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Ključne reči: zgrada; prirodna ventilacija; mehanička ventilacija; softver EnergyPlus

PRIMENA RAZLIČITIH TIPOVA VENTILACIONIH STRATEGIJA U STAMBENIM ZGRADAMA – STUDIJA SLUČAJA

Key words: building; natural ventilation; mechanical ventilation; EnergyPlus software

APLICATION OF DIFFERENT VENTILATION STRATEGIES IN RESIDENTIAL BUILDINGS – CASE STUDY

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Zgrade su postale ključni predmet interesovanja u razvoju održivih rešenja zbog velikog doprinosa emisijama i ogromne potrošnje energije. Posebna pažnja posvećuje se ventilaciji zgrada, koja ima značajan udeo u potrošnji energije zgrade. KGH sistemi su neophodni za održavanje zdrave sredine korisnika zgrade. Prirodna ventilacija koristi prirodne sile poput vetra i razlike temperature za cirkulaciju svežeg vazduha. Mehanički ventilacioni sistemi su dizajnirani da obezbede kontinuiranu cirkulaciju svežeg vazduha u zgradama, čime se poboljšava kvalitet unutrašnjeg vazduha. Moderno projektovani mehanički ventilacioni sistemi koriste napredne tehnologije kao što su rekuperatori toplote, čime se smanjuje potrošnja energije i unapređuje energetska efikasnost. Ovaj rad prikazuje modeliranje različitih ventilacionih strategija u stambenoj zgradi, korišćenjem softvera EnergyPlus. Simulacije su sprovedene za izabrane zimske i letnje dane. Dobijeni rezultati simulacija prirodne ventilacije su pokazali ventilacione gubitke i dobitke, dok je sistem mehaničke ventilacije sa rekuperacijom toplote modeliran sa naglaskom na kvalitetu vazduha u zatvorenom prostoru.

Buildings have become a key issue in developing of sustainable solutions due to their significant contribution to total CO_2 emissions and substantial energy consumption. Special attention is devoted to building ventilation, which has a significant rate of building energy consumption. HVAC systems are essential for maintaining a healthy environment for building occupants. Natural ventilation uses natural forces such as wind and temperature differences to fresh air circulation. Mechanical ventilation systems are designed to provide continuous circulation of fresh air in buildings, thereby improving indoor air quality. Modernly designed mechanical ventilation systems utilize advanced technologies such as heat recovery units, which reduce energy consumption and improve building energy efficiency. This paper presents modeling of different ventilation strategies in a residential building, using EnergyPlus software. Simulations were provided for selected summer and winter days. Obtained results for natural ventilation showed zone ventilation heat losses and gains, while mechanical ventilation system with heat recovery is modeled with emphasis on indoor air quality.

1. Introduction

Today's lifestyle often revolves around indoor environments, unlike in the past, when outdoor activities and social gatherings were more common. As a result of this shift towards indoor living, building energy consumption has increased significantly. Eurostat's data indicates a substantial influence of the building sector on overall energy consumption in recent years. In 2020, energy use across EU countries' residential, commercial, and public buildings accounted for approximately 42% of the total energy consumption [1]. As a result, the focus on building energy consumption has become increasingly crucial. Adopting strategies that improve energy efficiency is essential, thus lowering costs and mitigating environmental impacts. For comfortable living conditions, buildings must be equipped with efficient heating and cooling systems, which provide a pleasant indoor environment throughout the year.

Energy-efficient building is a highly prioritized issue. In this context, the energy-efficient design of the implemented ventilation system is of great importance. The goal of this design is to optimize natural ventilation while minimizing the dependence on mechanical systems. This strategy is aimed at achieving energy savings [2].

Heating, Ventilation, and Air Conditioning System (HVAC), is a crucial system in modern buildings that ensures comfortable and healthy indoor environments by regulating temperature, humidity, and air quality. Effective HVAC systems are essential for maintaining optimal living and working conditions, and they are also important for reducing energy consumption and minimizing environmental impact. Today, various companies offer efficient mechanical ventilation systems, often featuring heat recovery mechanisms [3]. These systems prevent the need for random windows opening and aim to save energy by pre-heating cold external air using warm, exhausted internal air during winter. This paper investigates the modeling of various ventilation strategies in a residential single-family building.

2. Ventilation strategies

2.1. Natural ventilation

Natural ventilation is an age-old technique used for ventilating and cooling buildings, especially effective on mild summer days. Studies indicate that in areas with extreme heat and humidity during the summer, natural ventilation falls short of ensuring indoor air comfort. However, it offers considerable energy-saving potential during milder summer conditions [4]. Natural ventilation involves the removal of indoor air or introduction of fresh outdoor air using natural forces like wind. Properly designed natural ventilation can lower energy use, provide fresh outdoor air, and offer free cooling.

