The Impact of Air Infiltration on Energy Performance of Single-Family Detached Houses in Hot Climate

BY

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DEDICATION

This thesis is dedicated to my family, research institutions and groups, homeowners, construction consultancies, and concerned personnel.

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“Recite in the name of your Lord who created(1) Created man from a clinging substance(2) Recite, and your Lord is the most Generous (3) Who taught by the pen (4) Taught man that which he knew not (5)” (Surah 96: Ayah 1-5)

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ABSTRACT

Full Name : Mohamed Ahmed Makawi

Thesis Title : THE IMPACT OF AIR INFILTRATION ON ENERGY PERFORMANCE OF SINGLE-FAMILY DETACHED HOUSES IN HOT CLIMATE

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Lately, energy used in modern buildings has been increasing dramatically which results in making buildings responsible for consuming most of the energy produced in the world. In Saudi Arabia, buildings consume almost 70% of the total generated electricity most of it is consumed by the residential sector [15]. The characteristics of the building envelope are essential in determining and evaluating building energy performance.

Envelope airtightness is the most important envelope characteristic since, it quantifies and control the flow of the uncontrolled air to/from outside the building which is a phenomenon called air infiltration. Air infiltration plays a determinant role in reducing and/or increasing the building thermal load and subsequently the building energy consumption. In Saudi Arabia, there is a lack of information regarding buildings airtightness, which is required in assessing and improving the buildings energy performance. The airtightness of two identical 3-bedroom single-family detached houses, matching the local design trend of houses in Dhahran, was measured using the pressurization/depressurization method known as the blower door test (BDT) method. The air change rates under 50 Pa (ACH50) pressure difference of House-A and House-B were found 6.58 and 7.04 h^{-1} respectively. Furthermore, the leakage contribution of common air leakage paths was determined by repeating the test and seal the correspondent envelope component then find out the impact on the total building leakage. Windows were the most influencing air leakage source in House-A by 0.85 ACH50 of the total air leakage while in House-B lighting and maintenance contributed by 1.89 ACH50 of the total air leakage. The airtightness test results were used to determine the actual infiltration flowrate under normal operating conditions of the houses which was 2.90 ACH for House-A and 2.51 ACH for House-B.

An energy model was developed for the houses and the actual energy consumption was monitored in order to validate the model. Two infiltration modelling options were investigated using the BDT results and the calculated infiltration flowrate. The results showed that the annual energy consumption of House-B is increased by 32.1% due to air infiltration. Also, it was found that mis estimation of air infiltration by 5% will results in deviating the software output by 2%.

ملخص الرسالة

الاسم : **محمد أحمد مكاوي**

عنوان الرسالة : **تأثير تسرب الهواء على أداء الطاقة للمباني المنفصلة (للعائلة الواحدة) في المناخ الحار**

التخصص : **هندسة معمارية**

تاريخ الدرجة العلمية : **أبريل 2020**

مؤخراً، زادت الطاقة المستخدمة في المباني الحديثة بشكل كبير مما أدى إلى جعل المباني مسؤولة عن استهلاك معظم الطاقة المنتجة في العالم. في المملكة العربية السعودية ، تستهلك المباني حوالي 70٪ من إجمالي الكهرباء المولدة [15]. يستهلك القطاع السكني معظم هذه الطاقة.

تعتبر الخصائص الحرارية لغلاف المبنى أساسية في تحديد وتقييم أداء طاقة المبنى. تعتبر درجة إحكام الغلاف الخارجي من أهم الخصائص حيث تقوم بتحديد كمية تدفق الهواء غير المنضبط من و إلى المبنى والتحكم فيه وهي ظاهرة تعرف بتسرب الهواء. يلعب تسرب الهواء دورًا حاسمًا في تقليل و/أو زيادة الحمل الحراري للمبنى وبالتالي استهلاك الطاقة الكلي للمبنى. في المملكة العربية السعودية ، هناك نقص كبير في المعلومات المتعلقة بإحكام تسرب الهواء في المباني ، وهو أمر مطلوب لتقييم وتحسين أداء طاقة المباني.

في هذا البحث ، تم قياس درجة احكام الغلاف الخارجي لمنزلين متطابقين من الوحدات السكنية المنفصلة في مدينة الظهران ,كل منزل يتكون من 3 غرف نوم. تم القياس باستخدام طريقة الضغط / السحب التي تعرف بطريقة الباب النافخ. وجد ان معدل تسرب الهواء في الاول هو 6.58 مرة لكل ساعة بينما كان المعدل للمنزل الثاني 7.04 مرة لكل ساعة. علاوة على ذلك ، تم تحديد مساهمة منافذ التسرب في تسرب الهواء الكلي للمنزل عن طريق اعادة الاختبار عدة مرات وعزل احد المنافذ كل مرة لايجاد مقدار النقصان في التسرب الكلي للمنزل. كانت النوافذ هي أكثر مصادر تسرب الهواء تأثيرًا في المنزل الأول بمقدار 0.85 مرة في الساعة عند فر ق ضغط 50 باسكال من إجمالي تسرب الهواء بينما ساهمت فتحات الإضاءة والصيانة في المنزل الثاني ب 1.89 مرة في الساعة عند فر ق ضغط 50 باسكال من إجمالي تسرب الهواء. تم إستخدام نتائج اختبار احكام الهواء لتحديد معدل التسرب عند الظروف التشغيلية للمنزل والتي كانت 2.90 مرة في الساعة و 2.51 مرة في الساعة للمنزل الأول والمنزل الثاني على التوالي.

تم تطوير نموذج للطاقة للمنزلين وتم قياس و رصد الاستهلاك الفعلي للطاقة من أجل التحقق من صحة النموذج. تمت دراسة خيارين لنمذجة التسرب، الأول باستخدام نتائج إختبار الباب النافخ و الثاني بإستخدام معدل تسرب الهواء المحسوب عند الظروف التشغيلية. أوضحت النتائج أن الاستهلاك السنوي للطاقة في البيت الثاني ارتفع بنسبة 32.1٪ بسبب تسرب الهواء. كما وجد أن التقدير الخاطئ لتسرب الهواء بنسبة 5٪ سيؤدي إلى انحراف مخرجات نموذج الطاقة بنسبة 2٪.

CHAPTER 1

INTRODUCTION

1.1 Background

The U.S. Energy Information Administration (EIA) [1] indicated that the average gross rate of energy-related CO_2 emissions between 1990 and 2018 was 1.8% per year. The EIA reports predict that between 2018 and 2050 the world energy consumption will increase by approximately 50%.

Buildings are one of the major reasons for this dramatic increase in the energy use which is, according to the International Energy Agency, responsible for consuming 55% of the global produced electricity and 30% of the final energy [2].

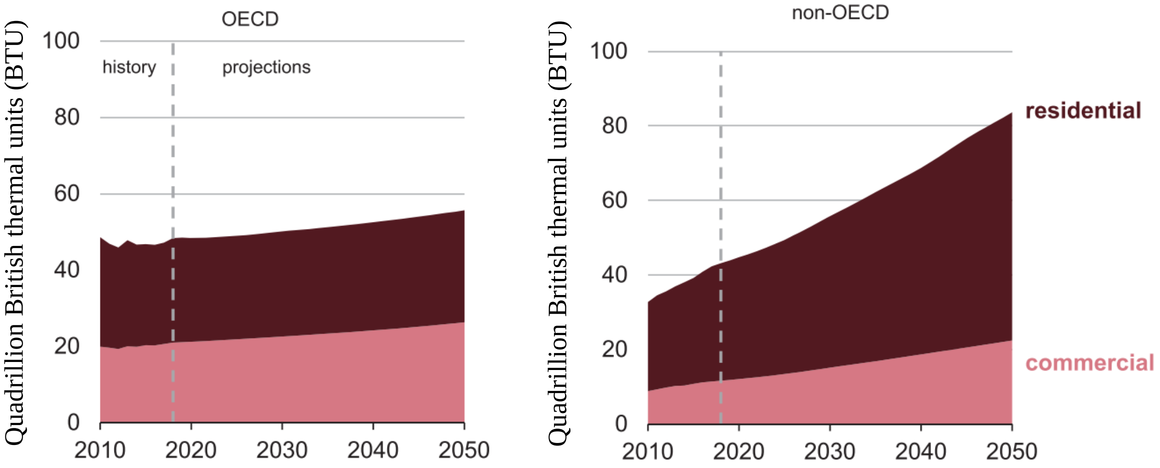


Figure 1.1: Prediction of building energy consumption from 2020 to 2050 [1].

A more recent report by the EIA predicts an increase in the building's shares in the consumption of the total delivered energy consumption from 20 % in 2018 to 22% in 2050. This increase is mainly from countries that are not part of the Organization for Economic Cooperation and Development (OECD) ash shown in Figure 1.1 [1].

Nowadays, due to the huge development in industrial technologies, the possibility to improve the living conditions inside the buildings has increased. This resulted in increasing the demand for comfort requirements recently more than in previous periods [3]. Furthermore, increasing comfort requirements may be followed by an increase in energy consumption. Not only the comfort requirements affect energy consumption, but the thermos-physical properties of the construction materials and the performance of the building systems have the same effect on the usage of energy [4]. Meeting the new occupants' requirements entails including, in a new modern building, several complex services such as lifts, air conditioning systems, and fire suppression systems in addition to quality fabrics. Progressively, new buildings are fitted with advanced green technologies such as resources recycling, energy recovery, and utilization of renewable energy [5].

In addition to the fact that most people spent more than 90% of their lives inside buildings. All those mentioned factors led to make buildings, commercial and residential, responsible for more than 40% of global energy consumption and a substantial proportion of global greenhouse gas emissions [4,6]. Therefore, many studies in different locations have conducted investigations on how to improve the energy performance of buildings, especially, residential ones [7].

1.2 Statement of the Research Problem

Residential buildings in Saudi Arabia are considered a major factor in the recent increase of the total energy use in the Kingdom. Residences consume approximately up to 50% of the total energy used by buildings [8]. Impacted by the hot weather of the country, most of this energy is consumed by intense use of the cooling systems. This high-intensity energy use affects the environment negatively because of the dependency on fossil fuel in electricity generation. Therefore, reducing the energy consumed by buildings has become an essential target for the government and the researchers. Reducing the energy used by the cooling system requires reducing the heat gain in buildings. Since the residential buildings are skin dominated when it comes to the cooling load, previous studies [31,32,33] have shown that the highest contributor in the cooling load is the air infiltration through the building envelope. Accordingly, this research will focus on studying the impact of air infiltration on houses energy performance under the hot-humid climate of Saudi Arabia.

1.3 Significant of the Research

The study will investigate the abilities of energy simulation software when inputting air infiltration data in order to have a reliable energy prediction and evaluation for the residential Single-family detached houses by utilizing different infiltration modelling methods and measured flow rates. The contribution of the study will also be valuable to overcome the lack of knowledge in building’s infiltration data in Saudi Arabia. Furthermore, it could provide a guide for infiltration input data in energy simulation process knowing that, the input for defining the envelope airtightness is a critical aspect in the model and could have serious consequences on the model and simulation results. Also, the study investigates the influence of different building components on the total building airtightness in addition to the behaviour of those components under various conditions.

1.4 Objectives

First	: Investigate the airtightness of a representative sample of single-family detached houses.
Second	: Investigate variation of predicted energy consumption by building energy simulations when utilizing measured and/or estimated air infiltration rates.
Third	: Study the impact of the air infiltration rate on the energy performance of single-family detached houses.

1.5 Scope and Limitations

This research is confined to the following:

1. Single-family detached houses.
2. The hot climate of Saudi Arabia specifically Dhahran weather.
3. Availability of energy simulation software with the ability to model air infiltration.
4. Available air leakage measurement method.

1.6 Research Methodology

The suggested methodology for achieving the research objectives involves utilizing infiltration field measurements as input data to define the envelope air leakage characteristics using different infiltration modelling approaches Figure 1.2. The purpose is to investigate the accuracy of the software prediction based on the model used to define the envelope airtightness in order to account for the effect of air infiltration on the building energy performance. The first stage was a selection of **2** unoccupied similar detached houses representing the local trend type of residential buildings. The envelope airtightness of the selected houses was determined using a pressurization/depressurization test which is also known as the Blower Door Test (BDT).

Then, using suitable energy software, an energy model was established, and envelope parameters other than air infiltration such as wall U value and window to wall ratio in order was defined based on a calibrated model developed in a previous study [12]. Energy monitors were installed in the selected houses to measure the actual energy use for a period of time. The monitor's readings were used to validate the energy model. After that, the results of the pressurization test were utilized in the energy model using different infiltration modelling approaches to determine the most accurate approach in defining air infiltration. The second stage involved using the selected infiltration modelling option in investigating the impact of air infiltration on the energy consumption of the selected houses.

The general steps for achieving the research objectives were:

1. Conduct a literature review to address related studies carried out in the field of building air leakage and its effect on buildings energy performance. Furthermore, the current standards related to buildings air leakage were reviewed to identify the state-of-the-art techniques for measuring envelope airtightness. Also, the literature review will target the available infiltration modelling approaches and the capabilities of the available energy software in accounting for air infiltration in energy consumption.
2. Select a sample of single-family detached houses representing the local trend and collect the physical and thermal specification data of them. The selection of the

houses will be based on the availability of the thermal, physical, and energy information in addition to the accessibility for the houses.

3. Install energy monitors on the selected houses to capture the actual amount of energy consumed during a specific period of time.
4. Assess the air leakage characteristics of the selected houses by conducting pressurization/depressurization tests using state of the art equipment according to relevant standards.
5. Establish an energy model for the selected tested houses based on their physical and thermal characteristics using state-of-the-art building energy simulation software with the ability to model building air infiltration.
6. Utilizing the measurements results in the energy model and study the effect of different infiltration modelling options on the predicted energy by the software.
7. Validate the model accuracy by comparing the predicted energy with the monitored energy consumption to determine the most accurate infiltration modelling method.
8. Conduct a parametric analysis using the validated energy model to assess the impact of air infiltration on the building energy performance under the hot climatic conditions of Saudi Arabia.

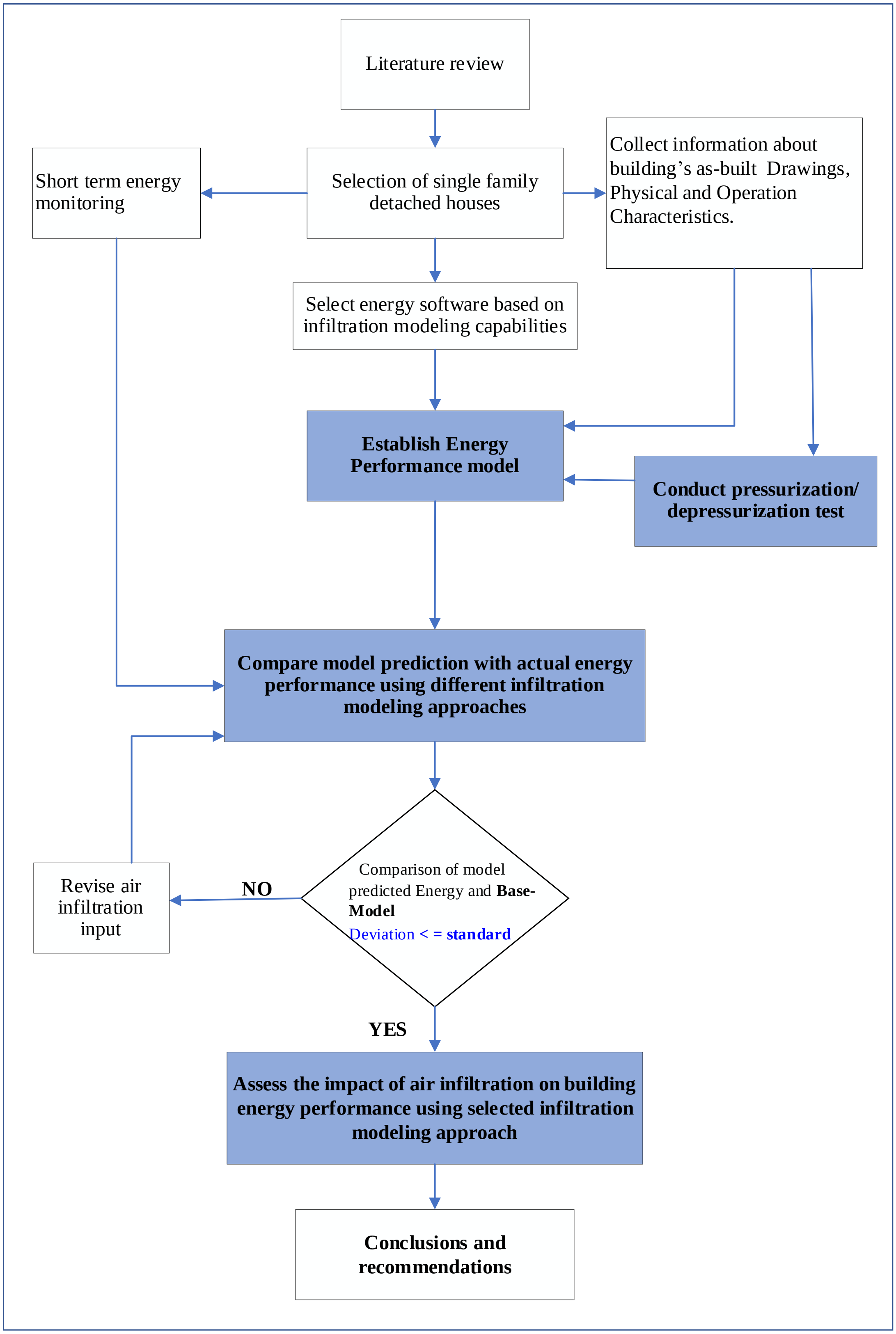


Figure 1.2: Research methodology

CHAPTER 2

LITERATURE REVIEW

2.1 Energy Status in Saudi Arabia

Saudi Arabia is considered one of the leading countries in the field of oil production and export which result in making the production and consumption pattern of energy unsustainable since the kingdom is relying mainly on fossil fuel with 59% and 41% on natural gas [8]. The main leaders of the electricity demand in Saudi Arabia are the desalination stations and cooling systems [13].

