Engineering*, vol. 3, pp. 94–103, Jul. 2015, doi: 10.1016/j.job.2015.07.002.
- [52] F. Feng, N. Kunwar, K. Cetin, and Z. O'Neill, "A critical review of fenestration/window system design methods for high performance buildings," *Energy Build*, vol. 248, p. 111184, Oct. 2021, doi: 10.1016/j.enbuild.2021.111184.
- [53] P. Lemarchand, J. Doran, and B. Norton, "Smart switchable technologies for glazing and photovoltaic applications," in *Energy Procedia*, 2014, vol. 57, pp. 1878–1887. doi: 10.1016/j.egypro.2014.10.052.
- [54] M. Casini, "Active dynamic windows for buildings: A review," *Renewable Energy*, vol. 119. Elsevier Ltd, pp. 923–934, Apr. 01, 2018. doi: 10.1016/j.renene.2017.12.049.
- [55] C. Aiello, N. Caterino, G. Maddaloni, A. Bonati, A. Franco, and A. Occhiuzzi, "Experimental and numerical investigation of cyclic response of a glass curtain wall for seismic performance assessment," *Constr Build Mater*, vol. 187, pp. 596–609, Oct. 2018, doi: 10.1016/j.conbuildmat.2018.07.237.
- [56] S. Shoeibi, H. Kargarsharifabad, N. Rahbar, G. Ahmadi, and M. R. Safaei, "Performance evaluation of a solar still using hybrid nanofluid glass cooling-CFD simulation and

- environmental analysis,” *Sustainable Energy Technologies and Assessments*, vol. 49, Feb. 2022, doi: 10.1016/j.seta.2021.101728.
- [57] L. Casagrande, J. Sisinni, A. Bonati, A. Occhiuzzi, and F. Auricchio, “Integrated shape memory alloy devices toward a high-performance glazed curtain wall seismic retrofit,” *Eng Struct*, vol. 179, pp. 540–555, Jan. 2019, doi: 10.1016/j.engstruct.2018.11.023.
- [58] K. H. Kim, “A comparative life cycle assessment of a transparent composite façade system and a glass curtain wall system,” *Energy Build*, vol. 43, no. 12, pp. 3436–3445, Dec. 2011, doi: 10.1016/j.enbuild.2011.09.006.
- [59] M. J. Bae, J. H. Oh, and S. S. Kim, “The effects of the frame ratio and glass on the thermal performance of a curtain wall system,” in *Energy Procedia*, Nov. 2015, vol. 78, pp. 2488–2493. doi: 10.1016/j.egypro.2015.11.234.
- [60] M. Fehrm, W. Reiners, and M. Ungemach, “Exhaust air heat recovery in buildings,” *International Journal of Refrigeration*, vol. 25, no. 4, pp. 439–449, 2002, doi: 10.1016/S0140-7007(01)00035-4.
- [61] C. Zhang, F. Xiao, and J. Wang, “Design optimization of multi-functional building envelope for thermal insulation and exhaust air heat recovery in different climates,” *Journal of Building Engineering*, vol. 43, no. July, p. 103151, 2021, doi: 10.1016/j.jobbe.2021.103151.
- [62] W. Li, Y. Li, W. Shi, and J. Lu, “Energy and exergy study on indirect evaporative cooler used in exhaust air heat recovery,” *Energy*, vol. 235, p. 121319, 2021, doi: 10.1016/j.energy.2021.121319.
- [63] X. Jia, G. Ma, F. Zhou, S. Liu, G. Wu, and Q. Sui, “Experimental study and operation optimization of a parallel-loop heat pump for exhaust air recovery in residential buildings,” *Journal of Building Engineering*, vol. 45, Jan. 2022, doi: 10.1016/j.jobbe.2021.103468.
- [64] Y. Tang, J. Ji, C. Wang, H. Xie, and W. Ke, “Performance prediction of a novel double-glazing PV curtain wall system combined with an air handling unit using exhaust cooling and heat recovery technology,” *Energy Convers Manag*, vol. 265, Aug. 2022, doi: 10.1016/j.enconman.2022.115774.
- [65] H. Y. Bai, P. Liu, M. Justo Alonso, and H. M. Mathisen, “A review of heat recovery technologies and their frost control for residential building ventilation in cold climate regions,” *Renewable and Sustainable Energy Reviews*, vol. 162. Elsevier Ltd, Jul. 01, 2022. doi: 10.1016/j.rser.2022.112417.