There are two models for natural ventilation in EnergyPlus software, “Design Flow Rate” model and “Wind and Stack with Open Area” model. First model depends on environmental conditions that change the design flow rate. The second model is based on equations defined in ASHRAE Handbook of Fundamentals [5]. These two ventilation objects may be used independently or combined to specify ventilation air for a zone. The total ventilation flow rate equals the sum of the individual air flow rates calculated by each object. EnergyPlus utilizes weather data from its proprietary database, which includes weather files. These files provide hourly or sub-hourly readings of temperature, relative humidity, air pressure, wind direction, wind speed, and data on rain and snow.

The Design Flow Rate specifies the amount of outdoor air that needs to be introduced into a building or zone to meet ventilation requirements. This helps ensure good indoor air quality and occupant comfort. The zone ventilation described by this input object can be controlled via a schedule and by setting temperatures. Detailed information can be found in the Input/Output reference document [6].

The Ventilation by Wind and Stack with Open Area in EnergyPlus refers to the natural ventilation modeling approach that utilizes the principles of wind-driven and stack effect ventilation. With this approach, natural ventilation flow rates can be regulated through a multiplier fraction schedule and by setting temperature values.

2.2. Mechanical ventilation with Heat Recovery

Mechanical ventilation enhances indoor air quality, which involves significant heat loss through exhaust air. To mitigate energy consumption, the heat from the exhaust air is reclaimed. The efficiency of this process depends on airflow (higher airflow reduces efficiency) and the temperature difference between indoor and outdoor environments (greater gradient improves efficiency). Ventilation systems with heat recovery have been recognized since the 1970s as a means to decrease heating and cooling energy consumption [7]. Mechanical ventilation systems with HR, implemented in modern buildings, can reduce building heating and cooling energy by up to one-third [8]. The Energy Performance of Buildings Directive (EPBD) mandates incorporating heat recovery in mechanical ventilation systems [9]. Additionally, the 'Ecodesign' Directive [10] establishes efficiency standards for heat recovery systems in the European Union, requiring a minimum efficiency of 68% for intermediate systems and 73% for other systems.

A specific feature of EnergyPlus includes the airflow network model, which simulates the operation of an air distribution system. This model can account for supply and return leaks, and calculate airflow across multiple zones driven by outdoor wind and forced air during HVAC system operation. The model is limited to a single forced air system with a constant volume supply air fan, and it operates through three consecutive steps: (1) calculating pressure and airflow, (2) determining node temperature and humidity, and (3) computing sensible and latent loads.

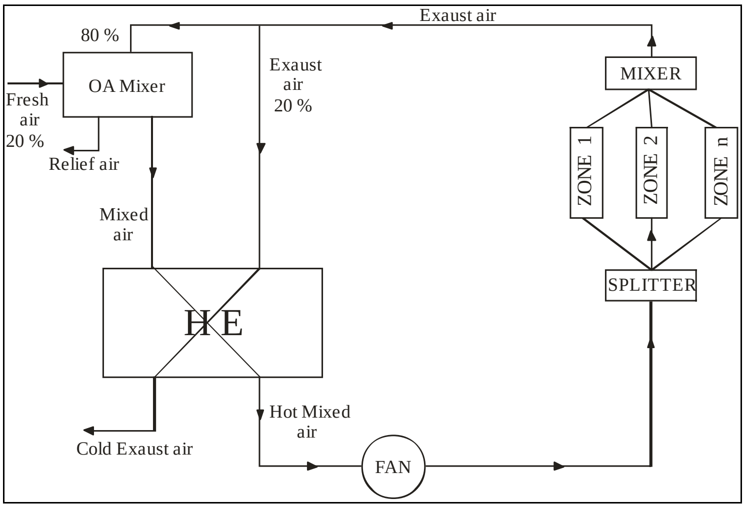


Figure 1. Schematics of mechanical ventilation system with HR unit and OA MIXER

Figure 1 illustrates a simplified diagram of the mechanical ventilation system with air-to-air heat exchanger (HE) and the outdoor air mixer (OA MIXER) [11]. The main part of the mechanical ventilation system is heat exchanger (HE). This component simulates energy transfer between the supply air stream and the exhaust air stream based on user-specified effectiveness values in the input data file. Typically used for exhaust air, the air-to-air flat plate HE allows exhaust air from the building to pass through one side, while fresh outdoor air flows in a cross or counter-current flow through the other side. This process preheats the fresh air entering the rooms as per user requirements.

OA Mixer (Outdoor Air Mixer) is a critical component frequently used in outdoor air systems. It divides the return air from the primary air system into relief and recirculated air streams. Subsequently, it blends the outside air stream with the recirculated air stream to create a mixed air stream.