In Saudi Arabia, the government considers that "it is a strategic imperative for the Kingdom that energy efficiency becomes a major topic for all decisions related to an increase in demand for fuel and feedstock" [14]. Buildings are considered one of the main targets for the government initiatives since they consume more than 70% of the total energy produced in the country and this consumption is annually increasing as shown in Figure 2.1 [15,16]. The breakdown for the total energy consumed by the building sector in 2014, shown in Figure 2.4, indicates that residential buildings have a major share with 49% of the total electricity consumed by Saudi buildings [16]. According to the EIA [17], the energy consumption have been increased annually between 1990 and 2017 with an average rate of 26.5% as shown in Figure 2.1. Furthermore, Figure 2.3 shows that the rate of increase in the residential sector is the highest when comparing with other final energy use sectors. Electricity is mainly used for cooling, desalination, industrial, and domestic needs in Saudi Arabia. It is produced from fossil energy sources, but using other sources such as nuclear energy, solar energy, and renewable energy in electricity generation activities is still ongoing.

In many countries, energy policies have been targeted energy efficiency and savings strategies in buildings, making it a priority, driven by the huge increase of CO_2 emissions and energy consumption in building sector [6].

To decrease the building energy consumption in the Kingdom, several programs and standards have been presented to the Saudi building sector. For example, the National Energy Efficiency Program (NEEP) which was established at King Abdul-Aziz City for Science and Technology (KACST) in order to assist in achieving the country's targets regarding energy use [18].

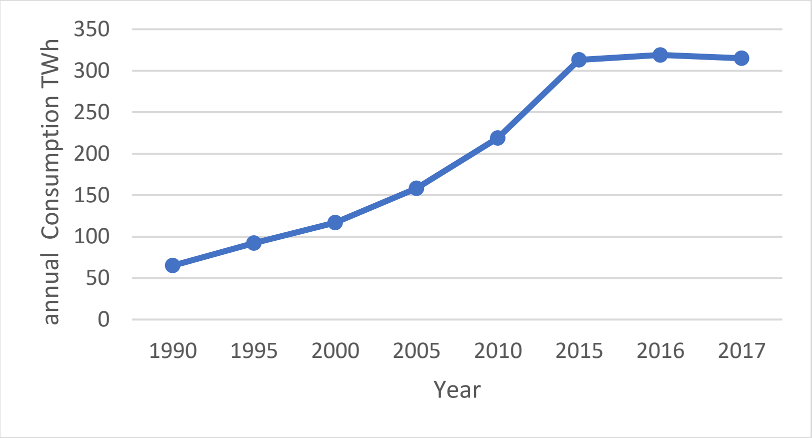


Figure 2.1: The annual increase in domestic energy use in Saudi Arabia [17].

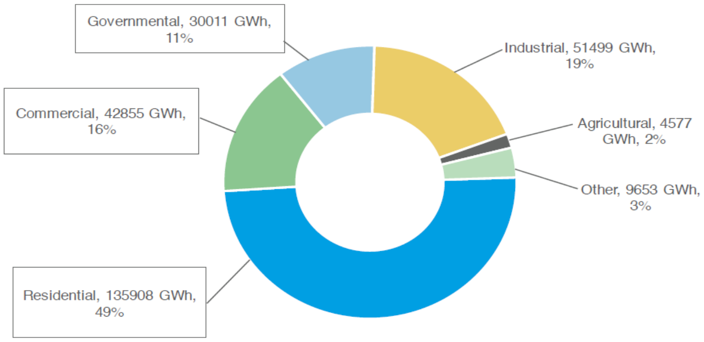


Figure 2.2: 2014 electricity consumption breakdown in Saudi Arabia [9].

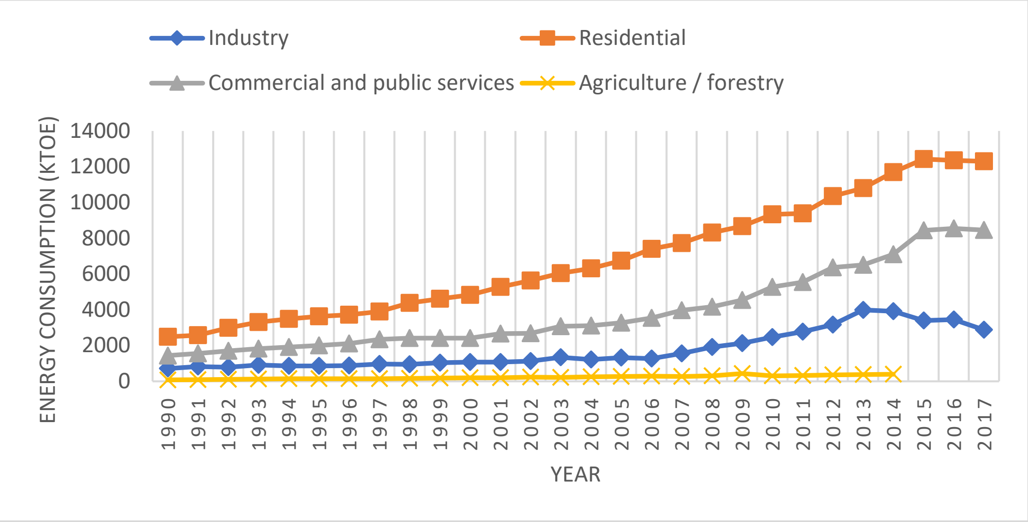


Figure 2.3: Electricity end-use consumption by sector between 1990-2017 [17].

M. Asif [19] reviewed the status of the building sector in the Gulf Cooperation Council (GCC) region focusing mainly on the United Arab Emirates and Saudi Arabia considering them the most influential countries in the region based on the size of the economy, ongoing investments in the buildings sector and population. He recommended the European Union's joint action on sustainable development to be considered in the two countries to establish policies and practices in the building sector to force and lead the buildings towards sustainability.

2.2 Indoor Environmental Quality

The (ASHRAE) standard defined the acceptable indoor environment (IEQ) by “an environment that has been determined to be acceptable according to the process and individuals involved” [20]. The IEQ has a direct impact on the occupant and their activity inside the building. For example, providing the occupants in an office building with high (IEQ) will improve their productivity [21]. The IEQ has four main factors which are thermal comfort, visual comfort, acoustical comfort, and indoor air quality [22]. In order to satisfy the requirements of the IEQ factors, new techniques were developed, and modern buildings are equipped with quality fabrics and complex facilities like air-conditioning systems, lifts, fire services installations, etc. Especially in hot climates, thermal comfort is considered the central and most important parameter of IEQ. The requirements of the IEQ factors represent the building loads which, in order to fulfil, energy is consumed in buildings.

2.2.1 Thermal Load and HVAC Systems

The HVAC system is the system responsible for the thermal parameter of IEQ. Its main objective is to meet the thermal comfort requirements by delivering proper air circulation, ventilation, and better thermal conditions in the building [23].

Excessive use of heat, ventilation and air-conditioning (HVAC) installations have resulted from the growing demand for superior thermal comfort conditions inside the buildings. Therefore, mainly in developed countries, The HVAC system could account for half of the building energy, particularly in non-domestic ones, making it the primary energy end-use system [24].

Therefore, HVAC systems could harm the environment by needless and unnecessary consumed energy which will lead to lessening the age of the nonrenewable energy resources, especially fossil fuels, through the generation of thermal energy or electricity which ultimately will subsidize the pollution of the environment [25]. The awareness of the harm that HVAC system could cause to the environment and how important of this system to the occupant comfort have encouraged researchers to study and try different strategies to save energy while delivering its required performance [26].

A constituent step to reduce the energy used by the HVAC systems is to understand the configuration of the system and what are the main elements and equipment assist in increasing the amount of energy used by the system. Completing this step will help in selecting and focusing on the central factors which will eventually lead to more efficient buildings [27].

Building air-tightness is one of the most important building characteristics related to the building energy performance since it could affect occupant thermal comfort, indoor air quality, and HVAC system design, selection, and performance [23, 24]. Also, it plays a determinant role in the energy performance of the building because of the additional cooling/heating load that could be added by the air leakage, which will, in turn, increase the energy used by the HVAC system and ultimately affect the building overall performance.

2.3 Building Air-tightness and Air infiltration

The outdoor air could be introduced to the building via two means. The first mean is through the ventilation system either natural or mechanical which provide outdoor air, intentionally, to improve and maintain the indoor air quality by polluting the indoor air contaminants and there are plentiful calculation methods and standards to determine the required ventilation rate for each building type and application [25, 26, 27]. The second mean is by the infiltration through the building envelope driven by temperature and/or pressure difference. The American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE(defines the infiltration as “the flow of outdoor air into a building through cracks and other unintentional openings and through the normal use of exterior doors for entrance and egress” [25, 26, 27].

Infiltration is a physical phenomenon while Airtightness is the envelope characteristic which impacts and quantifies the occurrence of the infiltration through the envelope [31, 28]. Also, many scholars tend to target the term air permeability ($m^3/h \cdot m^2$) in their studies which could be defined as the amount of air that could pass through the building envelope [36]. Therefore, less air permeability means the envelope is more airtight and less infiltration.

Researches assessed that air infiltration in both residential and commercial buildings could be responsible for 25%-50% of the total cooling/heating loads [31, 32, 33]. Furthermore, air infiltration could also have a serious negative impact on the indoor air quality, as it may allow moisture, outdoor particles, and gaseous contaminants inside the building [34, 35, 36].

The infiltration and airtightness could be linked together mathematically. One of the simple empirical relations is the assumption that the building infiltration in 1/20th its airtightness and it is known as a “rule of thumb” [35]. Several factors with a direct impact on air infiltration were not considered in this empirical relation. In 1987, a recognized model was developed by Sherman which is the LBL (Lawrence Berkeley Laboratory) model [40]. Sherman proposed the addition of correction factors in order to consider the effect of the type of cracks, the wind exposure and the building height on the building air infiltration.

Walker and Wilson developed the “AIM-2 (Alberta air Infiltration Model) in 1990 which considers the total airflow correlated with the wind flow and stack flow [35].

The envelope airtightness is a determinant factor to the building energy performance especially the skin dominated ones like the residential buildings. Therefore, various studies have been performed addressing the relationship of the envelope airtightness and energy consumption.

Cara H. Lozinsky et al. [41] indicated that many previous studies focused on quantifying the influence of air infiltration on the residential buildings energy consumption and found that infiltration is responsible for 45% of the annual space heating in the multi-unit residential homes and 15-30% in single-family homes.

Steven J. Emmerich et al. [42] studied the effect of air infiltration on the heating and cooling energy in 25 office buildings, as a representative sample for the US office building, and found that 33% of the heating energy is used to overcome the air infiltration through the envelope and the cooling energy is reduced by 3.3% due to the same reason.

ASHRAE highlights the importance of infiltration in residential building specifically, while emphasizes on ventilation in commercial buildings. However, even in commercial buildings, it instructs that infiltration should not be overlooked [43]. This was concluded from a previous literature review [43, 44] which indicates that 40% of residential buildings cooling/heating load is due to air infiltration while the infiltration contribution in the commercial buildings is 15%. ASHRAE [46] stated that the infiltration contribution of different building components as shown in Table 2.1.

Table 2.1: Envelope components contribution to residential building air infiltration [46].

Building component	Percentage range	Average
Walls	18%-50%	35%
Cooling systems	3%-28%	18%
Fireplace	0%-30%	12%
Windows and doors	6%-22%	15%
Vents	2%-12%	5%
Others	≤ 1%	

2.3.1 Airtightness Measurements

Various field measurements and surveys have been established to quantify the level of air infiltration in a building under a certain pressure difference across the building envelope [47]. The ISO 9972:2015 [48] and ASTM E779:2010 [49] are the most widely standards for the field measurements of the air permeability of the building or part of it. The test method is conducted by creating mechanical pressurization or de-pressurization of a building until reaching a specific pressure difference between indoor and outdoor and measuring the airflow rate. The different airflows and correspondent pressure differences are plotted in a log-log plot graph as shown in Figure 2.4 for both pressurization and depressurization measurements.

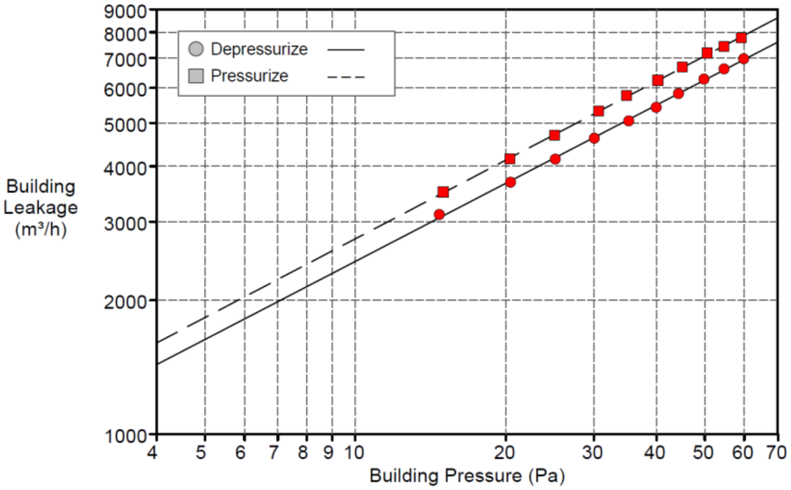


Figure 2.4: Example Air leakage graph from blower door test [50].

The data in the air leakage graphed is used to determine the pressure exponent (n) and the air leakage coefficient (C) as shown in Equation 2.1 which describes the relationship between air leakage flow rate and the pressure difference across the envelope [49].

$$Q = C(\Delta P)^n \tag{2.1}$$

Lone H. Mortensen et al. [51] used the pressurization test to measure the airtightness of 16 existing detached houses in Denmark naturally ventilated in order to cover the lack of knowledge regarding air infiltration. The measurements results showed that the buildings air leakage was between 1.1 to 5.8 l/(s·m^2) at 50 Pa pressure difference and the ventilation rates are below the recommended rate specified by the Danish building regulation. The study also highlighted the common air leakage paths, which were the penetration of the envelope by the ducts, electrical installation, and chimneys. These observed factors could be used to advise and guide in construction activities and details during renovation processes.

F.R.d’Ambrosio Alfano et al. [52] used the Blower Door test field measurements in order to study the influence of air infiltration and main metrological aspects in airtightness on the building energy use and occupant comfort. The studied buildings were 20 residential houses in Mediterranean southern Italy representing the common residential building in the region. The experimental results of the study revealed that old houses tend to have higher air leakage flow rate than new ones, which mean they are consuming more energy. In addition, the common causes of overventilation in the selected buildings were the natural ventilation system, chimney without sealing, and windows.

A. Sfakianaki et al. [53] measured the airtightness and air infiltration of 20 houses, in the area of Attica, Greece, using the two methods, the pressurization/depressurization test in accordance with EN ISO 13829 and the tracer gas method. The resulted average air change per hour ACH from the pressurization/depressurization test and tracer gas was 7 ACH50 and 0.6 ACH respectively. The houses were categorized based on the pressurization test results into three air tightness categories and the results were tested statically to identify their homogeneity. The statistical evaluation showed that buildings belong to the low airtightness houses were statically homogenous while the medium and high airtightness buildings sample were statistically uneven. Further statically evaluation will require a larger number of samples.

Jesús Feijó-Muñoz et al. [54] assessed the envelope air leakage using blower door test on 225 different types and sizes of residential buildings located in Málaga, Las Palmas de Gran Canarias, Alicante, Sevilla and Barcelona to determine the influence of air infiltration on the energy consumption and the results indicated that, for each year, air infiltration could add 0.54to 3.06 kWh/m^2.year to the cooling load and 2.43 to 16.44 kWh/m^2 to the heating load.

J. Šadauskienė et al. [55] conducted infiltration field measurements on 27 single-family detached houses in order to evaluate the energy performance methodology proposed by the local jurisdiction in Lithuania. The results of the study indicated that the outcome of the currently used energy calculation method could only be reliable if the airtightness of the building was verified.

Targo Kalamees [56] used infiltration field measurements on 32 detached houses combined with an infrared camera and smoke detector to determine the common air leakage paths on the selected houses. The typical air leakage paths observed were:

1. The points of penetrations in the air barrier systems by the chimney, the electrical installations, plumbing installations, and ventilation ducts.
2. The junction of the external wall with ceiling/floor and with the separating walls.
3. The leakage around the electrical sockets, switches, doors, and windows, in addition, the leakage through them.

2.4 Summary of Findings of Literature Review

- The energy consumption of the Buildings, residentials particularly, have been increasing recently due to several reasons.
- One of the main sources of this increase is caused mainly by infiltration and exfiltration a phenomenon which are major components of the heat gain in the residential buildings.

- Increasing buildings airtightness to minimize air infiltration have been applied and investigated widely as an energy efficiency measure in order to reduce energy consumption.
- In Saudi Arabia, there is a lack of infiltration data on the buildings stock which is needed to be investigated in order to assess the infiltration impact on the energy consumption.

CHAPTER 3

AIR TIGHTNESS MEASUREMENTS AND INFILTRATION ESTIMATION

3.1 Introduction

This chapter presents a description of the selected house as a case study for this research focusing on the airtightness measurements and the calculation of the air infiltration rate. First, the blower door test was conducted with several setup scenarios which allow the determination of the contribution of the different building components on the building airtightness. The results of the airtightness test for selected scenarios were used to determine the infiltration flowrate using the relationship between the pressure difference across the envelope and the infiltration flowrate. The chapter also includes the reporting of the conducted measurements for the wind speed and direction with the pressure difference across the building envelope.

3.2 Air Tightness Measurements

3.2.1 Building Description

The selection of the house sample was based on the availability of the thermal and physical information in addition to the accessibility of the house. Furthermore, the selected house type and capacity is the common residential used type in the Eastern Province of Saudi Arabia. In this research, two identical adjacent houses were selected, each house is a 3-bedroom single-family detached house located in the eastern province of Saudi Arabia, the city of Dhahran in the KFUPM faculty housing. The floor areas, in each house, of the ground and first floors are 189 m^2 and 135 m^2 respectively with a building height of 2.7 m per floor. The shape of the houses is rectangular as shown in Figure 3.1 which demonstrates the house floors plans. The houses are oriented to the south-west (SW) with an angle of approximately 212° from the north direction. The area of the first floor is less than the ground floor thereby the additional space is used to accommodate the HVAC units.