- [66] B. Nourozi, A. Ploskić, Y. Chen, J. Ning-Wei Chiu, and Q. Wang, “Heat transfer model for energy-active windows – An evaluation of efficient reuse of waste heat in buildings,” *Renew Energy*, vol. 162, pp. 2318–2329, 2020, doi: 10.1016/j.renene.2020.10.043.
- [67] E. Korol and O. Korol, “Modelling of energy consumption at construction of high-rise buildings,” *E3S Web of Conferences*, vol. 33, 2018, doi: 10.1051/e3sconf/20183302076.
- [68] J. Wei, J. Zhao, and Q. Chen, “Energy performance of a dual airflow window under different climates,” *Energy Build*, vol. 42, no. 1, pp. 111–122, 2010, doi: 10.1016/j.enbuild.2009.07.018.
- [69] C. Zhang, W. Gang, J. Wang, X. Xu, and Q. Du, “Numerical and experimental study on the thermal performance improvement of a triple glazed window by utilizing low-grade exhaust air,” *Energy*, vol. 167, pp. 1132–1143, 2019, doi: 10.1016/j.energy.2018.11.076.
- [70] C. Zhang, J. Wang, X. Xu, F. Zou, and J. Yu, “Modeling and thermal performance evaluation of a switchable triple glazing exhaust air window,” *Appl Therm Eng*, vol. 92, pp. 8–17, 2016, doi: 10.1016/j.applthermaleng.2015.09.080.
- [71] J. R. Gosselin and Q. (Yan) Chen, “A computational method for calculating heat transfer and airflow through a dual-airflow window,” *Energy Build*, vol. 40, no. 4, pp. 452–458, 2008, doi: 10.1016/j.enbuild.2007.03.010.
- [72] I. Poza-Casado, A. Meiss, M. Á. Padilla-Marcos, and J. Feijó-Muñoz, “Airtightness and energy impact of air infiltration in residential buildings in Spain,” *International Journal of Ventilation*, no. Spiekman 2010, 2020, doi: 10.1080/14733315.2020.1777029.
- [73] S. Verma, R. Panneer Selvam, Z. Tang, and D. Zuo, “Comparison of Tornado-induced pressures on building from CFD model with TTU experimental measurements,” *Journal of Wind Engineering and Industrial Aerodynamics*, vol. 228, Sep. 2022, doi: 10.1016/j.jweia.2022.105076.
- [74] J. Foroozesh *et al.*, “CFD modeling of the building integrated with a novel design of a one-sided wind-catcher with water spray: Focus on thermal comfort,” *Sustainable Energy Technologies and Assessments*, vol. 53, Oct. 2022, doi: 10.1016/j.seta.2022.102736.
- [75] M. A. William, M. J. Suárez-López, S. Soutullo, M. M. Fouad, A. A. Hanafy, and W. M. El-Maghlany, “Multi-objective integrated BES-CFD co-simulation approach towards pandemic proof buildings,” *Energy Reports*, vol. 8, pp. 137–152, Nov. 2022, doi: 10.1016/j.egyr.2022.06.091.
- [76] Y. Hu, Y. Peng, Z. Gao, and F. Xu, “Application of CFD plug-ins integrated into urban and building design platforms for performance simulations: A literature review,” *Frontiers of Architectural Research*. Higher Education Press Limited Company, 2022. doi: 10.1016/j.foar.2022.06.005.