Air Loop denotes a central forced-air HVAC system. The term "loop" refers to the system's configuration where air is often recirculated, forming a continuous flow. Air loop represents the "air-side" segment of a comprehensive HVAC setup. For simulation purposes, the air loop is divided into two main parts: the primary air system, which handles the supply side of the loop, and the zone equipment, which addresses the demand side. The primary air system includes essential components (supply and return fans, central heating and cooling coils, an outdoor air economizer, and other centralized conditioning equipment and controls). The zone equipment section of the loop comprises air terminal units, fan coils, baseboards, window air conditioners, and similar devices.

Splitter divides an incoming air stream into multiple outgoing streams. Each outlet air stream is adjusted to match the humidity ratio, pressure, enthalpy, and temperature of the incoming air stream. The mass flow rate of the incoming air stream is set to equal the sum of the mass flow rates of the outgoing air streams. Mixer merges several incoming air streams into one outgoing air stream. Calculations for the air mass flow rate are conducted to determine both, the maximum and minimum available rates.

3. Mathematical models

Mathematical models for different ventilation strategies are not simple, especially for ventilation systems with heat recovery. In further analysis, it will be presented only equations for some basic values for natural and mechanical ventilation, which are implemented in EnergyPlus software.

3.1. Natural ventilation

The ventilation flow rate can be modified by the temperature difference between the inside and outside environment and the wind speed. The basic equation for this EnergyPlus model is:

$$V_{vent} = V_{des} F_{sch} \{A + B|T_{zone} - T_{odb}| + C(WS) + D(WS)^2 \tag{1}$$

where: V_{des} – maximum design volume flow rate (m^3/s); F_{sch} – open area fraction (user-defined scheule value, dimensionless); *A, B, C, D* – EnergyPlus models constants (-); T_{zone} – zone temperature (K); T_{odb} – local outdoor dry-bulb temperature (K); *WS* – local outdoor wind speed (m/s).

The ventilation rate driven by wind is:

$$Q_W = C_W A_{op} F_{sch} V \tag{2}$$

where: Q_w – volumetric air flow rate driven by wind (m^3/s); C_w – opening effectiveness (-); A_{op} – opening area (m^2); F_{sch} – open area fraction (user-defined schedule value, dimensionless); V – local wind speed (m/s).

The equation used for calculating the ventilation rate due to stack effect is:

$$Q_S = C_D A_{op} F_{sch} \sqrt{2g\Delta H_{NPL}\left(|T_{zone} - T_{odb}| / T_{zone}\right)}$$

where: Q_S – volumetric air flow rate due to stack effect (m^3/s); C_D – discharge coefficient for opening (-); ΔH_{NPL} – height from midpoint of lower opening to the neutral pressure level (m).

The *total ventilation rate* is the quadrature sum of the wind and stack air flow components:

$$V_{WindAndStock} = \sqrt{Q_S^2 + Q_W^2} \tag{3}$$

1.1 Mechanical ventilation wit Heat Recovery

Node Temperature Calculations – for calculating the temperature distribution across a duct element at the given airflow rate and inlet air temperature, the following equation is used:

$$\dot{m}C_p \frac{dT}{dx} = UP(T_\infty - T) \qquad (4)$$

where: $\dot{m}$ – air flow rate (kg/s); C_p – specific heat of airflow (J/kgK); P – perimeter of a duct element (m); T – temperature as a field variable (°C); T_∞ – temperature of air surrounding the duct (°C); U – overall heat transfer coefficient (W/m^{2}K). The inlet temperature at one linkage is the outlet temperature for the connected linkage, so the outlet air temperatures at all nodes are solved simultaneously.

Sensible, total and latent heat recovery (HR) rates can be obtained by next equations:

$$Q_{sensible} = (\dot{m}_{C_p,Sup}) \cdot (T_{SupAirIn} - T_{SupAirOut}) \qquad (5)$$

$$Q_{Total} = \dot{m}_{SupAir} \cdot (h_{SupAirIn} - h_{SupAirOut}) \qquad (6)$$

where: $Q_{sensible}$ – sensible HR rate (W); Q_{Total} – total HR rate (W); $\dot{m}_{C_p,Sup}$ – heat capacity rate of the supply air stream (W/K); $T_{SupAirIn}$ – supply air inlet temperature (°C); $T_{SupAirOutn}$ – supply air outlet temperature (°C); $\dot{m}_{SupAir}$ – mass flow rate of the supply air stream (kg/s); $h_{SupAirIn}$ – supply air inlet enthalpy (J/kg); $h_{SupAirOut}$ – enthalpy of the supply air leaving the HE (J/kg) calculated by EnergyPlus routine.