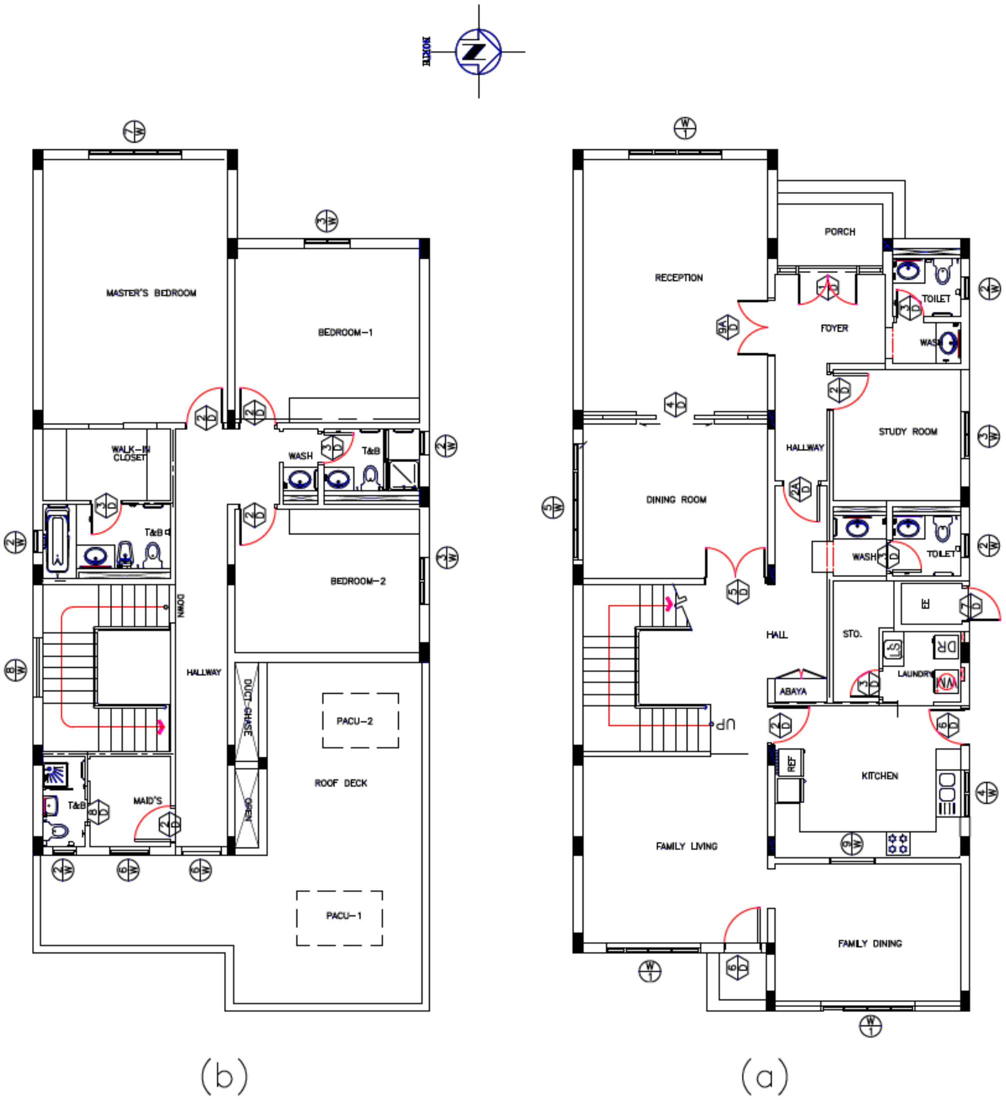


Figure 3.1: (a) Ground floor plan, (b) First floor plan

air conditioning units. The walls and roof of the houses are designed with a very good heat insulation performance where the overall heat transfer coefficient for the exterior walls and roof are 0.466 and 0.539 W/m^2.k respectively [12].

The HVAC system type used in the two houses is a constant volume (CV) direct expansion package unit wherein a unit specified for each floor. The total cooling capacity and supply airflow for the ground floor unit is 40.7 kW (139.8 MBTUH) and 8121.3 m^3/h (4780 CFM) while, for the first-floor unit are 27.9 kW (95.4 MBTUH) and 5402.9 m^3/h (3180 CFM). The size and quantities of windows and exterior doors are shown in Table 3.1.

Table 3.1: Details of windows and exterior doors of the houses

Door/ Window code	Area (m^2)	Dimensions (m)	Quantity
D/1	6.75	2.7 x 2.5	1
D/6	2.15	1.0 x 2.2	2
W/1	5.04	2.4 x 2.1	3
W/2	0.36	0.6 x 0.6	5
W/3	1.44	1.2 x 1.2	3
W/4	1.32	1.2 x 1.1	1
W/5	1.8	3.0 x 0.6	1
W/6	1.2	1.0 x 1.2	2
W/7	2.88	2.4 x 1.2	1
W/8	3.15	1.5 x 2.1	1
Total	26.09		

3.2.2 Measurements Method

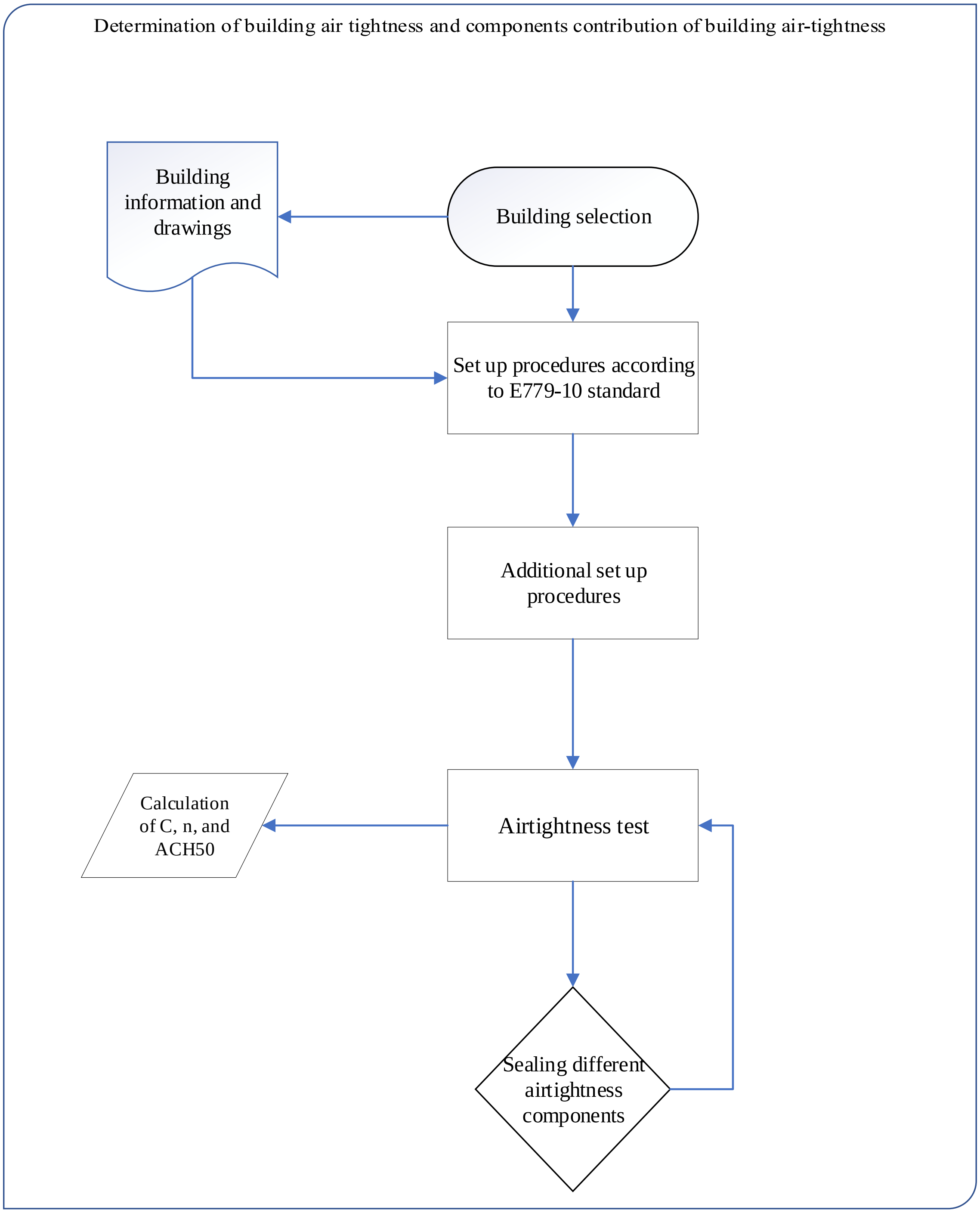


Figure 3.2: Methodology of airtightness measurements

The airtightness of the houses was determined using the blower door test following the methodology shown in Figure 3.2 and it was conducted according to E779-10 standard where several parameters should be checked and multiple procedures are needed to set up the house before starting the test such as:

1. All interior doors should be open during the test to create a uniform pressure.
2. Fireplace and operable dampers should be closed except AC system balancing dampers should not be adjusted.
3. The multiplication of the outdoor/indoor temperature difference (K) and the building height (m) should not be more than 500 m.K.
4. Building volume and wind velocity during the test should not exceed 4000 m^3 and 2 m/s respectively.

For the case study, the plumbing fixtures were sealed after filling with water as an additional set up step needed to ensure the accuracy of the test because the house was not occupied, and empty U-traps and other fixtures could affect the test results significantly.

The used test system, shown in Figure 3.3, consists of the door assembly with two fans capable of creating the required pressure difference across the envelope and two gauges to measure the pressure and the airflow rate. The test has two modes, pressurization and depressurization, each fan is dedicated to one mode, and both modes were applied for the measurements of the air leakage. The system is computerized and controlled using TECTITE Express Ver. 4.0 software provided by the system manufacturer which gives the options to conduct the test either automatically, semi-automatically, or manually. The use of the software allows obtaining the results after correcting the input data such as building baseline pressure, site location altitude, and indoor/outdoor temperature difference. Also, the control software provides auto-identification of results deviation from the selected test standard.

Figure 3.3: Used blower door assembly and pressure gauges

The used gauge model DG-700 as shown in Figure 3.3 has two different pressure channels, one channel for measuring the pressure difference and the other for the fan flow rate. As per the E779 standard requirements, during the airtightness test, the pressure difference across the envelope should change from 60 Pa to 15 Pa with 5 Pa intervals and the airflow rate to achieve each pressure difference should be also measured.

The common blower door results determine the airtightness of the entire building and show the data plotted in the air leakage graph, which is used to calculate the pressure exponent and the air leakage coefficient defined in Equation (2.1).

Another parameter obtained from the blower door test and used to describe the building airtightness is the n50 or ACH50, which is the air change per hour at 50 Pa pressure difference. This method was used for determining building airtightness and pressure exponent and the air leakage coefficient results were obtained. Furthermore, this method was formed to measure the contribution of different building components in the total building leakage by repeating the test after sealing the corresponding component and find the reduction in the n50 value.

The n50 value could be obtained using:

$$n50 = \frac{Q50}{V} \tag{3.1}$$

Where

Q_{50} = is the airflow rate at 50 Pa pressure difference, m^3/h;

V = is building internal volume, m^3.

The space above the ceiling is used as return plenum for the HVAC system where return air will rise freely as it gains heat from the conditioned zones through the return diffusers and the return duct move it to the package unit. Since the return duct is not connected to the return diffusers, every intentional or unintentional opening in the ceiling is a possible air leakage path.

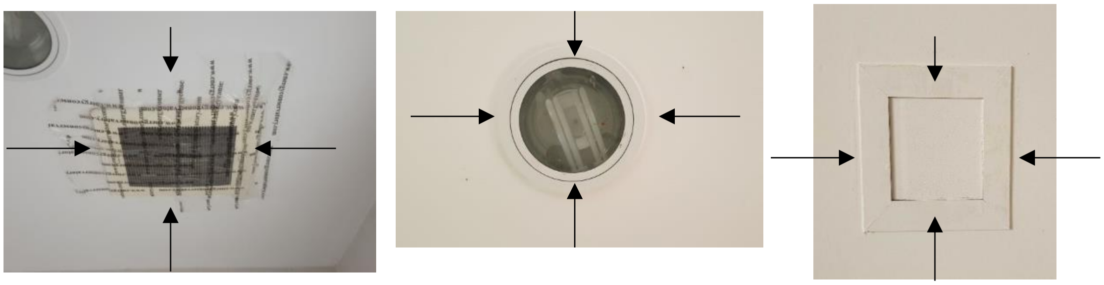


Figure 3.4: Possible air leakage paths in the ceiling

Therefore, the tested components were the supply and return diffusers, doors, maintenance openings in the ceiling as shown in Figure 3.4, lighting fixtures, and exhaust fans intake located in the kitchen, bathrooms, and laundry area. All components were sealed from inside using sealing paper and adhesive plastic tape. Windows were investigated only in House-A to check the test system calibration and the accuracy of the obtained results.

Furthermore, the outdoor air inlet terminals in the return ducts near the package units, shown in Figure 3.5, were also sealed during the airtightness test scenarios to eliminate any air leakage through them. However, in House-B, the dampers in both outdoor inlet terminals were found closed.

Figure 3.5: Outdoor air inlets

3.2.3 Air-Tightness Test Results

The selected first house will be referred to as House-A while the second house will be referred to as House-B.

Table 3.3 show the airtightness test results under various setup scenarios for House-A and House-B respectively. In Test-1 the houses were prepared according to the selected standard E779. Therefore, this scenario could be considered a base case for the two houses. The average air change rates of House-A and House-B in the base case when all components were not sealed were 6.58 and 7.04 ACH50 respectively.

Table 3.2: House-A air-tightness test results

	Supply diffusers	Return diffusers	Exhaust fans	Maint. openings+ lighting	Doors	Windows	PRESS ACH50 (h^{-1})	DEPRESS ACH50 (h^{-1})	AVG. ACH50 (h^{-1})
Test-**1A**	○	○	○	○	○	○	6.83	6.34	6.58
Test-**2A**	○	○	●	○	○	○	6.64	6.30	6.47
Test-**3A**	●	●	●	○	○	○	5.57	5.72	5.64
Test-**4A**	●	●	○	○	○	○	6.51	6.04	6.27
Teat-**5A**	●	○	○	○	○	○	6.95	6.70	6.82
Test-**6A**	●	○	●	○	○	○	6.82	6.69	6.76
Test-**7A**	○	●	●	○	○	○	6.89	7.07	6.98
Test-**8A**	○	●	○	○	○	○	6.86	6.45	6.65
Test-**9A**	●	●	●	●	○	○	4.68	5.39	5.03
Test-**10A**	●	●	●	●	●	○	4.32	4.11	4.22
Test-**11A**	●	●	●	●	●	●	3.37	NM	3.37

*○ component left without sealing; ● component is sealed; NM= Not measured

Test-5, when only supply diffusers are sealed, can also be considered a base for comparison between the two houses since it simulates the operation condition of the house when the cooling system is running. Accordingly, House-A is more airtight than House-B since it achieved the lower ACH50 results in Test-1 and Test-5.