- [77] M. A. Mohammed, N. Hamza, and S. J. Dudek, “Natural Ventilation in Hospitals of Semi-Arid Climates: A Case for Excluding Mosquitoes and Harmattan Dust Assessment of different shading design scenarios on air temperature and wind speed in urban street View project Sustainable Green Markets View project Natural Ventilation in Hospitals of Semi-Arid Climates: A Case for Excluding Mosquitoes and Harmattan Dust,” 2013. [Online]. Available: <https://www.researchgate.net/publication/308634259>
- [78] W. Zuo, “Introduction of Computational Fluid Dynamics.”
- [79] R. Bhaskaran and L. Collins, “Introduction to CFD Basics.”
- [80] M. Shirzadi and Y. Tominaga, “CFD evaluation of mean and turbulent wind characteristics around a high-rise building affected by its surroundings,” *Build Environ*, p. 109637, Nov. 2022, doi: 10.1016/j.buildenv.2022.109637.
- [81] P. E. Bournet and F. Rojano, “Advances of Computational Fluid Dynamics (CFD) applications in agricultural building modelling: Research, applications and challenges,” *Computers and Electronics in Agriculture*, vol. 201. Elsevier B.V., Oct. 01, 2022. doi: 10.1016/j.compag.2022.107277.
- [82] A. A. Chowdhury, M. G. Rasul, and M. M. K. Khan, “Thermal performance assessment of a retrofitted building using an integrated energy and computational fluid dynamics (IE - CFD) approach,” *Energy Reports*, vol. 8, pp. 709–717, Dec. 2022, doi: 10.1016/j.egy.2022.10.365.

Vitae

Name : Mahmoud Mohammed Majzoub |

Nationality : Sudanese |

Date of Birth : 10/29/1995 |

Email : majzoob555@gmail.com |

Address : Dammam, Saudi Arabia, PO32422 |

Academic Background :- B.Sc. in Building and architecture engineering (Honor
Excellent Graduate), college of architecture and planning, Imam Abdulrahman
University, June 2018 |

- M.Sc. in Architectural engineering, college of design and
built environment, King Fahd University of Petroleum and Minerals, December 2022 |

Professional Experience:

- ATPCO Construction Company (Oct2020-Now): Architect, Dammam: Responsible for making schematic design, and creating BIM modeling for Architecture and ID drawings.
- ASD Architects: BIM Engineer/Architect, Riyadh (2019April-March2020): Responsible for architecture and interior Shopdrawings for Ministry of Housing for Bisha Housing project. Also, I was responsible for preparing tender drawings using BIM for variant type of buildings, with different spaces and functions.

- ACC Consultants: Architecture Coordinator, Jabal Omar Project. Makkah (2018Nov-2019April): I am architecture coordinator in technical office of BAYTOR, for four hotels operated by Helton & Winston. My responsibility is to prepare coordinated Shopdrawings and supervise site execution.

- ACC Consultants: Architecture Coordinator, NOEM City. Sharma, Tabuk province (2018Jul-2018Nov): I was architecture coordinator in technical office of AZMEEL & BAYTOR, for tourist resort in Sharma, Tabuk, NOEM city, my duties were making Shopdrawings and prepare required BOQ, and check coordination between discipline through BIM technology.

Memberships:

- SCE Membership: Architecture and Building Science, ID: 707250

Patent Project:

A Buoyant Force Conversion Device and Method, published in 11/10/2018, Reference number: US-2018-0291866-A1

Research Projects:

- The Assessment of Energy Active Window in Hot Climates: Under Review. Publisher: Energy & Buildings, Elsevier (under review).
- Probability of Winning the Tender When Proposing Using BIM Strategy: A Case Study in Saudi Arabia, Issue: Advanced BIM sApplication in Construction. Publisher: Buildings ,MDPI.
- Mathematical proofs in equality of positive and negative infinity, presented in student's sixth conference for high education.
- Mathematical spherical model of 4-dimensional space-time, presented in student's sixth conference for higher education.

Appendices:



Testing window in extremely high temperature of at 80 °C



Testing window in extremely high temperature of at 80 °C, closer shot



Model 1-heating the chamber



Model 1-insider outdoor chamber



Model 2a –Inlet air temperature



Model 2a –Inlet air temperature



Model 2a –experiment to study solar impact.



Model 2a –Air inlet from AC



Model 2 –General view 01



Model 2 –General view 02



Model 2 –General view 03



Model 2 –Measuring



Model 2A –experiment to study solar impact.



