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Energy Performance: Effects of Air Distribution Systems and Building Envelope Design on Indoor Air Quality and Energy Efficiency

First Author (Na Han)[1], Second Author (Shinming Shyu)[2], Third Author (Suleiman Ashur)[3]

Eastern Michigan University, Ypsilanti, MI 48197, USA
nhan1@emich.edu

Abstract
Building design and systems are essential for indoor air quality and energy efficiency. This research emphasized enhanced building envelope design, which was related to measuring the exterior walls with a thermal resistance (R-value), the windows with window-to-wall ratio, and the rate of solar heat gain coefficient values based on building codes and standards. In addition, emphasis was placed on advanced air distribution systems by comparing traditional and advanced air-handling unit systems. The systems were related to outdoor air airflow with ventilation requirements based on building codes and standards that include the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) 62.1; ASHRAE 90.1; the U.S. Green Building Council (USGBC) Leadership in Energy and Environmental Design (LEED) v4; and the International Energy Conservation Code (IECC). This research found significant improvements from manipulated building envelope and air system treatments. Total energy consumption was decreased, and indoor air quality was improved when building conditions were improved with an envelope design and building system changes.

Keywords
Building Envelope Design, Air Distribution Systems, Indoor Air Quality Factors, Energy Efficiency Factors, Building codes, ASHRAE 62.1—Ventilation for Acceptable Indoor Air Quality, ASHRAE 90.1—Energy Standard for Buildings, USGBC LEED v4, IECC.

1. Introduction

Introduction and Background

Increasing consideration of climate change and limited natural resource problems have emphasized the need for sustainable building design and systems because of the considerable impact that buildings have on society, the environment, community, and the economy (USGBC, 2013). Based on an energy review report, around 40% of the total energy consumed annually in the United States was consumed by buildings (USGBC, 2013). Also, based on the U.S. Energy Information Administration (EIA)'s report, it was estimated that the major source of energy consumption is electricity (EIA, 2020). Generally, buildings consumed electricity to operate systems such as heating, ventilation, and air-conditioning (HVAC).

According to the U.S. Environmental Protection Agency (EPA)'s report, almost 30% of new or renovated buildings have experienced indoor air quality problems (EPA, 1991). The leading causes were inadequate ventilation and indoor/outdoor chemical pollutants. Indeed, indoor air problems contributed to building-associated illnesses, such as sick building syndrome (SBS), building-related illness (BRI), and multiple chemical sensitivity (EPA, 2020 a). As occupants spend more of their time indoors, they are likely to suffer from more health problems.

Multiple research outcomes and records provided evidence that building systems and designs caused indoor air problems that impact human health and that a significant amount of energy is required to operate air systems. Other research indicates that building systems and designs were directly related to both indoor air quality and energy efficiency because of buildings' energy (thermal/heat) performance and energy demand/supply. In the energy performance process, air contains energy (thermal/heat) in the forms of temperature and humidity (Tao & Janis, 2001).

For these reasons, this research determined that sustainable applications to building systems and designs are critical for improving both indoor air quality and energy efficiency. The problem to be studied in this research was to identify different factors of traditional and advanced air distribution systems and building envelope design methods for indoor air quality and energy efficiency. This research used a building energy design and energy performance simulation software program (Carrier Hourly Analysis Program [HAP] 5.11) for manipulating variables to find their effects.

Statement of the Problem

Facing the challenges of energy efficiency and indoor environmental health, building research professionals were prompted to formulate solutions to meet needs. This research study was based on the fact that the effects of advanced air distribution systems and enhanced building envelope design on indoor air quality and energy performance had not been well addressed.

Hypotheses

Both active and passive building envelope designs and systems contribute to indoor environmental quality and energy efficiency. Factors of advanced air distribution systems and enhanced building envelope design methods might affect the indoor air quality and energy efficiency in educational buildings.

Based on an understanding of the research problem and related literature, this research investigates concisely phrased hypotheses. The study attempted to address the following research hypotheses:

- Hypothesis 01: Factors of advanced air distribution systems, outdoor air (OA) intake, and variable air volume (VAV) will be able to improve indoor air quality (i.e., reduce CO2 level) and reduce energy consumption.
    - Hypothesis 01.a: OA-intake and VAV will be able to improve indoor air quality by 30% or more based on LEED v4 or meet ASHRAE 62.1—Table 6-1 "Minimum Ventilation Rates on Breathing Zone."
    - Hypothesis 01.b: OA-intake and VAV will be able to reduce energy consumption by 15% or more to meet ASHRAE 90.1.
- Hypothesis 02: Factors of enhanced building envelope design, R-value, solar heat gain coefficient (SHGC), and window-to-wall ratio (WWR) will improve indoor air quality and energy efficiency.
    - Hypothesis 02.a: Enhanced building envelope design will improve indoor air quality by 5% or more based on building envelope infiltration and 20% based on passive ventilation to meet ASHRAE 62.1- OA Ventilation Data.
    - Hypothesis 02.b: Enhanced building envelope design will improve energy efficiency by 40–50% or more to meet ASHRAE 90.1 based on 50% Advanced Energy Design Guide.