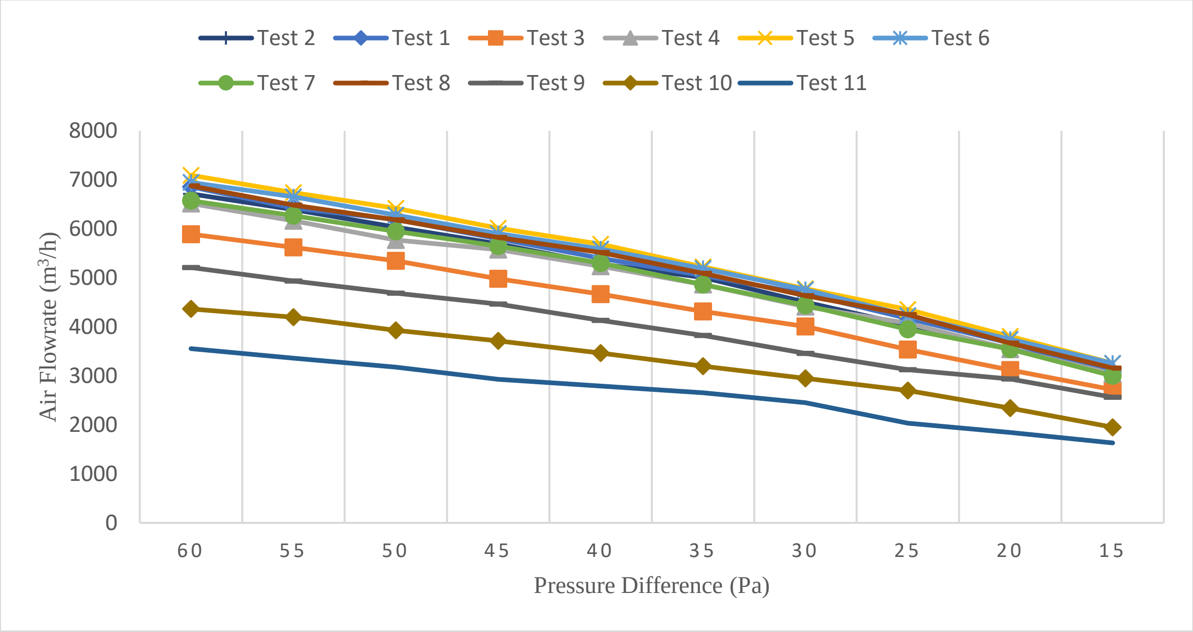


Figure 3.6: House-A air leakage graphs

Table 3.3: House-B air-tightness test results

	Supply diffusers	Return diffusers	Exhaust fans	Maint. openings+ lighting	Doors	PRESS. ACH50 (h^{-1})	DEPRESS. ACH50 (h^{-1})	AVG. ACH50 (h^{-1})
Test-**1B**	○	○	○	○	○	7.43	6.65	7.04
Test-**2B**	○	○	●	○	○	7.41	6.57	6.99
Test-**3B**	●	●	●	○	○	4.81	4.89	4.85
Test-**4B**	●	●	○	○	○	6.72	5.97	6.34
Test-**5B**	●	○	○	○	○	7.56	6.68	7.12
Test-**6B**	●	○	●	○	○	7.16	6.44	6.80
Test-**7B**	○	●	●	○	○	6.48	6.07	6.27
Test-**8B**	○	●	○	○	○	7.12	6.29	6.71
Test-**9B**	●	●	●	●	○	4.24	4.56	4.40
Test-**10B**	●	●	●	●	●	3.41	3.38	3.40

*○ component left without sealing; ● component is sealed

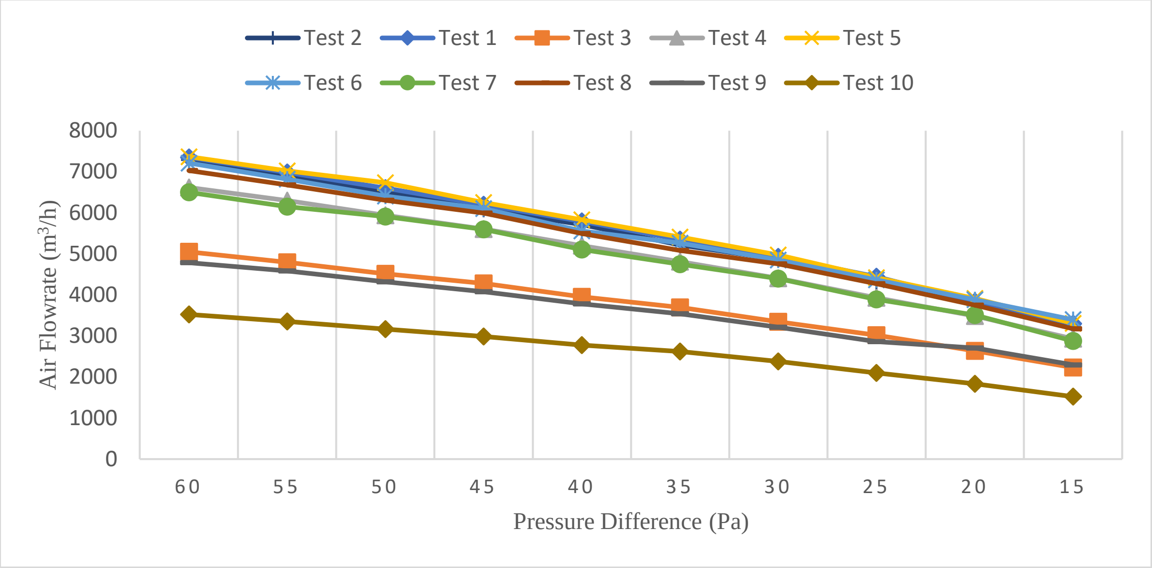


Figure 3.7: House-B air leakage graphs

There is not a specific value for buildings airtightness set as a standard value in Saudi Arabia. Therefore, other measurement results for north American housing, referenced in ASHRAE [34], were reviewed. As shown in Figure 3.8 the majority of measured houses airtightness are between (8-12) ACH rate under 50 Pa pressure difference. Based on Test-1 results of the two houses the measured ACH50 values for the selected houses are within the average range when compared with the American houses.

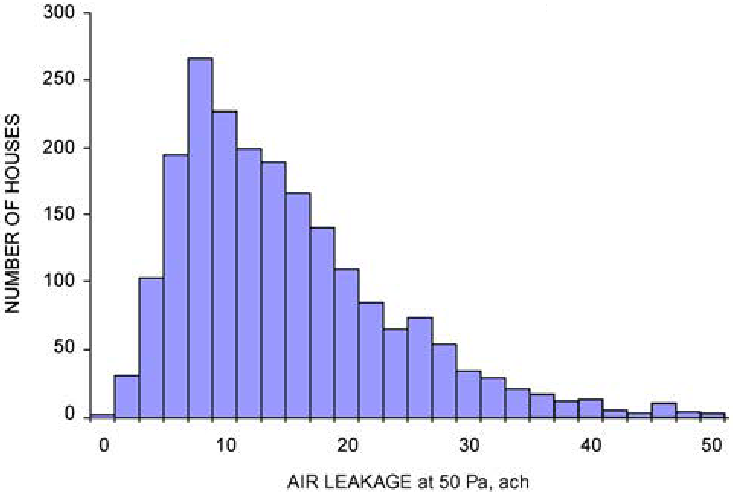


Figure 3.8: Air tightness test results for 2080 U.S houses

Table 3.4 shows the impact of each tested component on the air leakage for both houses when considering Test-1 scenario as a reference.

For House-A, the exhaust fans have a contribution of 0.11 ACH50 to the building leakage obtained from Test-**1A** and Test-**2A**. Furthermore, the results of Test-**5A**, Test-**6A**, and Test-**8A** after sealing the HVAC system partially with and without the Exhaust fans are higher than the base case scenario where all tested components were not sealed as demonstrated in Figure 3.6. The same observation can be highlighted for House-B as shown in Figure 3.7. This means the air leakage paths behaviour is almost the same in the two samples houses. Also, the difference between Test-**10A** and Test-**11A** demonstrates windows contribution which is 0.85 ACH50. Furthermore, the reduction between Test-**3A** and Test-**10A** represent maintenance openings, lighting, and doors share on the building leakage which is 0.72 ACH50 in House-A and 1.89 ACH50 in House-B.

Windows were the highest contributors on House-A air leakage with 0.85 ACH50 while the ceiling openings of maintenance and lighting were the highest ones in House-B with 1.89 ACH50.

For House-A and House-B, the highest average ACH50 values were obtained after sealing the supply diffusers only (Test-**5A** and Test-**5B**) which were 6.82 ACH50 and 7.12 ACH50 receptively.

This indicates that some of the air leakage paths, particularly maintenance openings cover and exhaust fans louvres, have variable behaviour depending on the applied pressure difference and the availability of other air leakage paths. The behaviour of the exhaust fans louvres could be detected from the high value of ACH50 under pressurization mode obtained in those scenarios where exhaust fans were not sealed.

Sealing all tested components in House-A resulted in 3.37 ACH50 and the value was obtained from Test-10 in House-B which is the same scenario without sealing the windows. Comparing between Test-**11A** results for House-A and Test-**10B** results for House-B reflects that those openings with variable behaviour in House-B have more contribution to the air leakage of those in House-A.

Table 3.4: Tested components contribution on the total air leakage

	Component contribution (ACH50)	
	House-A	House-B
Exhaust fans	.11	0.05
Maintenance and lighting openings	0.72	1.89
Doors	0.70	1.00
Windows	0.85	NM
HVAC system	.83	0.70

3.3 Infiltration Determination

The calculation of building air infiltration is mainly determining the air change rate of the building under specific conditions [43]. As a further utilization for the blower door results, the infiltration airflow was calculated using the mentioned relationship between airflow rate and the pressure difference across the envelope in Equation (2.1).

In order to determine the building normal operating pressure which can be used in Equation (2.1), a pressure measuring device was placed to measure and record the pressure difference across the envelope, with 5 minutes intervals, as shown in Figure 3.9. The pressure device was located in the North, West, and East side of the houses with two days for each side.

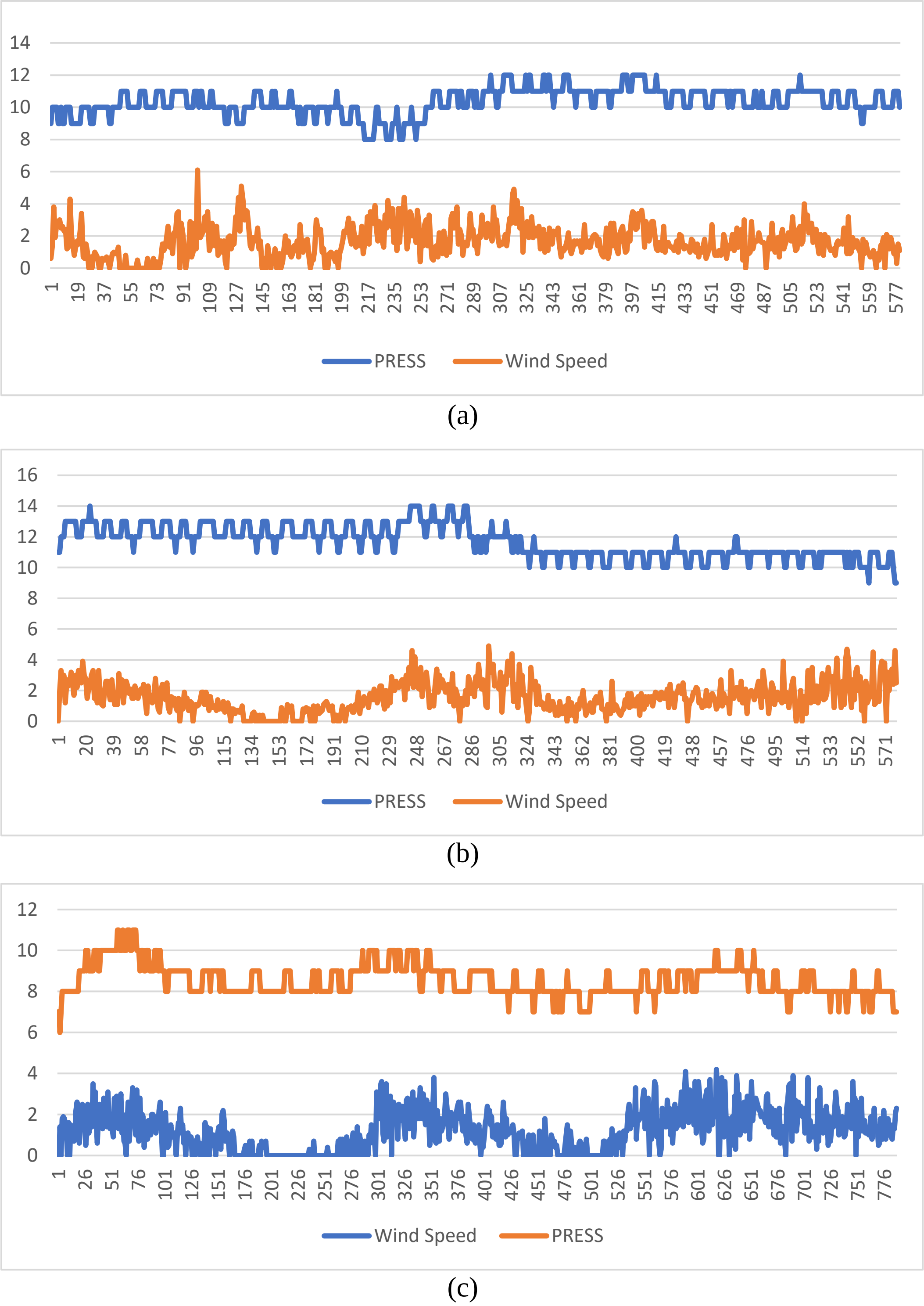
The HVAC system was running during the measurements period to mimic the operating conditions of the house as it is conditioned with constant air HVAC system type. In House-A, the pressure difference was recorded for six days with two days at each side of the building while in House-B it was recorded for three days only on the Northside of the building since it contains most of the openings and the longest side.

Simultaneously, as shown in Figure 3.9, a weather station was placed on the top of the house to calculate and record the wind velocity and direction. This data was used to investigate the relationship between the variation of the wind velocity and/or direction with the pressure difference across the envelope.

(a) Pressure difference measuring device

(b) Installed weather station in the roof

Figure 3.9: Used pressure differential equipment and weather station



(a) West side (front door) (b) East side (back door) (c) North side (kitchen door)

Figure 3.10: Variation of pressure difference across the envelope and wind speed in House-A

Pressure fluctuated in House-A within a range of (8-12 Pa) which is higher than the fluctuating range of House-B (7-11 Pa), as shown in Figure 3.10 and Figure 3.11, and this due to maintenance and cleaning work conducted on the cooling system in House-A prior to the measurements. The maintenance included modifications to the fan belt in the unit resulted in increasing the airflow rate and hence, the mechanically induced pressure difference.

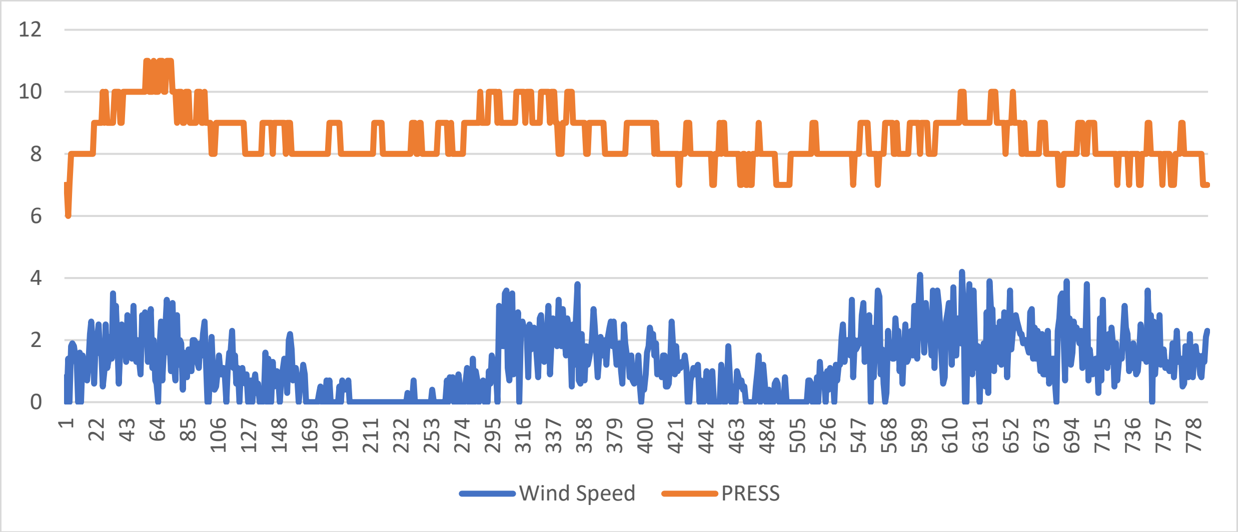
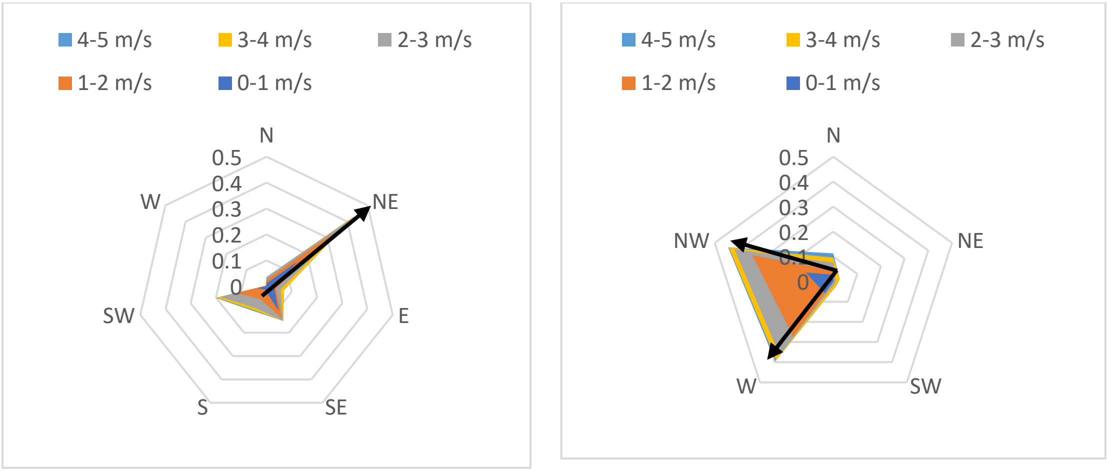


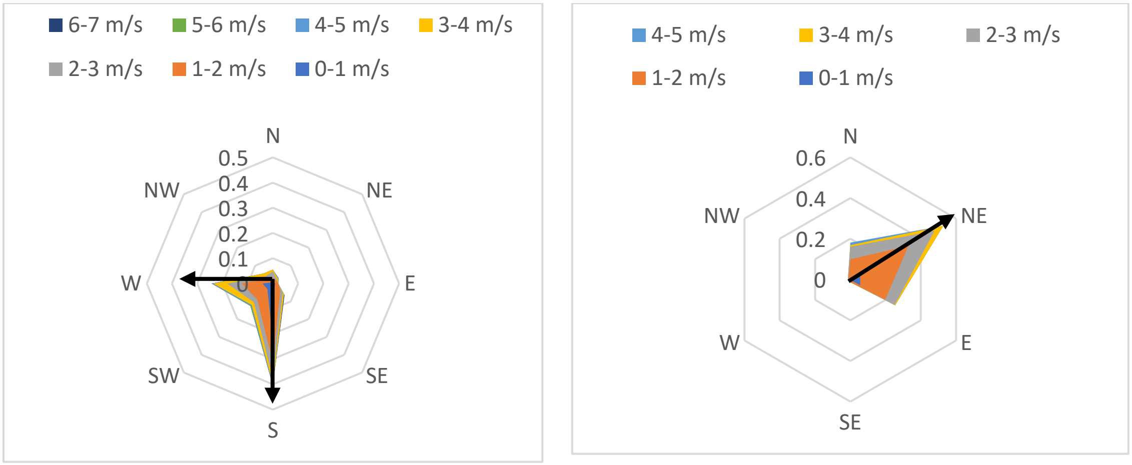
Figure 3.11: Variation of pressure difference across the North side (kitchen door) and wind speed in House-B

Furthermore, the measurement time of the year considers the active period of wind which was reflected in the recorded data where there was a wide range of wind velocity moving in different directions. Figure 3.12 and Figure 3.13 show that for each day during the measurements time there was a different predominant direction with a wide range of wind velocity.