Model 2A –experiment to study solar impact 01



Model 2A –experiment to study solar impact 02



Failed trails- Glass structural failure



Failed trails- Glass structural failure



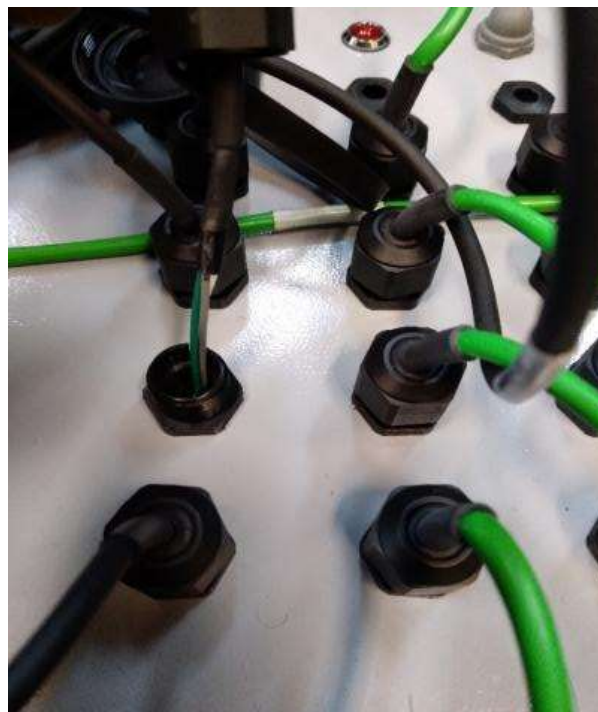
Tools used to measure
experimental factors, Hukefluks



Tools used to measure
experimental factors, Hukefluks



Model3 Noa setup- failures, fix measuring devices



Model3 Noa setup- failures, fix measuring devices



Model 03 setup- cooperating with IR and Mr. Aftab to learn and fix measuring devices