Research Questions

Based on an understanding of the research problem and related literature, this research investigates concisely phrased research questions (see Figure 1). The study attempted to address the following research questions:

- Research Question 01: To what extent will air distribution systems affect indoor air quality and energy efficiency?
    - Research Question 01.a: What is the impact of constant air volume (CAV) on indoor air quality and energy efficiency?
    - Research Question 01.b: What is the impact of variable air volume (VAV) on indoor air quality and energy efficiency?
- Research Question 2: To what extent will building envelope design factors affect indoor air quality and energy efficiency?

- Research Question 02.a: What is the impact of R-value on indoor air quality and energy efficiency?
- Research Question 02.b: What is the impact of SHGC on indoor air quality and energy efficiency?
- Research Question 02.c: What is the impact of WWR on indoor air quality and energy efficiency?

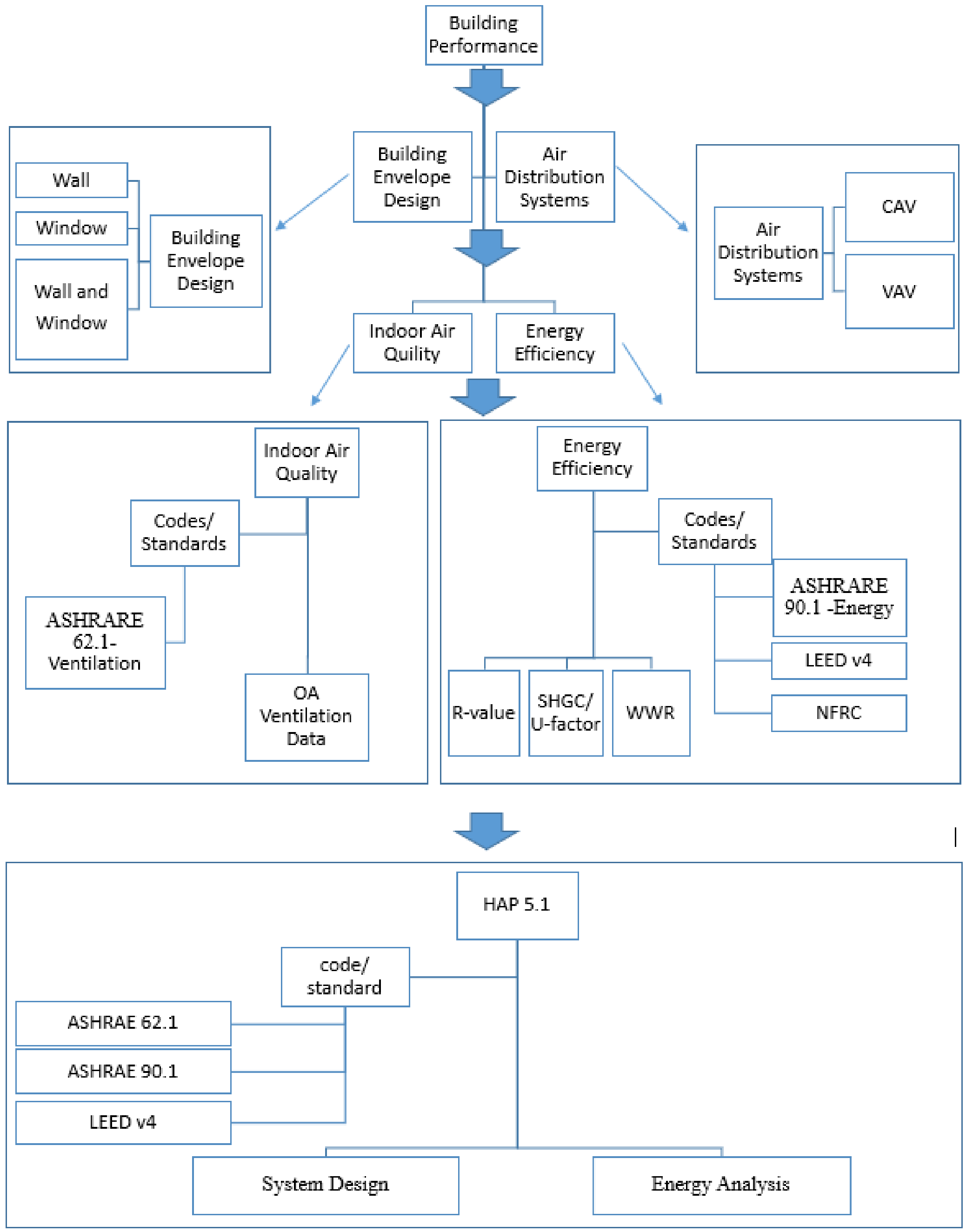

Fig. 26. Research map/framework.

Significance of the Study

The quality of indoor building environments has a significant impact on human health. This is because the average American spends approximately 90% of their time indoors, based on a survey by the EPA. Many indoor environmental factors, such as temperature and humidity, collectively shape indoor environmental quality, which in turn moderates the productivity of building users.

Thermal performance is related to a human factor that describes the state of mind that expresses satisfaction with the surrounding environment. Thermal performance refers to several conditions in which most people feel comfortable (Healey & Webster-Mannison, 2012). The body loses heat by conduction, convection, radiation, and evaporation of heat flow in indoor environments (Binggeli, 2010). The human body produces heat depending on activity level and expels heat according to the surrounding environmental conditions. Three main factors affect thermal performance, and they should be controlled to keep a healthy balance for occupants in an indoor environment.

This research also explains buildings' air distribution systems and envelope methods that can bring about the treatment of heat/thermal transfer, infiltration, and moisture control. Indeed, they improve indoor energy performance. Through building envelopes, heat transfers and solar energy enters buildings to provide acceptable thermal performance conditions for its occupants (Zemella & Faraguna, 2014).

Building systems operate heating, ventilation, and air conditioning (HVAC) systems. Specifically, an air distribution system monitors, measures, and controls outside air and the ventilation system for an optimal indoor environment. The building envelope defines the boundaries of the built environment, which functions to protect users from adverse natural elements, house various activities, and provide comfort and security.