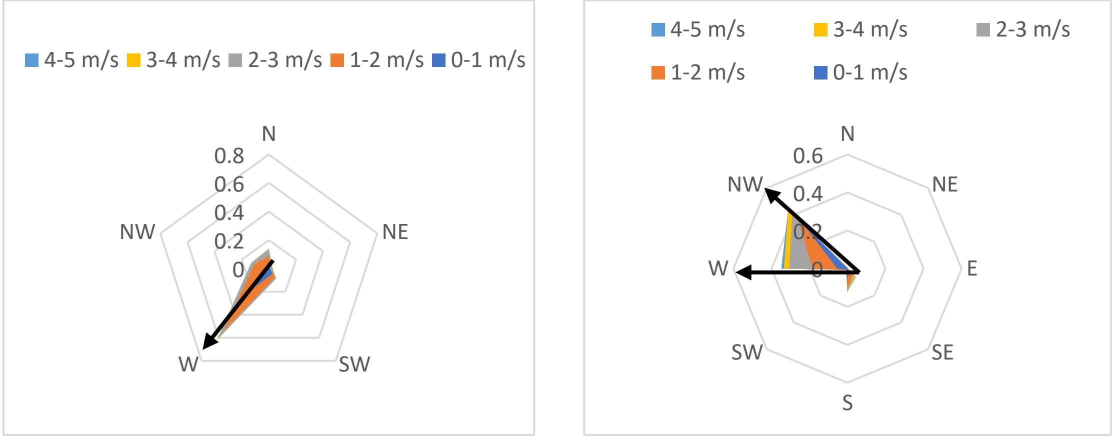
From Figure 3.10 and Figure 3.11 it can be observed that the same pressure difference was repeated with different wind speed and several directions. This indicates that the predominant impact of the mechanically induced pressure by the fans which marginalize the effect of the wind pressure on the building surfaces, particularly, if the high surroundings shielding effect of the tested houses are noticed as shown in Figure 4.11. The operating conditions of the fans in additions to the air filters status, considering the dusty weather of Dhahran, other possible factors for the variation of the pressure difference can contribute.



(a) East side (back door) [Day-1, Day-2]



(b) West side (front door) [Day-3, Day-4]



(b) North side (kitchen door) [Day-5,Day-6]

Figure 3.12: Predominant wind direction and speed during the measuring period in House-A

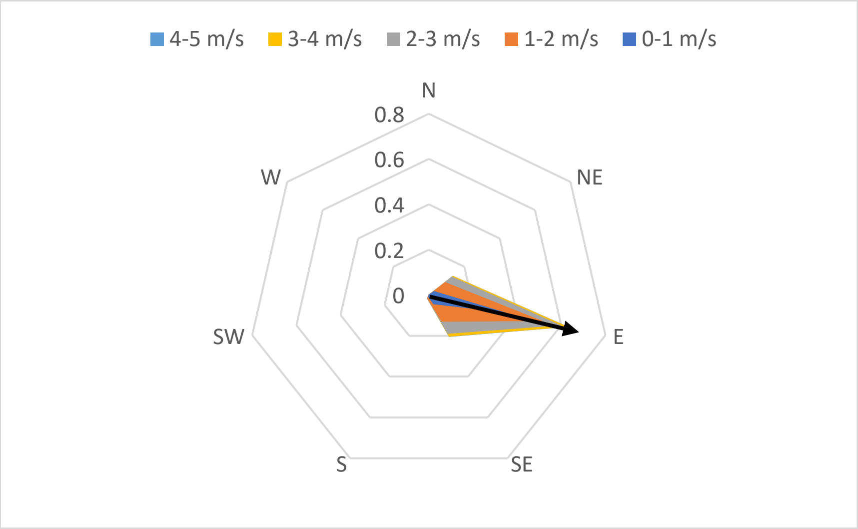


Figure 3.13: Predominant wind direction and speed during the measuring period across North side the (kitchen door) in House-B

3.3.1 Infiltration Calculation Method

The values of the pressure exponent n and the air leakage coefficient C obtained from Test-1 and 5 in the two houses were used to calculate the infiltration flow rate. Test-1 was selected because it represents the base case when the house is prepared according to the standard E779-10 while Test-5 represents the normal operating condition of the house when the cooling system is running.

In House-A the measured pressure difference across the envelope fluctuated between 9-12 Pa with an average value of 11 Pa while in House-B the pressure difference rang was (7-10 Pa) and the average pressure difference was 9 PA. Furthermore, Figure 3.10 and Figure 3.11 show that the use of constant air AC system could reduce or eliminate the effect of the wind velocity on the pressure difference across the envelope.

3.3.2 Calculated Infiltration Results

Table 3.5 and Table 3.6 shows the values of the air leakage coefficient C, the pressure exponent n, infiltration flow rate, and the air change rate for the selected houses. The obtained infiltration rates represent the results of the regression relationship obtained from the leakage graph generated from the blower door test data.

Table 3.5: Calculated infiltration for House-A

	$C(m^3/h.Pa^n)$	n	$\Delta P(Pa)$	$Q(m^3/h)$	$ACH(h^{-1})$
Test-1	650.85	0.578	11	2602.6	2.79
Test-5	700.8	0.566	11	2722.8	2.90

Table 3.6: Calculated infiltration for House-B

	$C(m^3/h.Pa^n)$	n	$\Delta P(Pa)$	$Q(m^3/h)$	$ACH(h^{-1})$
Test-1	664	0.588	9	2416.9	2.58
Test-5	661.7	0.578	9	2356.2	2.51

The obtained operating pressure in the two houses reflects that the use of constant air AC system with such will cause exfiltration of the indoor conditioned air to the outside which could be considered a huge source of energy waste. The cooling system will have to compensate the exfiltrated conditioned air with unconditioned outdoor air which will increase the amount of energy needed for cooling.

Also, the use of the above ceiling space as a return plenum will add more to the energy loss by exfiltration since the behaviour of all envelope openings above the ceiling is unknown in addition to the inherent inaccessibility. However, with further investigation, this high airflow rate can eliminate the need for a fresh air system since the HVAC system will compensate for the exfiltrated amount of conditioned air with outside fresh air.

CHAPTER 4

INFILTRATION MODELLING

Building simulation and energy modelling software is a very useful tool when it comes to studying the energy performance of the building. For example, EnergyPlus is an accepted and known software tool used in building energy analysis [57].

It can easily model all kind of energy flows in the building such as lighting, heating, ventilating, and cooling as well as water. These potentials made widely used in previous studies regarding the energy performance of buildings [56,57]. Several literature reviews [58,59] on building energy modelling. Different methods have been developed to build energy consumption models to simulate building performance and predict cost-saving estimates.

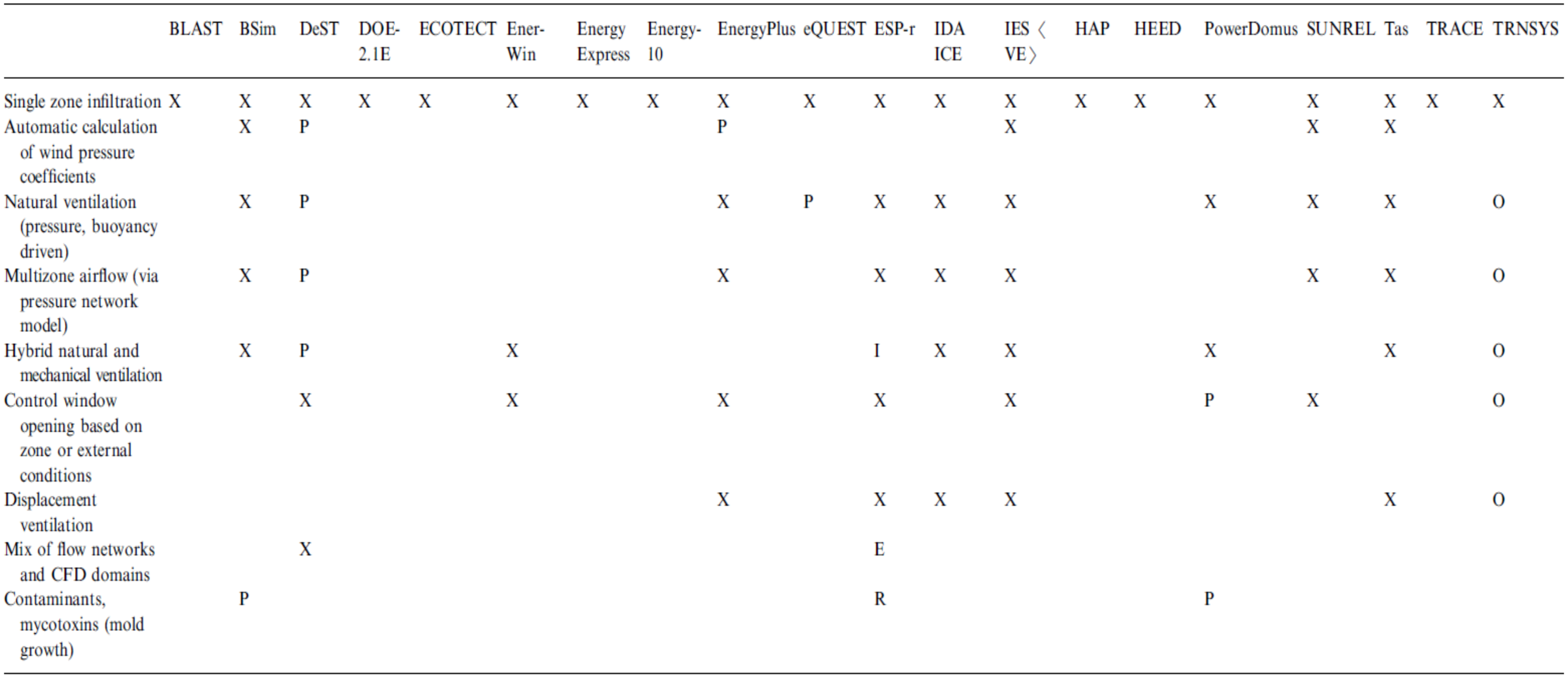
4.1 Selection of Energy Modelling Software

The influence of envelope air infiltration on the building energy use can be determined by energy simulation software utilizing different approaches. Detailed and complex infiltration modelling approaches like computation fluid dynamics (CFD) and airflow networks (AFN) are available yet, common building energy simulation tools estimate the infiltration rate based on the building airtightness determined through pressurization/depressurization tests following a simplified approach [62]. Nevertheless, specifying the air infiltration rate is an important input to energy simulation program in order to define the building envelope characteristics and could have a determinant effect on the accuracy of the software results.

One of the known applicable energy conservation measures is to increase the building envelope airtightness yet, most of the available used simulation software tools do not have the ability to simulate envelope infiltration accurately which mean the expected result of increasing the envelope airtightness maybe misrepresented [28].

Zhengen Ren and Dong Chen [63] made a comparison between three infiltration models which are the simple approach, the modified simple approach with blower door test results, and the multi-zone infiltration model. The three approaches were integrated with AccuRate, which is a recognized housing energy star rating tool in Australia. Eight houses with different climatic conditions (Cairns represent hot climate, Melbourne as a cold climate, and Sydney as a moderate climate) and different envelope leakage characteristics were selected as a case study. The study presented a comparison of the buildings energy performance and the calculated infiltration rates using the three methods and the results showed that, in Melbourne and Sydney, there were 37% differences between the three models in calculating the average infiltration rates and 40% differences in Cairns.

Figure 4.1 shows the differences in the capabilities of the building performance software in modelling the movement of outdoor air weather by ventilation or by infiltration. All of the software tools claim to have the ability to model single-zone infiltration while fewer calculate the pressure coefficients automatically [64].



	BLAST	BSim	DeST	DOE-2.1E	ECOTECT	Ener-Win	Energy Express	Energy-10	EnergyPlus	eQUEST	ESP-r	IDA ICE	IES〈VE〉	HAP	HEED	PowerDomus	SUNREL	Tas	TRACE	TRNSYS
Single zone infiltration	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Automatic calculation of wind pressure coefficients		X	P						P				X				X	X		
Natural ventilation (pressure, buoyancy driven)		X	P						X	P	X	X	X			X	X	X		O
Multizone airflow (via pressure network model)		X	P						X		X	X	X				X	X		O
Hybrid natural and mechanical ventilation		X	P			X					I	X	X			X		X		O
Control window opening based on zone or external conditions			X			X			X		X		X			P	X			O
Displacement ventilation									X		X	X	X					X		O
Mix of flow networks and CFD domains			X								E									
Contaminants, mycotoxins (mold growth)		P									R					P				

X feature or capability available and in common use; P feature or capability partially implemented; O optional feature or capability; R optional feature or capability for research use; E feature or capability requires domain expertise; I feature or capability with difficult to obtain input.

Figure 4.1: Infiltration, ventilation, room air and multizone airflow [62]

For this study, DesignBuilder was selected for conducting the energy analysis for the case study in order to investigate the impact of the air infiltration on the house energy performance. Maile et al. [65] established an information flow chart describing the workflow in DesignBuilder shown in Figure 4.2. It uses the latest EnergyPlus engine for the simulation and assessment of the building design features according to Maile et al. [65], it had the most comprehensive user interface to this simulation engine.

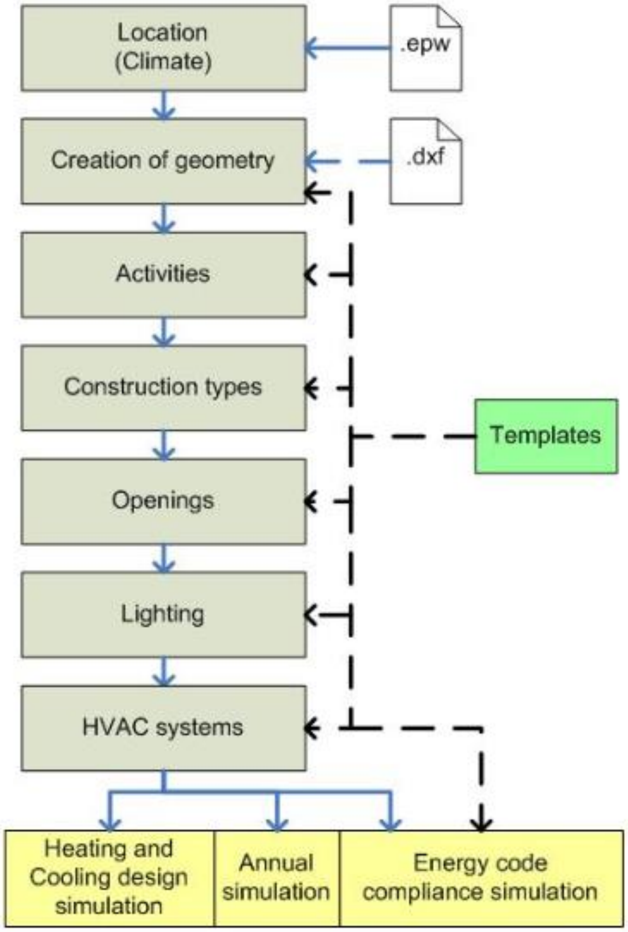


Figure 4.2: Established work flow for DesignBuilder [65]

EnergyPlus engine has been incorporated into many user interfaces such as DesignBuilder which indicates it was comprehensively validated and gives trust in the results obtained. When it comes to air infiltration, the EnergyPlus engine applies the multi-zone model and Airflow Network making this calculation engine suitable and recommended for analyzing small residential buildings according to several kinds of research investigated the used infiltration models[66].

4.2 Features of the Selected Software

common features of DesignBuilder include, but not limited to [67]:

1. Determining the impact of different design alternatives on building energy performance.
2. Sizing of cooling and heating equipment.
3. Energy models of LEED and ASHRAE 90.1.
4. Economic analysis.
5. Optimization of the building's design.
6. Communication helps in design meetings.
7. Life cycle analysis
8. A useful educational tool for engineering and architecture students to learn building energy simulation.
9. Assessing facade options.

4.2.1 Infiltration Modeling in the Selected Software

Building airtightness can be defined in two ways depending on the model option of the natural ventilation which has two options, scheduled and calculated. In this research, the natural ventilation model option will be scheduled which means the ventilation airflow rate will be defined using the maximum air change rate adjusted through the schedule of the operation. With the natural ventilation model option, there are 4 different options to define the infiltration flowrate as follows:

Option-1:	ACH: air changes rate per hour under operation pressure, this is the default option.
Option-2	$m^3/h.m^2$ at 4 Pa: infiltration is defined as the unit flow rate per unit of the exposed surface area under 4 Pa indoor/outdoor pressure difference.
Option-3	$m^3/h.m^2$ at 50 Pa: same as Option-2 but under pressure difference of 50 Pa.
Option-4	n50: which is the air change rate at 50 Pa pressure difference.