Model 03 setup- wiring system for instruments



Model 03 setup



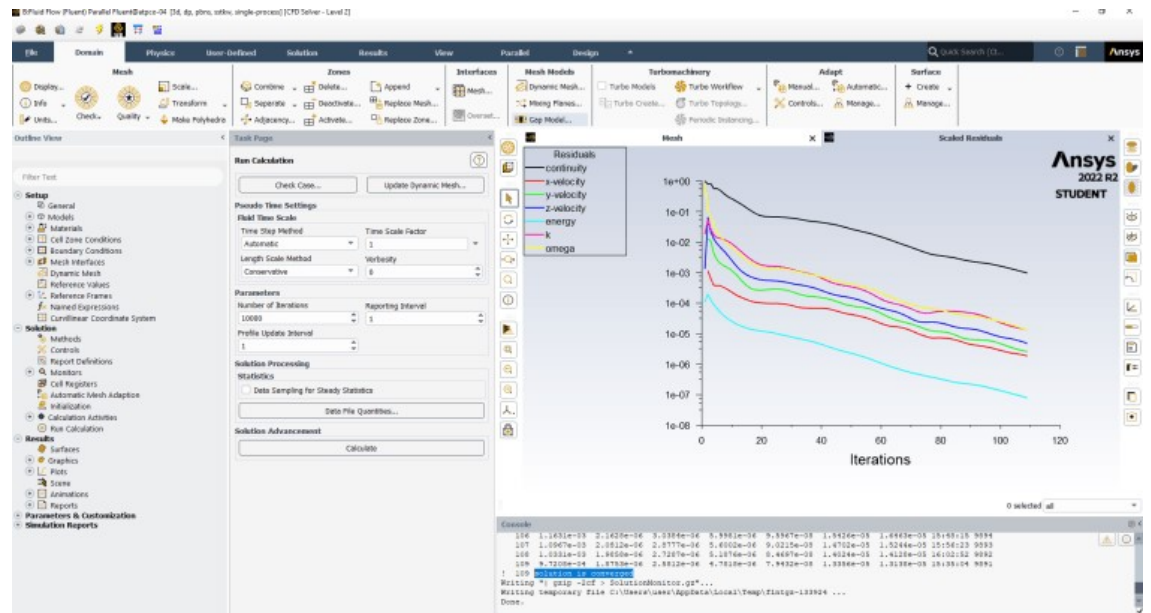
Model 03 outdoor chamber warming up



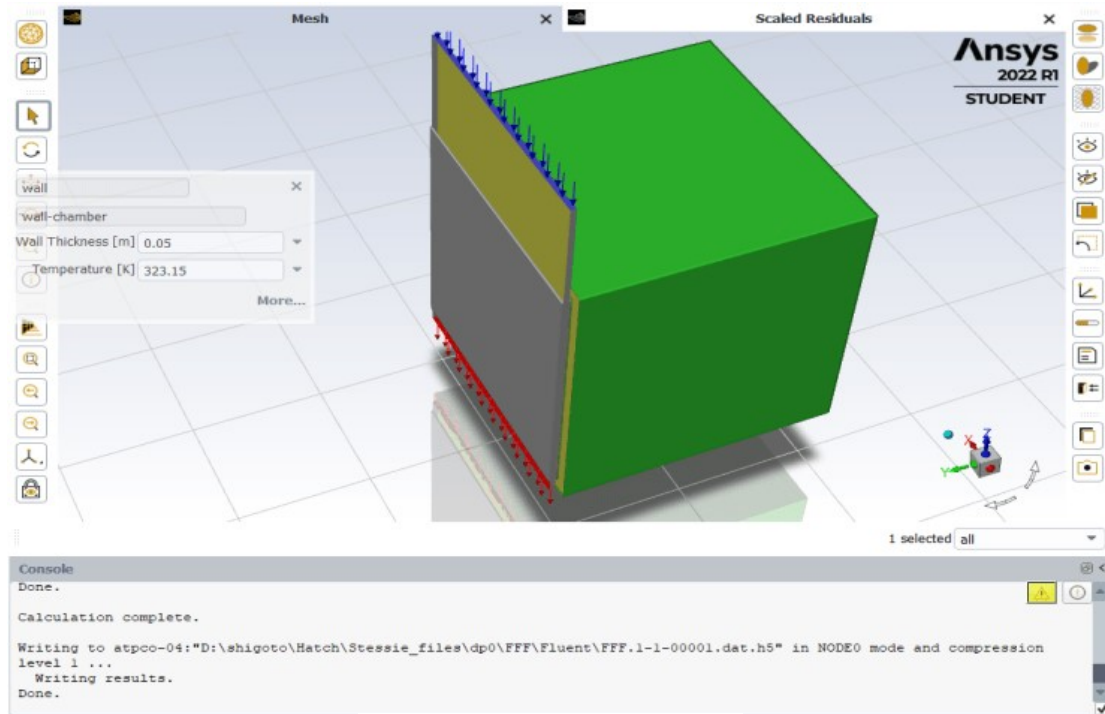
Model 03 setup-surface temperature measuring