For these reasons, this study planned to investigate the effects of advanced air distribution systems for indoor environmental quality and energy efficiency of buildings. In addition, this research focused on building envelope designs for their indoor environmental quality and energy performance. First of all, this research emphasized enhanced building envelope design, which is related to a measure of the exterior walls with a thermal resistance (R-value), the windows with the WWR, and the rate of SHGC values based on building codes and standards.

Then, it also emphasized advanced air distribution systems by comparing traditional and advanced systems. The systems were related to OA airflow with ventilation requirements based on building codes and standards: ASHRAE, and LEED. The codes and standards used in this research are specified below:

- ANSI/ASHRAE/IES 90.1—Energy Standard for Buildings Except Low-Rise Residential Buildings
- ANSI/ASHRAE 62.1—Ventilation for Acceptable Indoor Air Quality
- ANSI/ASHRAE/IES 169—Climate Data for Building Design Standards

Purpose of the Research

This research aimed to approach integrated building design and systems regarding the sustainable building. This research studied air distribution systems and building design, which determined building performances regarding indoor air quality and energy efficiency. Indeed, the stated objectives of the research were to examine combinations of building design methods and building systems, and determine their impacts on indoor air quality and energy efficiency.

For these reasons, this proposed study investigated the relationships between building design, air distribution systems, and the indoor environmental quality of buildings. It used building codes, standards, and guidelines for buildings' performance of airflow and energy. This research also used related data sets of building performance as a baseline, which was compared with current requirements for building system and design methods, such as CO2 monitoring systems, outside-air intake systems, and automatic ventilation systems. The systems were specified in building codes and related industry standards, including International Mechanical Code (IMC), IECC, and ASHRAE 62.1-Ventilation standard.

This research intended to introduce the factors of building envelope design and air distribution systems affecting building performance of heat and airflow. It also investigated building behavior and performance of heat flow and airflow in response to surrounding climate changes. This research understood factors of heat gain/loss, which were directly related to heat flow and airflow of energy performance with building design and system methods for discovering indoor air quality and energy efficiency.

To address building envelope design, this research discovered building performance in response to envelope design methods through wall, window, and door designs, knowing that the envelope design was directly related to building tightness and air ventilation. This research intended to describe thermal transfer, infiltration, and moisture control concerning building technology and science in building design for indoor air quality.