Option-3 and Option-4 for defining infiltration represent the outcome of the blower door test (BDT). The conversion of the units in Option-2, Option-3, and Option-4 in the EnergyPlus engine to ACH at normal pressure, driven by wind and temperature difference, is based on the method described in EN 12831[68]. In this method, the infiltration flow rate (Q_{inf}) is obtained from Equation 4.1:

$$Q_{inf} = 2 * \nu * n50 * e * i \tag{4.1}$$

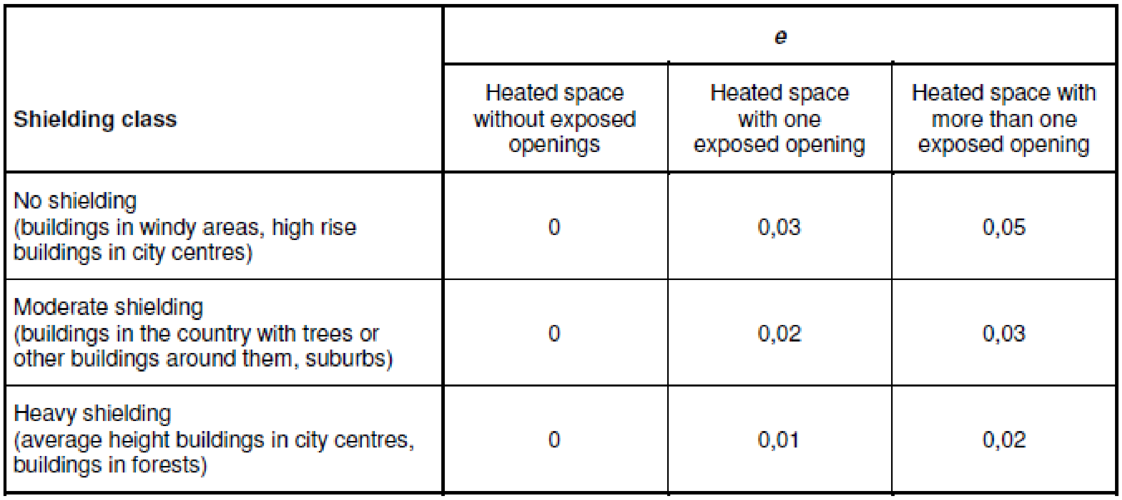
Where:

Q_{inf}	Infiltration flow rate (m^3/h);
n50	Air change rate at 50 Pa pressure difference (h^{-1});
e	Shielding coefficient, can be obtained from Table 4.1;
i	Height correction factor, can be obtained from Table 4.2;
ν	Volume of the conditioned space (m^3)

However, it is important to highlight that, the used shielding coefficients in the referenced table in standard EN12831 are for heated space while the selected houses in this study are cooled. Heated buildings are usually subjected to more air infiltration spaces since there is less mechanically induced pressure while cooled spaces are exfiltration dominated because of the use of fans in the cooling systems.

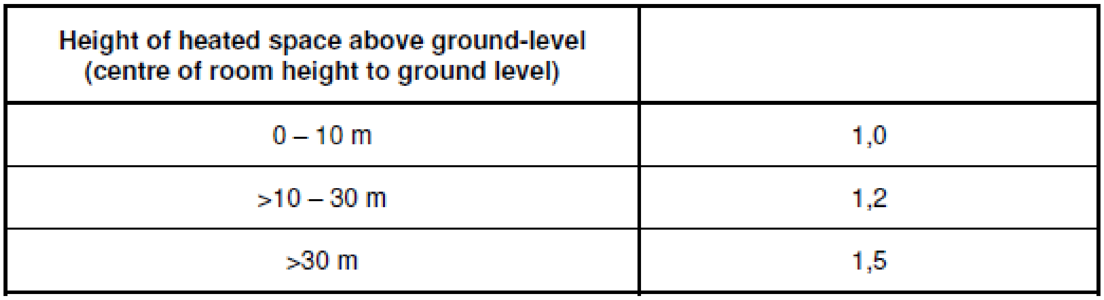
Utilizing the results obtained in Chapter 3, Option-1 and Option-4 for defining building infiltration were examined in order to investigate the validity and the accuracy of the software results.

Table 4.1: Shielding coefficient values [68]



Shielding class	*e*		
	Heated space without exposed openings	Heated space with one exposed opening	Heated space with more than one exposed opening
No shielding (buildings in windy areas, high rise buildings in city centres)	0	0,03	0,05
Moderate shielding (buildings in the country with trees or other buildings around them, suburbs)	0	0,02	0,03
Heavy shielding (average height buildings in city centres, buildings in forests)	0	0,01	0,02

Table 4.2: Height correction factors [68]



Height of heated space above ground-level (centre of room height to ground level)	
0 – 10 m	1,0
>10 – 30 m	1,2
>30 m	1,5

4.3 Phsical Characteristics of the Selected Buildings

Part of the geometrical characteristics of the selected houses were described in section 3.2.1 of this report. The details of the house envelope characteristics and input model data were taken from a previous study conducted by Ashraf Sayed [12] on one of the faculty houses on KFUPM university campus. Table 4.3 shows the summary of house envelope components with their layers and their thermo-physical features.

Table 4.3: Envelope components details [12]

Envelope part	Layers: outside to inside	U-value W/m^2.K
External walls	16 mm Plaster (Dense) + 100 mm Concrete Block (Medium) + 50 mm Extruded Polystyrene + 100 mm Concrete Block (Medium) + 13 mm Plaster (Lightweight)	0.466
Floor	Glazed ceramic tiles + cement mortar + dense reinforced concrete + high density polyethylene + sand + Earth, gravel	0.792
roof	40 mm Concrete Tiles (Roofing) + 0.2 mm Polyethylene (High Density) + 50 mm Extruded Polystyrene + 4 mm Bitumen Felt + 59mm Cement Screed + 300 mm Reinforced Concrete (Cast, Dense)	0.539
External windows	4mm Glass, generic tinted + 12 mm air gap + 6 mm Glass, generic tinted	2.709

4.3.1 HVAC System Information

The thermal requirements of the house are been met by two constant air package units where one unit is dedicated for each floor. The capacity of the ground floor unit is higher than the first-floor unit. No heat recovery or any energy efficiency measures are considered in the cooling system of the house. The specifications and details of the two package units are shown in Table 4.4.

Table 4.4: Details of the Used cooling system in the selected houses

Unit’s location	Capacity	Supply airflow	Outside airflow
Ground floor	40.7 KW (11.58 tons)	8121.3 m^3/h (4780 CFM)	1223.3 m^3/h (720 CFM)
First floor	27.9 KW (7.95 ton)	5402.9 m^3/h (3180 CFM)	305.8 m^3/h (180 CFM|)

4.4 Model Development and Formulation

Utilizing the previously mentioned data, a base case model was formulated using the state-of-the-art software tool DesignBuilder which was described early. Variety of ways are available in the software to add and draw the plan which eventually will take the shape of the house model. From the house floor plans, a DXF file was generated and imported directly in DesignBuilder as a first step after specifying the location of the model. The extruded model is shown in Figure 4.3. For simplicity, all conditioned spaces in each floor were considered as one zone while the rest of the unconditioned indoor spaces (bathrooms, laundry area, etc) were separated.

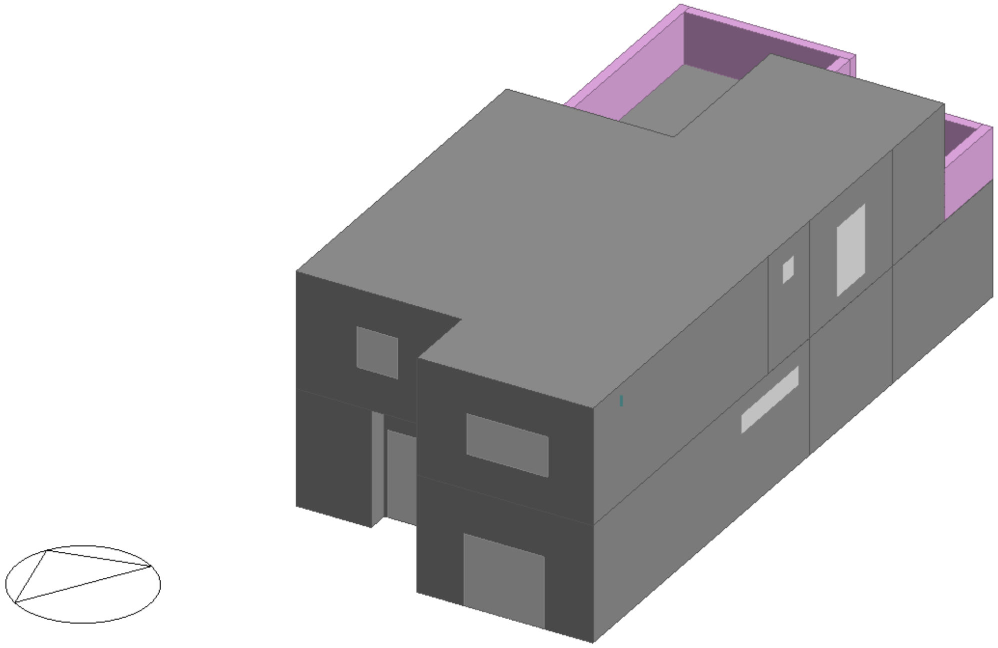


Figure 4.3: Established energy model by DesignBuilder

4.4.1 Envelope System

The envelope system components are considered critical and detrimental elements in the model since they control the process of heat gain and loss. Therefore, using the mentioned information in Table 4.3 the external walls, roof, and the floor of the house were defined in the simulation software and the values of the heat transfer coefficient were obtained accordingly. Furthermore, the default value of the air infiltration is 0.7 ACH under common operating pressure which was not modified in the developed base case.

4.4.2 HVAC System Definition

DesignBuilder supports a wide variety of input details for the definition of the HVAC system depending on the complexity of the system and the level of accuracy needed. Three options are available which are simple, compact, and detailed. For this base case model and based on the presented system information, the latter option was selected. Critical inputs for defining the HVAC system such as total cooling capacity and air flowrate can be auto-sized by EnergyPlus by determining indoor and outdoor conditions. However, those HVAC input data were inserted to the base model with reference to Table 4.4. Each unit was defined separately and assigned to its conditioned zone on each floor. The system operation schedule was set to 24/7 which means the system is operating all the time since this was the case during the energy monitoring period to validate the model.

Other system information such as the coefficient of performance (COP), availability of the system, and the system fuel were input. Also, DesignBuilder provides three ways for the house occupancy input which are people density, area per person, and the number of people directly. For this model, the number of people option was selected, and it was set to 0 since there were no occupants during the energy monitoring for the model validation. Furthermore, the environmental control data, particularly, the cooling and heating setpoints and setbacks were set to 21°C. DesignBuilder considers changing the operation of the HVAC system according to the specified setback temperature and the occupancy schedule.

However, this was not the case since there are no occupants and the setback temperatures for cooling and heating were set equal to the setpoint temperatures.

4.4.3 Definition of Lighting and Equipment Loads

With three different model data options, DesignBuilder provides great depth for the lighting system definition depending on the complexity of the model. These include lighting power density, normalized power density, and absolute zone power. Also, it offers three lighting categories which are general, task and display, and exterior lighting with separate input section for each category and possibility to add lighting control. Like the cooling and heating system, EnergyPlus allows the lighting load to be modulated through an operation schedule based on the occupancy and operation of the house. Same options are available for defining the equipment load and operation which could have a critical impact on the outcomes of the model. Both lighting and equipment definitions were excluded from the model since they were not operated during the energy monitoring period.

4.5 Model Validation

Following the definition of the building HVAC, lighting, equipment, and envelope systems and other input parameters, the software simulated the base model for the selected location of the house. Since the objective of the energy modelling process is to investigate the impact of the air infiltration on the total energy consumption, all systems were switched off and set to zero in the input section except the HVAC system which is directly related to the air infiltration. Therefore, the output of the simulation was mainly the annual energy use of the cooling system and fans. The model validation is based on the infiltration definition options and values. For the default case, where infiltration value was 0.7 ACH and the selected infiltration modelling option was Option-1 which means this air change is under normal operating conditions.

The annual energy per the total building area was found 289 kWh/m^2 and the annual energy distribution, shown in Figure 4.4, indicates a percentage of 87% of the total energy is used for cooling while 12 % is used by the system fans and 1% for heating during the simulation period.

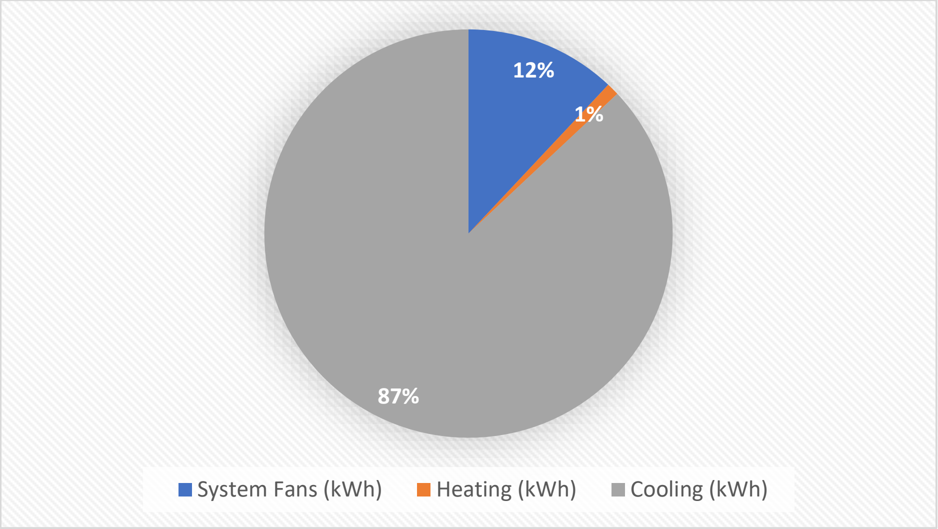


Figure 4.4: Base case total energy distribution

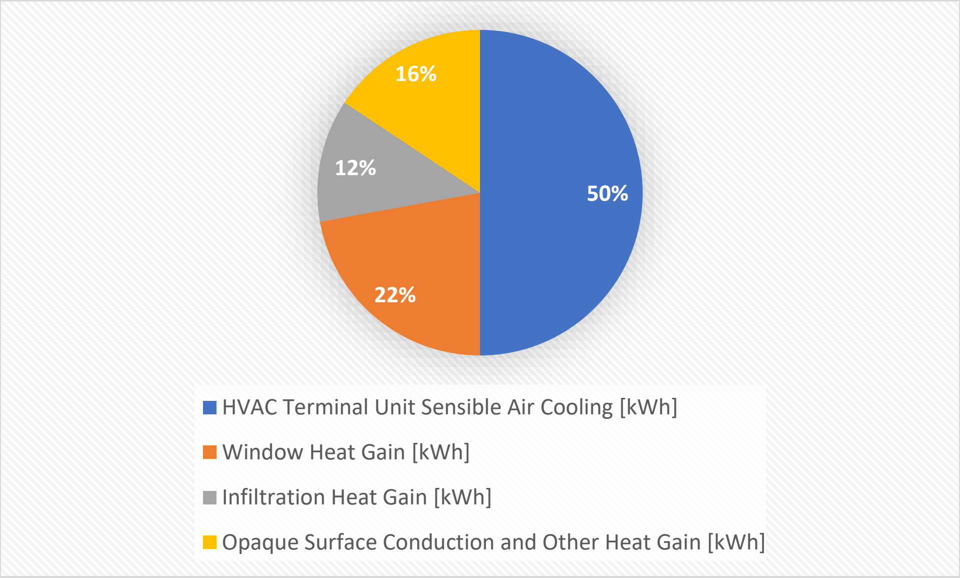


Figure 4.5: Energy consumption breakdown

Also, the air infiltration adds 12% of the total annual heat gain as illustrated in Figure 4.5. All critical input data such as envelope parameters and cooling system information, except infiltration input data, were analyzed based on the previous study on the KFUPN campus[12] in which a validated model for the faculty housing was established. Therefore, the validation of the current base case model will be based on the value of the infiltration input and the selected option to define it.

4.5.1 Energy Monitoring Setup

In order to verify the cooling system energy consumption of the 3-bedrooms single-family detached houses sample on KFUPM campus, the actual energy use was monitored. This was done on-site as shown in Figure 4.6 since the houses in the KFUPM campus are not equipped with separate energy meters. Therefore, an energy data logger was set, calibrated, and installed in the main house electric panel in order to monitor and record the energy consumption for a specific period. Since the focus of the study is the cooling system energy, only the HVAC system was operating during the monitoring time while lighting and other energy end-use systems were switched off.

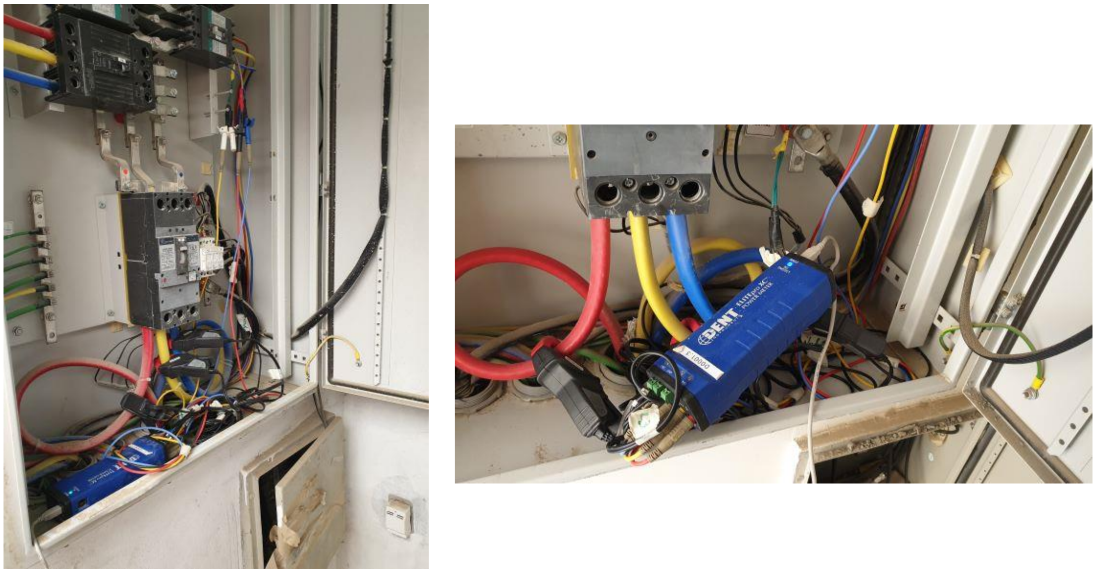


Figure 4.6: Energy recording setup

4.5.2 The Model Validation

In House-A, the energy monitoring data logger was installed to record data throughout October till the 17th of December for a period of 50 days approximately while in House-B the energy data was recorded for 36 days between the 3rd of May and the 7th of June. It is important to mention that the recorded data of the first days in the two houses were excluded since the HVAC systems was found to be malfunctioning. Furthermore, the model was validated using recorded energy data for a short period of time due to time limitation which make it difficult to gather the annual cooling energy consumption in addition to the unavailability of the utility bills.