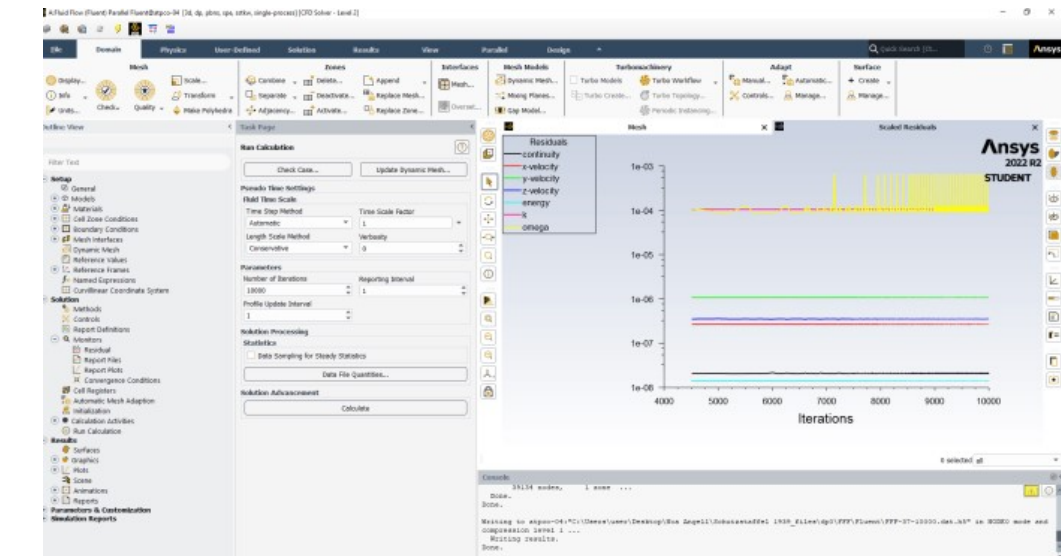
Model 03 setup and heat flux wiring



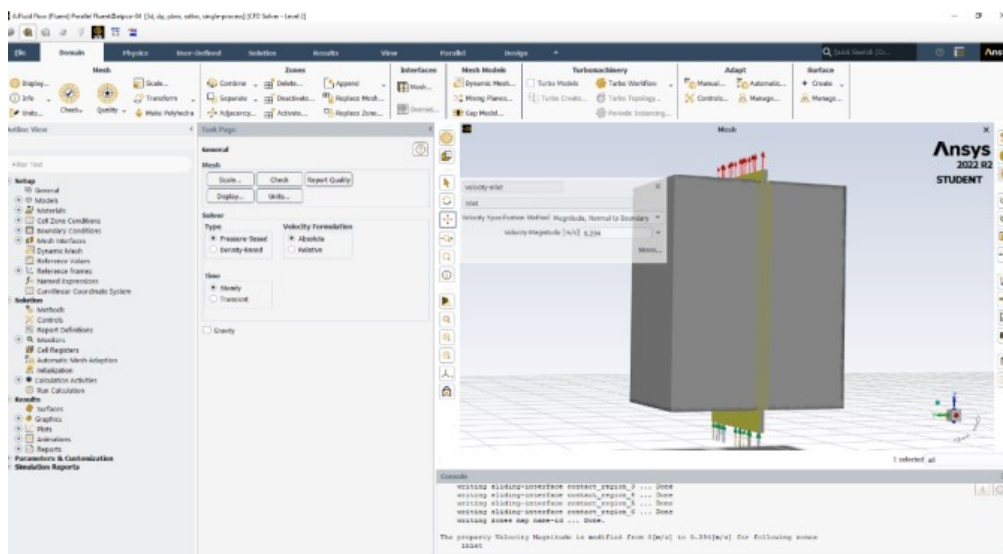
Simulation iteration, coverage at 1200 iterations