Besides, building tightness and air ventilation with air distribution control systems led to high energy performance and indoor air quality. The treatments of building envelope design methods contributed to human health issues of indoor contaminations in the building environment.

Overall human health was related to indoor air temperature, air humidity, and air speed, which affected indoor air quality by controlling air distribution systems. In addition, the study dealt with the symptoms of BRI and SBS, which resulted in decreased productivity/academic performance, increased absenteeism/sick days/health costs, restricted activity, and health issues.

For these reasons, it was critical to address building design and its impact on building tight and air ventilation control with air distributions systems for improving human health issues. Living and working building environments should be considered because buildings' human health issues, such as BRI and SBS, had adverse effects on occupants in the indoor environment of buildings (Bonda & Sosnowchik, 2007).

Providing healthy indoor environment quality was a significant design matter because it also related to social and economic issues. Therefore, the present research intended to study the ways in which the factors of building envelope design affect the energy performance of building designs.

The research goal was to determine a building's airflow and energy efficiency performance by using Carrier HAP software for testing. The major points explained in this research were air distribution system types and building envelope design methods, indoor air quality factors, and energy efficiency factors in buildings based on building codes/standards/reference guide ASHRAE and LEED v4.

As a result, this research determined that the enhanced advanced air distribution systems and building envelope design methods can affect indoor air quality and energy efficiency in buildings. This research explained that considering building design and the system is important because it adjusts heat flow with airflow through air distributions systems and the building envelope. Moreover, this research demonstrated that controlled heat flow with airflow through air distribution systems and building envelopes could reduce energy consumption and improve the indoor air quality of spaces in buildings.

2. Settings or Methods or Materials and Methods

Research Design and Methodology

Research Design

This research designed and used methodology for an experimental study. It explored/discovered the effects of air distribution systems and building envelope design methods on building performance: indoor air quality and energy efficiency in buildings.

Research Type

The type of research was an experimental study. It took an existing setting and used software programs to make incremental environmental factor adjustments to seek an optimum condition for indoor air quality and energy efficiency. Exploring the combination of factors and their various levels helped inform designers and builders about structural changes needed to address new and renovation construction that could ultimately affect climate change.

This research used experimental analysis to explore modifications to the building air system and envelope design methods by developing whole building simulation models that estimate indoor air quality and energy efficiency.

Research Population, Sample, And Subjects

The samples were classrooms and office areas within Sill Hall, an educational building at Eastern Michigan University. In addition, architectural drawings of the building were created by using the software programs Auto CAD and Revit.

Data Instrumentation(s)

The instrumentation of this experimental research was Carrier, eDesign Suite Software, Hourly Analysis Program (HAP version 5.1). The software enabled the design and analyze building air distribution systems

(HVAC systems) and building design methods (wall and window) by calculating energy peak load, sizing HVAC systems, and modeling energy performance.

Data Collection

The data collection explored the effects of advanced air distribution systems and enhanced building envelope design on indoor air quality and energy efficiency in educational buildings. This research used the software HAP 5.1 to run multiple energy design simulations for testing building performance: air distribution systems and their energy used in representative classrooms and office areas. It manipulated independent variables (i.e., air distribution systems and building envelope design methods) with middle variables (CAV, VAV, R-value, SHGC, WWR) of representative areas (classrooms and offices) based on the climate zone map. (Michigan is located in Zone 5, defined by ASHRAE and IECC.)

For collecting data, this research checked the existing conditions of building systems and building design methods of representative areas.

Data Collection Procedure

During the summer and fall semesters in 2019, this experimental research made a practical software setting of HAP 5.11 in Room 213, Roosevelt Hall, Eastern Michigan University. Then this research was conducted for testing variables and collecting data results.

After testing all treatments separately, this research tested treatment with the selected sample areas (total five times) for generating energy simulation data. Experimental treatments for the energy simulations were air distribution systems and building envelope design treatments. Experimental test procedures for the energy simulation were: CAV with existing conditions (TCAV-0), CAV with treatment 01 (TCAV-01), CAV with treatment 02 (TCAV-02), VAV with treatment 01 (TVAV-01), and VAV with treatment 02 (TVAV-02). The detailed experimental research procedure is listed below (see Figure 2):