4.6 Infiltration Modelling Options

As described in section 4.2.1 DesignBuilder has 4 options to define the building infiltration when the natural ventilation is set to scheduled. Option-1 and option-4 were investigated and applied on the energy model using the obtained data from the BDT and the actual infiltration flowrates described in CHAPTER 3. This will lead to determine the suitable utilizing for the test result and capture the infiltration impact on the total cooling energy and building energy performance. From the BDT results described in Table 3.2and Table 3.3, two scenarios results were selected and applied in the infiltration modelling options. The first scenario is Test-1 where only the building plumbing features were sealed while the HVAC system, ceiling openings, and exhaust fans were left without sealing. The second scenario is the Test-5 where only the supply diffusers were sealed. This scenario was selected because in the common operation condition of the house and during the operation of the cooling system, the supply diffusers are excluded from the air leakage paths. So, this scenario can be considered as a simulation of the normal operating conditions of the house.

For each infiltration modelling option, the simulated total energy consumption was compared with the actual measured energy consumption to identify the percentage variation of the simulated energy.

4.6.1 Infiltration Modelling Option-1

This option requires to define the air infiltration as air change per hour under normal operating pressure which will be mainly the mechanically induced pressure. The operation pressures of House-A and House-B were found 11.0 Pa and 9.0 Pa respectively. The calculated infiltration flowrates were found higher than the default air change rate in the software (0.7 ACH).

The calculated actual infiltration flowrates based on Test-**5A** for the houses are shown in Table 3.5. The variation of the actual total cooling energy and the simulated cooling energy throughout the simulation period is shown in Figure 4.7 and Figure 4.8.

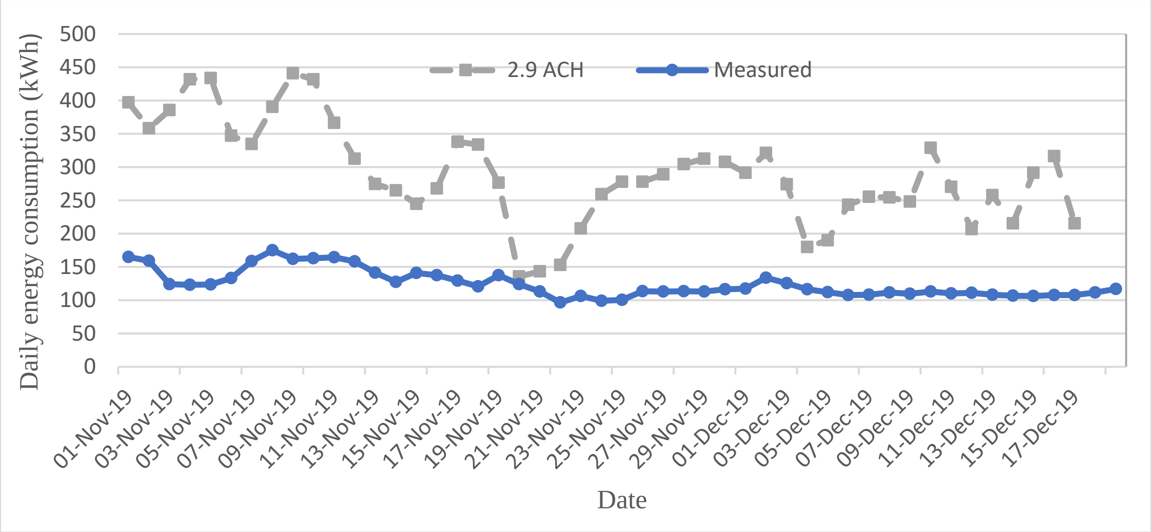


Figure 4.7: House-A daily energy consumption Vs simulation results using infiltration modelling Option-1

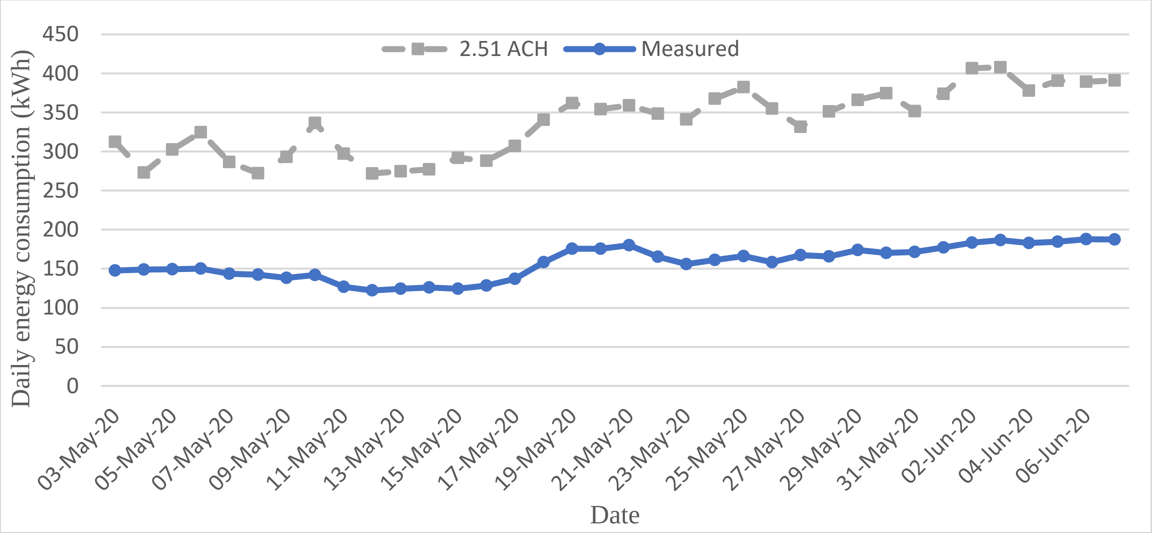


Figure 4.8:House-B daily energy consumption Vs simulation results using infiltration modelling Option-1

As shown in Table 4.5 and Table 4.6 the simulation results are more than twice the measured energy consumption which indicates that the input values are much higher than the actual infiltration flowrate.

Table 4.5: House-A simulation results deviation from measured energy when applying Option-1

Month	Measured Energy (kWh)	Simulation Consumption @ 2.90 ACH (kWh)	Deviation
November	3882.2	9301.5	-139.6%
December	1892.3	4361.0	-130.5%
Total	5774.4	13662.5	-136.6%

Table 4.6: House-B simulation results deviation from measured energy when applying Option-1

Month	Measured Energy (kWh)	Simulation Consumption @ 2.51 ACH (kWh)	Deviation
May	4397.2	9397.0	-113.7%
June	1289.9	2737.7	-112.2%
Total	5687.1	12134.7	-113.3%

The reason for this high simulated value is because the measured infiltration flowrate was induced mainly by the pressurization caused by the HVAC system fan which indicates that the direction of the airflow rate was from inside to outside (exfiltration). Therefore, the effect of the exfiltration on the energy performance of the house will be reflected as a system load which is the additional outside air compensating the exfiltrated conditioned air from the spaces.

Defining this value in the model as infiltration flow rate, which means it will be a space load, in addition to the presence of the ventilation flowrate will cause the heat gain to be calculated almost twice.

Therefore, in the next attempt using Option-1 the infiltration flowrate was inserted in the model as outside airflow divided between the two units based on the supply flowrate while the infiltration flowrate was cancelled from the conditioned zone load. The output of this attempt is illustrated in Table 4.7 and Table 4.8and in addition to Figure 4.9 and Figure 4.10.

Table 4.7: House-A error variation of the second attempt using Option-1

Month	Measured Energy (kWh)	Energy consumption @ 2.9ACH (kWh) (system load)	Deviation
November	3882.2	3839.4	**1.1%**
December	1892.3	1638.6	**13.4%**
Total	5774.5	5938.7	**5.1%**

Table 4.8: House-B error variation of the second attempt using Option-1

Month	Measured Energy (kWh)	Energy consumption @ 2.51ACH (kWh) (system load)	Deviation
May	4397.2	4440.3	**-0.98%**
June	1289.9	1434.3	**-11.2%**
Total	5687.1	5874.6	**-3.3%**

The results demonstrate a high degree of agreement between the model and the actual energy consumption with an overall deviation of 5.13% for House-A and 3.3% for House-B which validate this model and make it applicable to investigate the impact of the air leakage on the total energy consumption. The increase in the deviation during December for House-A is probably because of the difference in the outdoor temperature between the actual and the used weather data in the model. This difference effect could be noticed in the daily energy consumption shown in Figure 4.9.

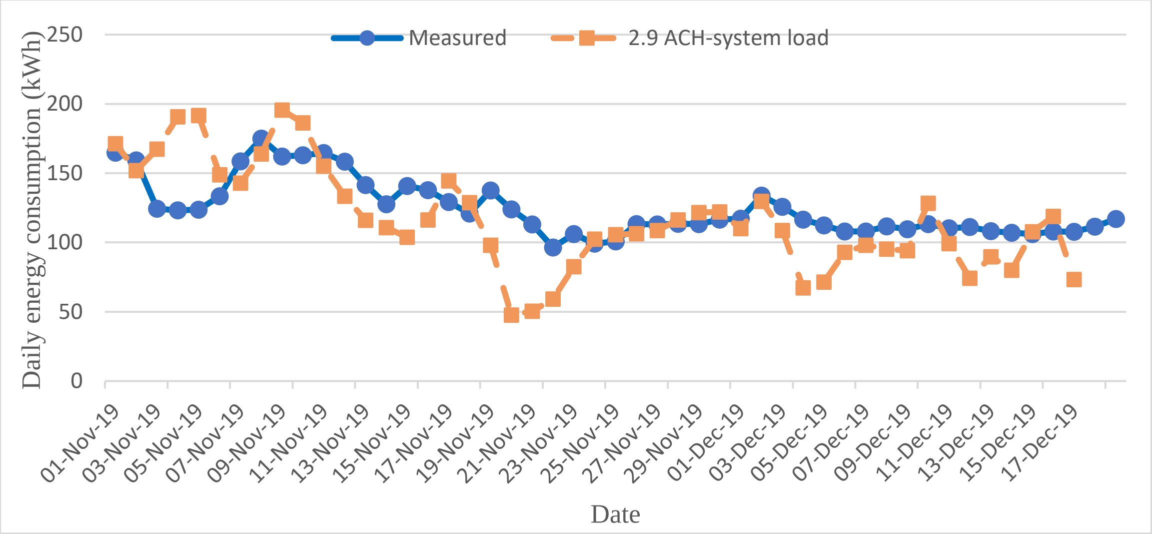


Figure 4.9: House-A daily energy consumption of the second attempt using Option-1

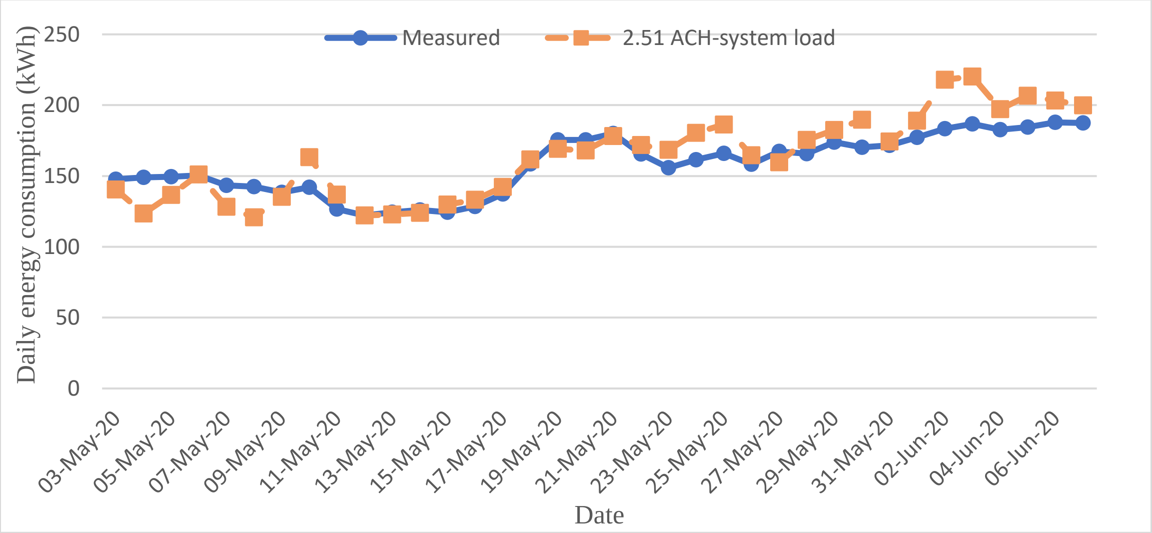


Figure 4.10: House-B daily energy consumption of the second attempt using Option-1

4.6.2 Infiltration Modelling Option-4

In this option, the infiltration is defined as air change rate per hour under 50 Pa pressure difference which represents the blower door test results. The EnergyPlus engine converts this value to normal infiltration flowrate caused by wind and stack effect using an established method in standard EN12831 which was described in section 4.2.1. for this Option, Test 5 scenario results (6.82 ACH50 for House-A and 7.12 ACH50 for House-B) were applied. Based on Figure 4.11, The selected houses were considered moderate shielded hence, the shielding coefficient on the energy model was set to 0.03.

Figure 4.11: Satellite view for houses location

The comparison between the actual daily energy use versus the simulated energy for House-A, shown in Figure 4.12, indicates a high degree of agreement. This agreement was further confirmed by calculating the variation deviation of the total actual energy consumption against the correspondent simulated energy use for the same period shown in

Table 4.9. The variation deviation was reduced from -136% obtained from Option-1 to approximately 0.98 % using the direct result of the BDT in Option-4.

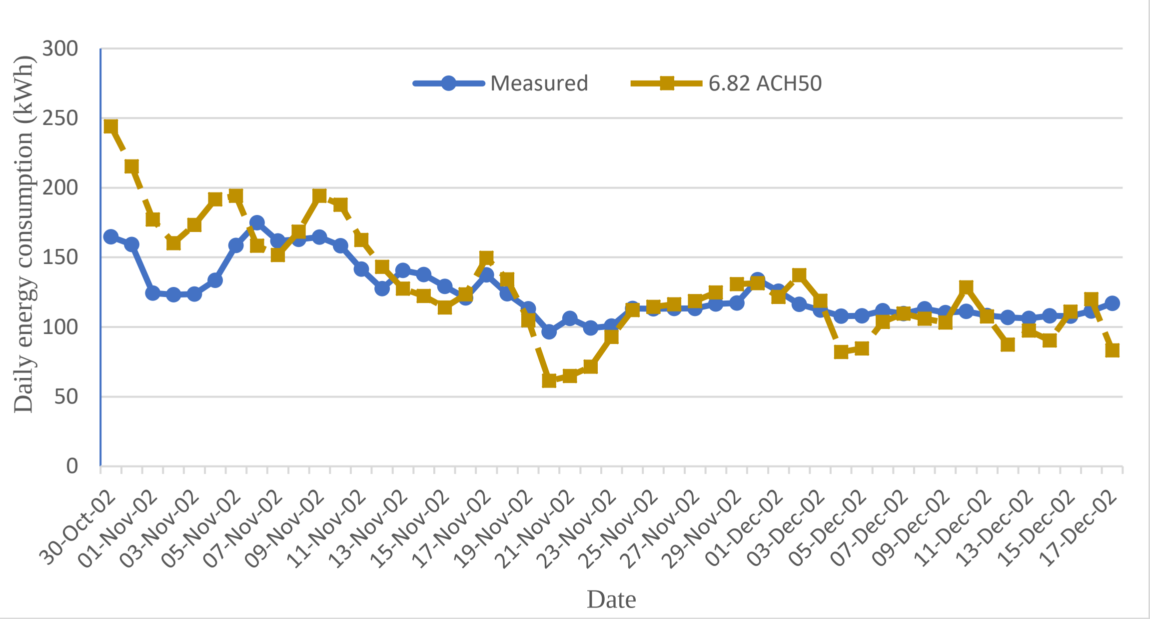


Figure 4.12:House-A daily energy consumption Vs. simulation estimation using infiltration modelling Option-4

Table 4.9: House-A simulation results deviation from measured energy when applying Option-4

Month	Measured Energy (kWh)	Energy consumption @ 7.51 ACH50 (kWh)	Deviation
Nov	3882.2	3981.4	-2.6%
Dec	1892.3	1736.4	8.2%
Total	5774.5	6331.0	0.98%

The outcome of using the BDT result to define air infiltration using Option-4 for House-B showed that the simulation energy is higher than the actual energy consumption as indicated in Figure 4.13. The overall deviation of the simulation results from the actual measured energy for this attempt is 20.4% as shown in Table 4.10.

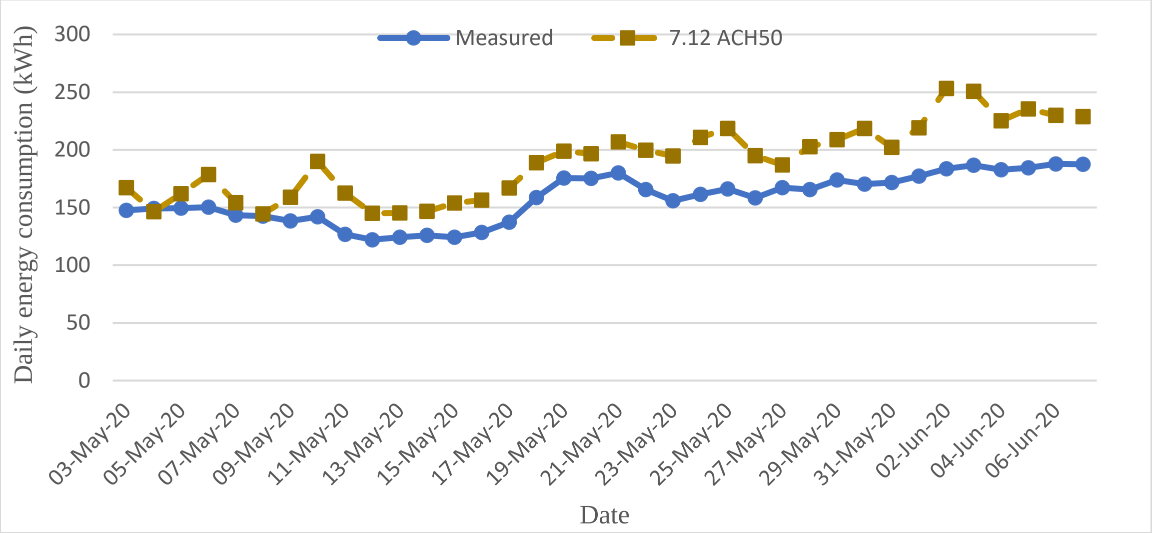


Figure 4.13:House-B daily energy consumption Vs. simulation estimation using infiltration modelling Option-4

Table 4.10: House-B simulation results deviation from measured energy when applying Option-4

Month	Measured Energy (kWh)	Energy consumption @ 7.12 ACH50 (kWh)	Deviation
Nov	4397.2	5206.99	-18.42%
Dec	1289.9	1642.19	-27.31%
Total	5687.1	6849.18	-20.44%

However, this case doesn’t represent the actual case since the outdoor air in the cooling system is calculated based on the area of the house and the inserted ACH50 is treated in the software as a space load while in reality, as described in the previous section, the outdoor air in the cooling system is directly related to the exfiltrated air and no air will be infiltrated from the space during the operation of the HVAC system. Therefore, to confirm this conclusion another attempt was conducted in which the obtained ACH50 for House-A was converted by Equation (4.1) used by the software to actual infiltration flowrate driven by wind and temperature difference. The resulted flowrate was 398.15 m^3/h which was inserted in the model as outdoor air throughout the cooling system. Furthermore, infiltration modelling was excluded from the space load modelling.