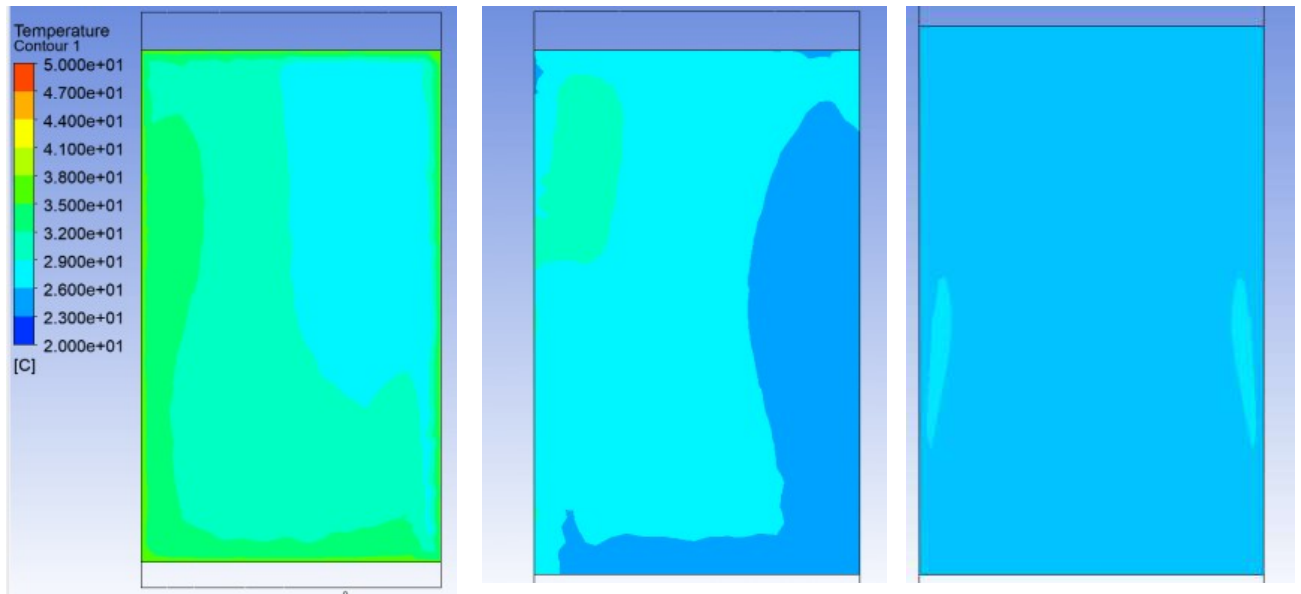
Simulation parameters



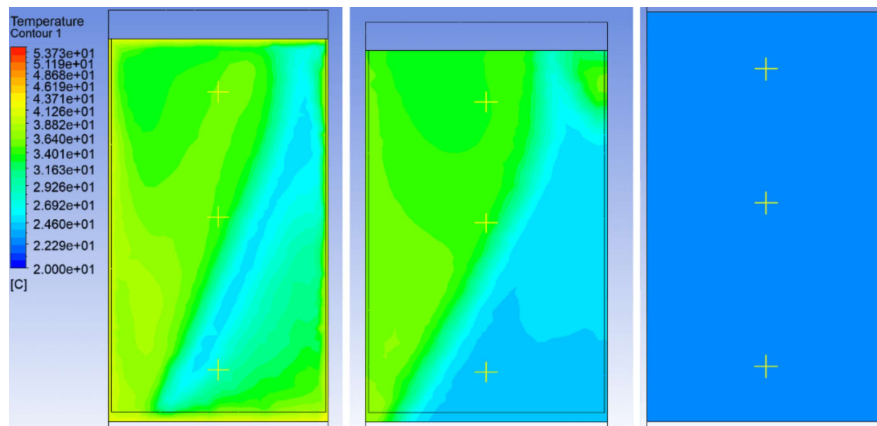
Simulation iteration, coverage at 10000 iterations



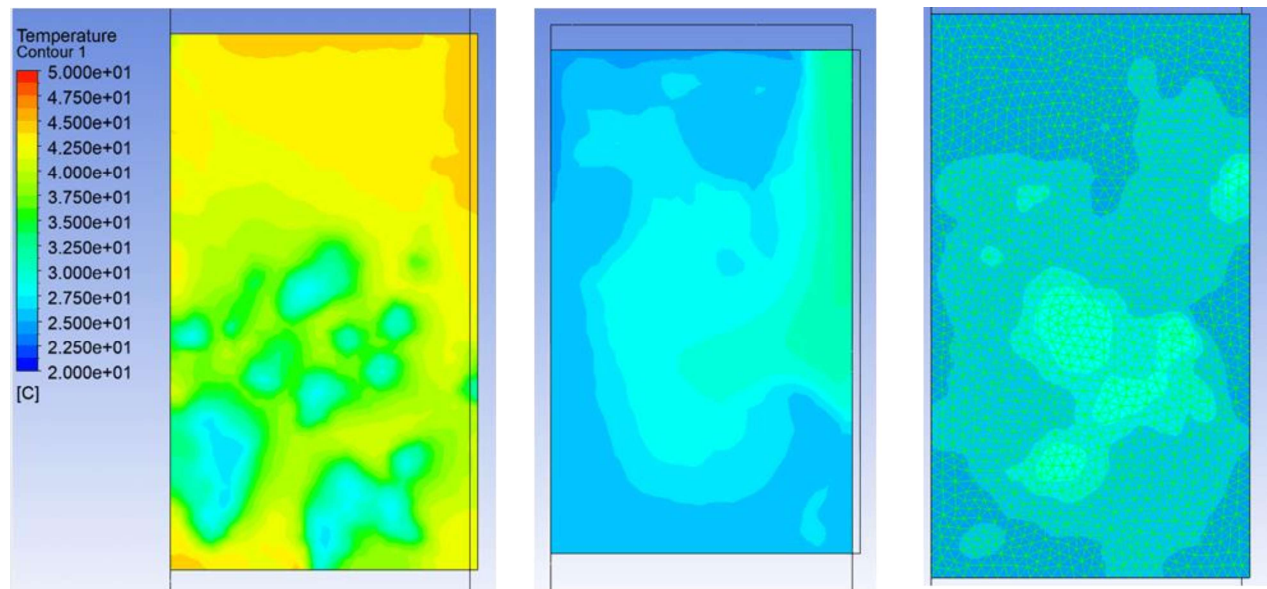
Simulation parameters



Contour of inner, middle, and outer windowpane for TGEW



Contour of inner and outer windowpane for DGEW at 8 cm air gap



Contour of inner, middle, and outer windowpane for TGEW