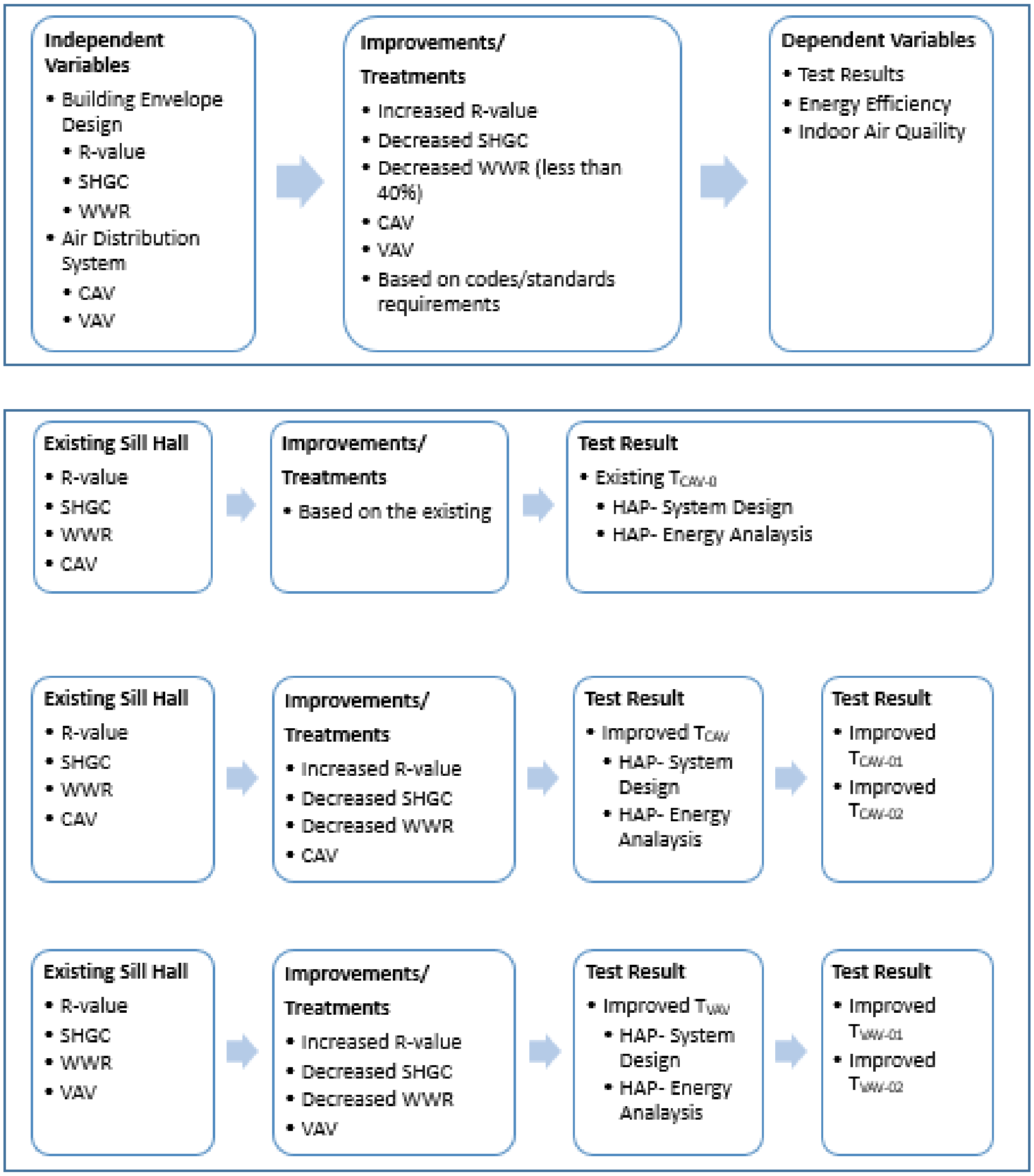

Fig. 27. Experimental research test procedure.

This research design explored the effects of building envelope design and air distribution systems on a building's energy performance. This research type was an experimental study. Its research sample was classrooms and office areas within Sill Hall at Eastern Michigan University. The data were collected by using data instruments Carrier's eDesign Suite Software Hourly Analysis Program (HAP version 5.1).

3. Results

Data Analysis and Findings

Data Results and Data Analysis

For the data procedure based on this research problems, the study gathered input content to enter data into software HAP 5.11 and to generate energy design simulation results (findings) for this experimental research. The tables and figures of data and results were examined and explained. Input data included settings for the weather conditions, wall constructions, window constructions, space sizes, and air system types for the sample. Then, output data results noted the impact of differing envelope designs and energy systems' airflow and energy usage for the air distribution system.

Input data.

Input data results were gathered, and the data were entered into HAP 5.11. Input data settings explained the weather, walls, windows, spaces, and air systems of the selected sample (classrooms and office areas within Sill Hall). The input data properties described problems of this research: types of air distribution systems and building envelope design methods that influenced the energy design analysis (HVAC systems design and energy usage for HVAC systems) in this research design.