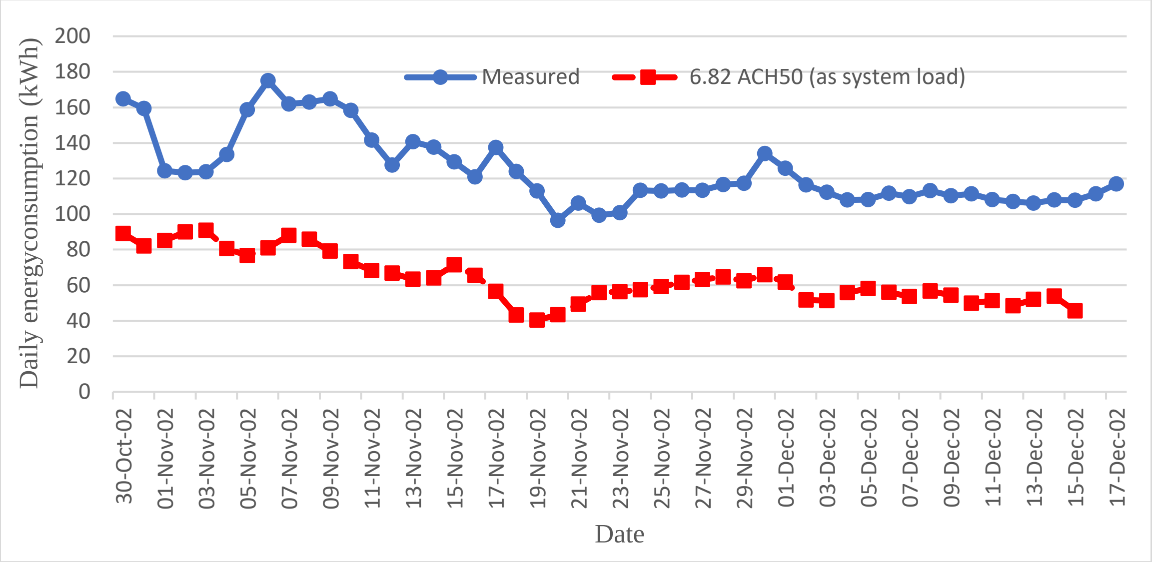


Figure 4.14: House-A Daily energy consumption Vs. simulation estimation using BDT result as system load

As expected, the resulted simulation energy decreased significantly since the inserted outdoor airflow rate is too low and does not equal to the actual amount of the leakage air as shown in Figure 4.14.

4.7 Infiltration Impact on Energy Consumption

Using the obtained validated model in section 4.6.1, in which the calculated actual infiltration flowrate was inserted as outdoor air in the cooling system, the impact of the infiltration on House-B energy performance was determined. Three scenarios were used to determine the impact of the air infiltration on the house energy consumption. For those scenarios, people and lighting loads were added to the energy model. The total wattage of the interior lighting system was calculated to be 2334 Watts and the lighting power density was found to be 8 W/m^2 while the inserted number of occupancies was 9.

In the first scenarios, since the validated model included the actual air infiltration flowrate inserted as outdoor air, the amount of outdoor air needed to ventilate the house was determined based on ASHRAE 62.1-13 [69] requirements as shown in Figure 4.15. The total number of people was assumed to be 9 while the total floor area was 292 m^2. Therefore, the total needed outdoor air is 110.1 l/s.

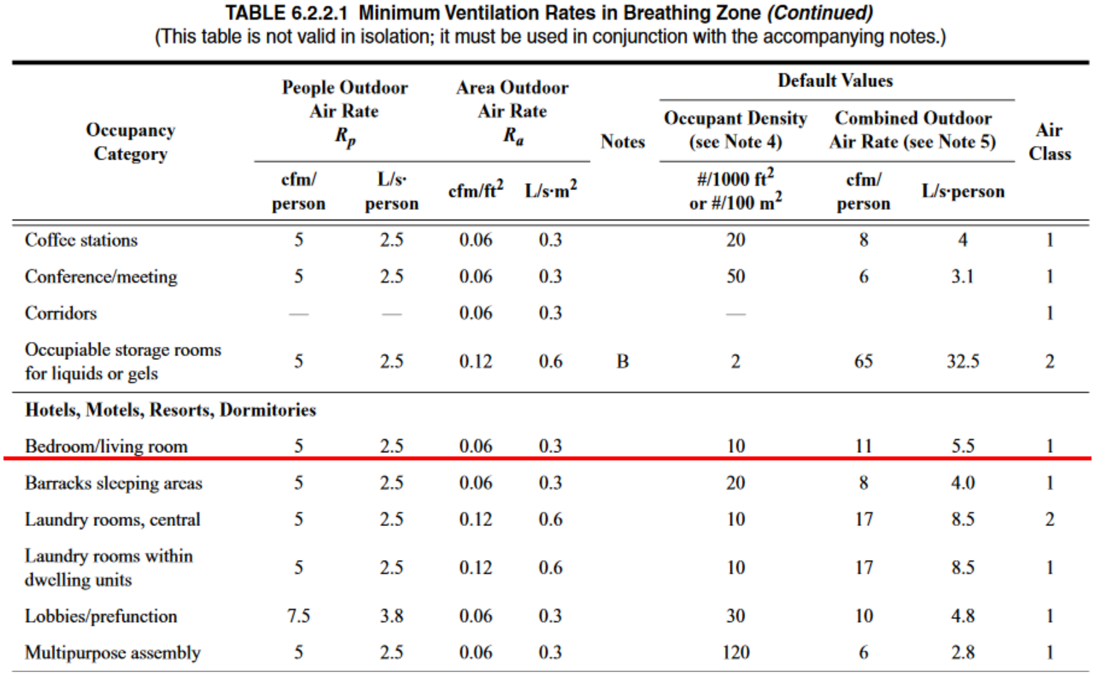


TABLE 6.2.2.1 Minimum Ventilation Rates in Breathing Zone *(Continued)*

(This table is not valid in isolation; it must be used in conjunction with the accompanying notes.)

Occupancy Category	People Outdoor Air Rate R_p		Area Outdoor Air Rate R_a		Notes	Default Values			Air Class
						Occupant Density (see Note 4)	Combined Outdoor Air Rate (see Note 5)		
	cfm/person	L/s·person	cfm/ft^2	L/s·m^2		#/1000 ft^2 or #/100 m^2	cfm/person	L/s·person	
Coffee stations	5	2.5	0.06	0.3		20	8	4	1
Conference/meeting	5	2.5	0.06	0.3		50	6	3.1	1
Corridors	—	—	0.06	0.3		—			1
Occupiable storage rooms for liquids or gels	5	2.5	0.12	0.6	B	2	65	32.5	2
Hotels, Motels, Resorts, Dormitories									
Bedroom/living room	5	2.5	0.06	0.3		10	11	5.5	1
Barracks sleeping areas	5	2.5	0.06	0.3		20	8	4.0	1
Laundry rooms, central	5	2.5	0.12	0.6		10	17	8.5	2
Laundry rooms within dwelling units	5	2.5	0.12	0.6		10	17	8.5	1
Lobbies/prefunction	7.5	3.8	0.06	0.3		30	10	4.8	1
Multipurpose assembly	5	2.5	0.06	0.3		120	6	2.8	1

Figure 4.15: ASHRAE ventilation requirements

The calculated ventilation air was inserted in the model as outdoor air in the cooling system and it was divided based on the unit flowrates. No infiltration was considered on the space level hence, the added outdoor air in the cooling system will compensate the exfiltrated air through the building envelope driven by the mechanically induced pressure. As illustrated in Table 4.11, inserting the ventilation flowrate as a system load indicates that, the building leakage characteristics are adding 32.1 % to the annual energy consumption.

In the second scenario, option-4 was selected to define the building airtightness where BDT result was inserted. The calculated infiltration flowrate based on the described method in section 4.2.1 used by the DesighBuilder software was 492.5 l/s. The cooling system was considered working with 100% recirculated air which means no outdoor air was introduced to the building. In this case, the infiltration driving force is mainly the wind. It was also found that the infiltration is adding 26.5% to the annual energy consumption as shown in Table 4.11. It is important to highlight that eliminating the outdoor air from the cooling system will not affect the indoor air quality since the converted infiltration flowrate from the BDT result is higher than the needed ventilation flowrate according to ASHRAE standard.

Table 4.11: Additional energy consumption due to infiltration.

Scenario Description	actual/Base Case	Ventilation as system load	7.12 ACH50 without ventilation
Annual energy consumption (kWh)	56913.5	38634.8	41819.8
Annual deviation	-	32.1%	26.5%

In the third scenario, a series of values for the outdoor air introduced by the cooling system was in inserted and for each value the deviation from the base case in the annual energy consumption was calculated. Eight values for the outdoor flowrate were examined ranging from 80% to 120% of actual infiltration flowrate with 5% interval between the values. Figure 4.16 shows the variation of the annual consumption with input value of the outdoor air through the cooling system.

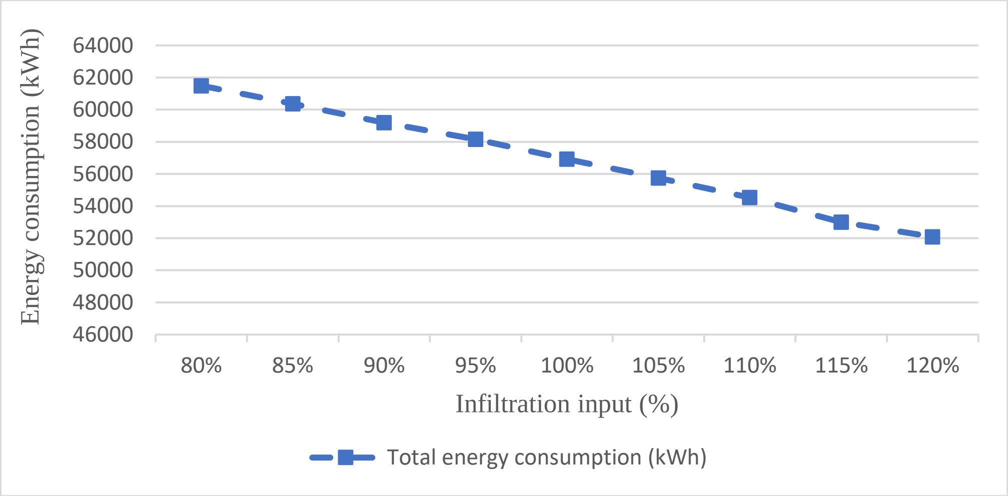


Figure 4.16: Variation of the simulation output with the infiltration input value.

Table 4.12 shows the deviation of the annual energy consumption from the base case when changing the outdoor flowrate which is governed by the air tightness characteristics of the house. It was found that wrong estimating the infiltration flowrate by 5% will result in a 2% deviation in the output of the software which indicates the importance of the accuracy of air infiltration input data.

Table 4.12: Effect of infiltration input data on simulation results

Infiltration input value	Energy consumption (kWh)	Deviation (%)
+20%	52088.7	8.0%
+15%	52992.7	6.1%
+10%	54527.0	4.0%
+5%	55738.1	2.2%
Base case	56913.5	0%
-5%	58146.6	-2.1%
-10%	59192.4	-4.2%
-15%	60357.9	-6.9%
-20%	61491.9	-8.5%

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Recently the international energy consumption has been increasing dramatically due to rapid industrialization in addition to the people's lifestyle. Statistics show that the buildings, in general, residentials, in particular, are major contributors to this increase. Since it has been determined that humans spend 80% of their life indoors, the use of energy in buildings focus on providing indoor environmental quality suitable to the building function. Hence, modern buildings are equipped with several different quality fabrics and systems. The Heating, Ventilation, and air conditioning (HVAC) system is responsible for meeting the thermal factor requirements of the Indoor Environmental Quality. It can be accountable for half of the building energy consumption which encourages researchers and manufacturers to investigate different strategies to reduce its energy use. Understanding the HVAC system configuration and its relationship with buildings showed that building airtightness is one of the most important building characteristics when it comes to reducing building energy consumption. Building airtightness is the physical characteristics controlling the phenomena of air infiltration and exfiltration which refers to the presentation of the outdoor air to the indoor and the opposite.

Infiltration could account for 40% of the total cooling energy especially in skin load dominated buildings such as residentials. Therefore, this research studied the impact of air infiltration on the energy performance of two identical 3-bedroom detached houses (House-

A, House-B) representing the region trend of the Eastern Province of Saudi Arabia. The houses airtightness was determined using the BDT method since it is a practical easy method commonly used. The house total leakage was measured then the leakage of the different components was determined by repeating the test after sealing the correspondent component and determining the reduction on the total building leakage. The air change rates under 50 Pa pressure difference of the House-A and House-B were found 6.58 and 7.04 h^{-1} respectively. The investigated air leakage paths in the Houses were the exhaust fans, windows, doors, lighting and maintenance ceiling opening, and cooling system air terminals. In House-A windows, doors, and exhaust fans were found to be the most influence air leakage sources with a contribution of 2.27 ACH50 while in House-B the leakage from doors, maintenance openings, and lighting openings was 2.19 ACH50. Furthermore, the airtightness test results were used to determine the actual infiltration rate under common operating conditions of the house. The actual air change rate under normal operating conditions of House-A and House-B was found 2.90 and 2.51 ACH respectively. In order to study the impact of the infiltration on the energy performance of the selected houses, an energy model was established using state of the art software DesignBuilder. The BDT results and the calculated actual infiltration flowrates were used as input data to define the model airtightness.

Two infiltration modelling options were studied for applying the BDT results and the determined infiltration flowrate. Option-1 requires the actual infiltration flowrate to be inputted and the simulation will consider it constant throughout the simulation period. The second applied option (Option-4) requires the air change rate under 50 Pa pressure difference and the software will convert this value to the infiltration flowrate driven by wind and temperature difference.

Since the houses are conditioned with CAV cooling system, the actual air leakage flowrate was inserted as outdoor air delivered through the cooling system in order to obtain a validated model.

To determine the impact of air infiltration on the annual energy of House-B, the needed ventilation flowrate based on ASHRAE requirements was calculated and inserted as outdoor air. The deviation of this scenario from the base case (validated model) was found to be 32.1% which represent the annual added energy by air Infiltration. Also, the results revealed that 5% error in the air infiltration input information will result in a 2% deviation in the annual energy consumption.

5.2 Recommendations:

The study focused on investigating the impact of air infiltration on the energy performance of the common constructed type of residential houses in the hot humid climate of the Eastern Province of Saudi Arabia. The following recommendations are proposed for determining building airtightness and understanding the effect of air infiltration on the building energy performance:

1) The building setup procedures prior to the BDT have a significant impact on the test results so, extra attention should be paid, and the test standard should be specified early.

2) The standard setup procedures could be insufficient for the house under consideration. It is recommended to study each house separately and collect the house sizing information on site with a high degree of accuracy.
3) The current study has revealed a remarkable behaviour of specific air leakage paths, particularly, the exhaust fans lovers and the maintenance openings in the ceiling. They were found out to have a variable contribution to the building air leakage depending on the induced pressure.
4) The reported air leakage paths data is meaningful and important to the building designers and constructors in order to improve the airtightness of the building and subsequently the energy performance.
5) It is recommended to consider the operation condition of the house and the characteristics of the installed system especially the used HVAC system when selecting the setup scenarios and the applied results on the energy model.
6) Also, it recommended considering the operation and specifications of the used HVAC system when defining the infiltration rate in the energy model particularly when defining the building airtightness by the actual infiltration flowrate.
7) When having a constant volume (CV) cooling system, the actual infiltration rate used to define the airtightness of the house in the energy model should be inserted as a system load rather than space/zone load. Since the operation of this type of units will cause exfiltration and eliminate the infiltration. Therefore, this amount of exfiltrated air will be compensated in the system by outdoor air.

5.3 Recommendations for Future Work

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

1. Investigation the impact of air infiltration on the energy performance in different climatic conditions of Saudi Arabia (Riyadh, Abha, Tabuk, etc.)
2. In Saudi Arabia, the relationship between air infiltration, HVAC system, and the ventilation flow rate should be studied in order to reach a good integration satisfying the indoor air quality requirements without consuming more unnecessary energy.
3. Proper scheduling for air infiltration in relation to weather conditions and HVAC system operation should be considered in modelling actual occupied buildings.
4. Airtightness determination and characterization of a representative sample for the buildings stock in Saudi Arabia is highly recommended and necessary which can assist developers, policymakers, and practitioners toward reducing buildings energy consumption.
5. The impact of air infiltration on the energy performance of different types of residential building in Saudi Arabia should be assessed and investigated.

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