Output data.

This experimental research generated energy design simulation reports (results) from the input data (weather, air systems, wall, window, and space) of the selected sample using HAP 5.11.

Output data reports analyzed the air distribution systems' design and building envelope design methods (regarding indoor air quality) and energy usage for air distribution systems (regarding energy efficiency) and for the input data (air systems, walls, and windows) of the sample classrooms and office areas within Sill Hall. The output data results addressed the research questions and hypotheses as well as the ways in which gathered input data settings influenced the healthy indoor environment and energy usage.

The energy design simulation reports presented air distribution system and building envelope design methods (regarding heat flow and airflow) and energy usage (regarding building loads): design load and system-psychrometrics. The results demonstrated the impact of input data on output data: the ways in which gathered input data settings improved indoor air quality by designing methods of air distribution systems/ventilation and energy efficiency by designing methods of building envelope design with air distribution system/ventilation.

In the sample spaces of the building, heat flow and airflow were addressed by modeling elements of loads: spaces of project, group of spaces (zones) sharing the same thermostat, air systems providing conditioned air to zones of a building, and plants providing cooling/heating to air systems. The software estimated the operating energy of the building.

The input data reports used independent variables, and the output data reports were dependent variables. Based on the output data reports, findings were compared to discover differences.

Address heat flow and airflow. This research demonstrated the ways in which air distribution systems and building envelope methods addressed heat flow and airflow for designing ventilation, heating, and cooling loads: the amount of energy to be added/removed to keep an acceptable range of temperature. The reports included calculated design loads for four (4) building areas.

For analyzing the results of energy efficiency (see Figure 3), this research identified result values of design loads with the following steps:

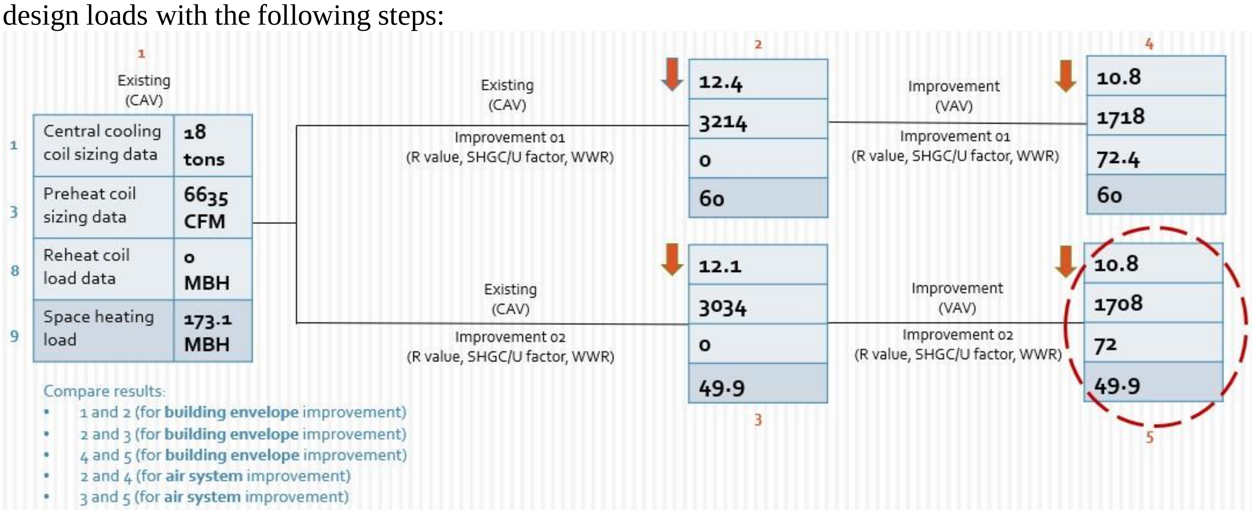

Fig. 28. Identified result values of design loads with steps.

For analyzing the results of indoor air quality (see Figure 4), this research identified result values of design loads with the following steps:

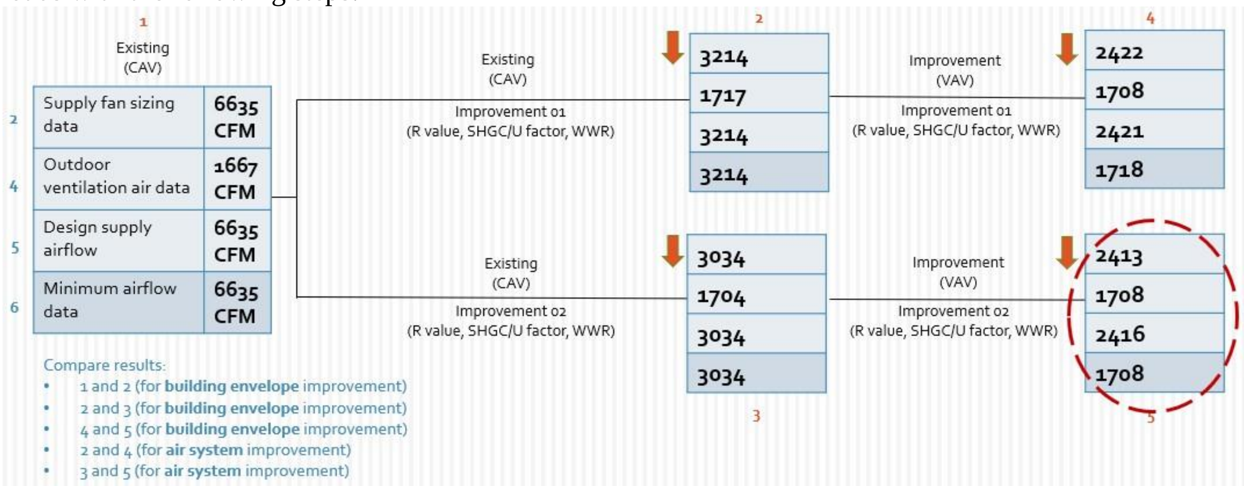

Fig. 29. Identifies result values of design loads with steps.

Address airflow with air-water mixtures. This research demonstrated the ways in which air distribution systems and building envelopes addressed airflow with air-water mixtures for designing ventilation, heating, and cooling loads: the amount of air to be added/removed to keep an acceptable range of airflow. The reports included calculated airflow with system-psychometrics for four areas in the building. The calculated values of airflow (CO2 level, airflow, latent heat/sensible cool) of system- psychrometrics' components for the sample are listed below and shown on the psychrometric charts.

For analyzing the results of indoor air quality (see Figure 5), this research identified result values of system-psychrometrics' components with the following steps:

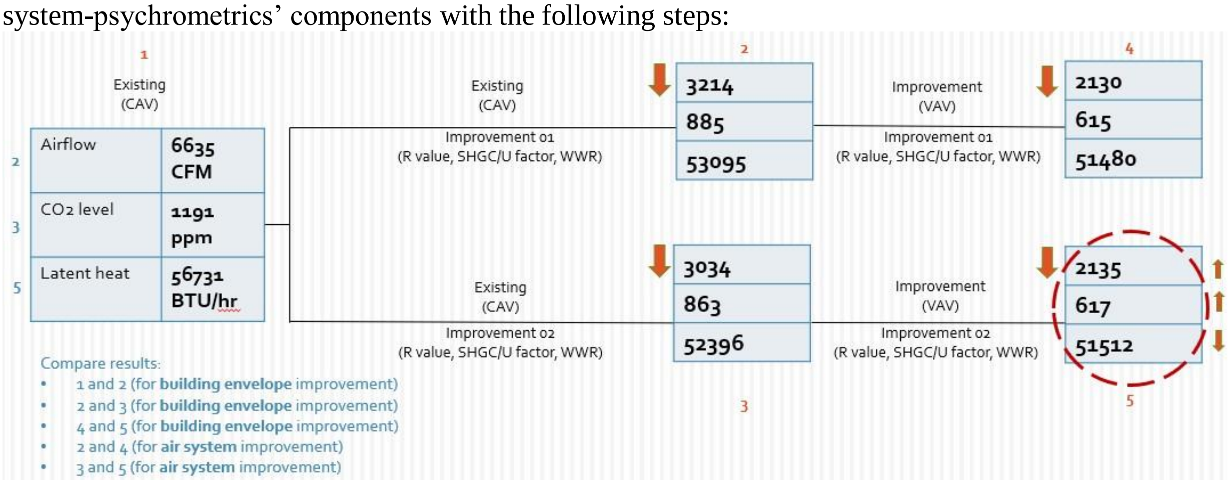

Fig. 30. Identified result values of system-psychrometrics' components with steps.

The results showed significant outcomes when comparing air systems (CAV and VAV) due to manipulated treatments of building envelope treatment for increased R values and decreased SHGC/U factors, and increased/decreased WWR for test results 01 and 02, 03 and 04, and 04 and 05.

When building conditions were modified with building envelope treatment 02 (increasing R value from 4.67 to 25, decreasing SHGC/U factor from 0.60 to 0.38, and modifying WWR from 16/16/32/48% to 35%) and air system treatment (VAV), the total energy consumption was decreased, and indoor air quality was improved.

Result values of the amount of energy usage were decreased. Result values of the amount of airflow to maintain adequate ventilation and indoor air quality were decreased. Result values of system psychrometrics components were airflow sizing, CO2 level, and latent heat/sensible cooling. The values of the amount of airflow and water vapor of air to maintain adequate ventilation and indoor air quality decreased. Moreover, result values of psychrometric charts were different in graphic slopes of points; improved results were steeper than the previous results. Slopes of points of results were steeper than the previous result; the less sensible heat/latent cool and latent heat/sensible cool loads existed. Airflow was circulated well in less sensible heat/latent cool and latent heat/sensible cool loads because the air was cooled and dehumidified. Points moved both horizontally and vertically: the air was mixed in an increased warm temperature and humidification; the air was changed to an increased cool temperature and dehumidification; the air was supplied to spaces in an increased cool temperature and dehumidification; and the air was returned to cooling/heating systems to manage temperature and humidity. The improved results—a range of mixed, cooled, supplied, returned air temperature and humidity—were wider than the previous results. Properly managing different conditions of various spaces depended on the demands of those spaces to maintain adequate indoor air quality. According to ASHRAE 55, cool temperatures from 72 to 80 and dry relative humidity of 30–60 will create a comfortable indoor zone; a slightly cooler temperature will be acceptable in spaces for indoor quality and energy efficiency (Tao & Janis, 2001). Under the proper cooling conditions, lower supply airflow speed was identified in this study, and reduced or lower airflow was required to maintain good air quality by supplying fresh air and managing temperature and humidity. The experiment showed these significant changes in both building envelope and air distribution system treatments, which can be connected to occupant safety and health.

After analyzing data results, this research verified the proposed hypotheses that factors of enhanced and advanced building envelope designs and air distribution systems contributed to indoor environmental quality and energy efficiency in buildings.

4. Discussion/Limitations/Delimitations of the Study

Limitations of this study might affect the findings and outcomes. Using available lab instruments, this research focused on outdoor air intake to ensure that carbon dioxide (CO2) and relative humidity levels followed building code requirements and ASHRAE 62.1. Other indoor air quality issues of cost and chemical analysis of volatile organic compounds (VOCs), dust, and mold were considered for future research.

Moreover, the results related to possible future research questions and hypotheses by modifying treatment values and expanding the range of independent variables. In addition, this research indicated that further research should include indoor spaces as a whole building simulation, energy recovery systems regarding advanced air system, window treatments on the interior or exterior, and commissioning processes after applying improved building system and design methods for indoor air quality and energy efficiency.

5. Conclusions

Findings

This experimental research study used air distribution system/ventilation rates for identifying indoor air quality. The research also used air in heating and cooling rates to determine energy efficiency. Air distribution systems and the modified properties of walls and windows were examined to check the ways in which they provide healthy indoor air quality and save energy usage in buildings. For the study building, examined data involved different types of air distribution, increased R-value for insulation, decreased SHGC/U-factor for thermal comfort, and increased/decreased WWR for the building envelope.

For Hypothesis 01 regarding indoor quality, this research demonstrated treatment when fan size decreased airflow supply and reached minimum airflow. Also, this research showed that CO2 levels and airflow sizing went down, and different values of psychrometric chart points’ slopes were steeper.

For Hypothesis 02 regarding energy efficiency, this research showed that efficiency improved when values of central cooling coil sizing data, supply fan sizing data, preheat coil sizing data, design supply airflow, minimum airflow data, reheat coil load data, space load, and airflow data decreased. The results ofthis research provided systematic testing and validation of air distribution systems and building design methods that can be used to impact building indoor air quality and energy efficiency.

Recommendations

This research considered heat flow and airflow of building design and system and the ways in which it caused healthy indoor air quality and energy efficiency in buildings. Indoor air quality treatments and reduced energy usage can be impacted by applying building design methods and air distribution system modifications for any building type.

This research aimed to apply sustainable strategies to air systems and building envelope design for improving indoor air quality and reducing energy usage. The research results encouraged sustainable strategies of air distribution systems and building envelope design by providing monitored changes in energy usage (building loads) and indoor air quality (airflow rate) of the test (sample building).

This experimental research verified the proposed hypotheses and research questions, proving that factors of enhanced and advanced building envelope designs and air distribution systems contributed to indoor environmental quality and energy efficiency in buildings.

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