Latent heat recovery (HR) rate can be obtained from equations (5) and (6):

$$Q_{latent} = Q_{total} - Q_{sensible}$$

Total heat recovery (HR) rates for the overall unit is reported for each simulation time:

$$Q_{TotalHeating} = \dot{Q}_{TotalHeating} * TimeStepSys * 3600 \qquad (7)$$

where: $\dot{Q}_{TotalHeating}$ – HE total heating rate, *TimeStepSys* – HVAC system simulation time step (hr). At the same way, the sensible and latent HR rates can be calculated for the overall unit (for heating and for cooling operations separately).

Zone Air Carbon Dioxide Concentration is calculated by EnergyPlus software, and represents the CO_2 concentration level in parts per million (ppm) for each zone. This is calculated and reported from the Correct step in the Zone Air Contaminant Predictor-Corrector module. The zone air carbon dioxide concentration updates at the current time step using the EulerMethod [5].

4. Results and discussion

The modeled residential building with different implemented ventilation strategies is shown in Figure 2. Analyzed building is located in the city of Kragujevac, Serbia. The air temperature in the heated rooms is set to 20^{0}C from 07:00-09:00 and from 16:00-23:00, and to 15^{0}C from 09:00-16:00 and from 23:00-07:00 (from October 15th to April 15th). For summer period (from June 1st to September 1st) the air temperature in the conditioned rooms is set to 26^{0}C, while in transition periods the air temperatures is set to 23^{0}C.

The modelled building has two floors with 7 conditioned zones (living room, two bedrooms, kitchen, bathroom, two halls) and 2 unconditioned zones – anterooms. Total floor area of the investigated building is 160 m^2. The building envelope is thermally insulated by polystyrene (thickness of 0.15m) and the windows are double glazed.

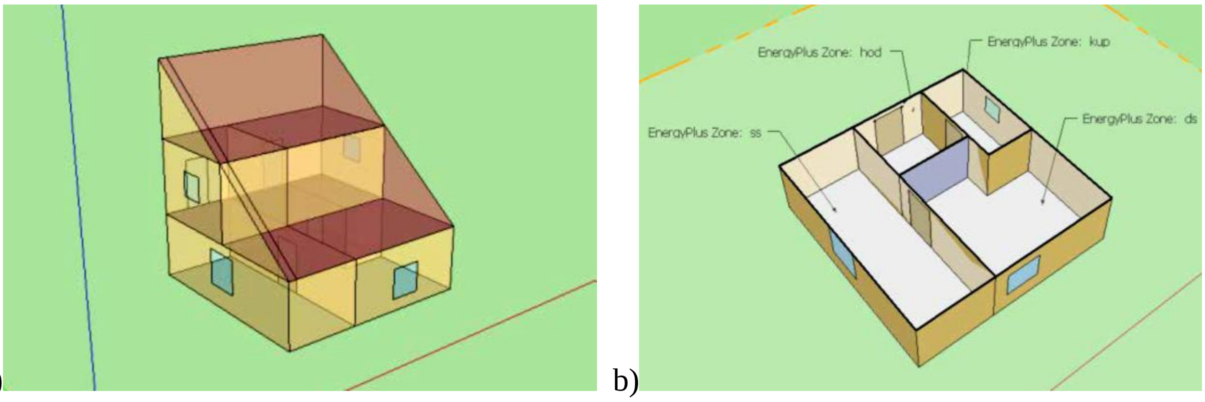


Figure 2. Modelled building: a) Schematics; b) Cross-section of the first floor

Figure 3 shows the outdoor dry bulb temperature and wind speed in the city of Kragujevac, for August – typical summer month with the highest temperatures during the year. The curve of temperature and wind speed was created based on the data from the weather file of EnergyPlus software.

Figure 4 represent the sensible heat gains due to natural ventilation in the modelled building, during August. This value is determined when the outdoor dry-bulb temperature is higher than the zone temperature; otherwise, the sensible heat gain is set to 0. The sensible heat gains have the highest values during the first days of August as there are the highest values of temperature (Fig.3).

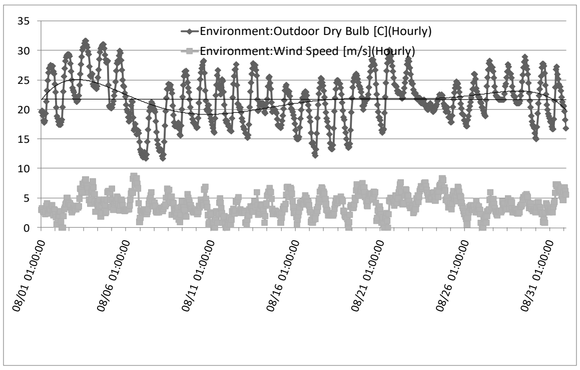


Figure 3. Outdoor dry bulb temperature and wind speed for August

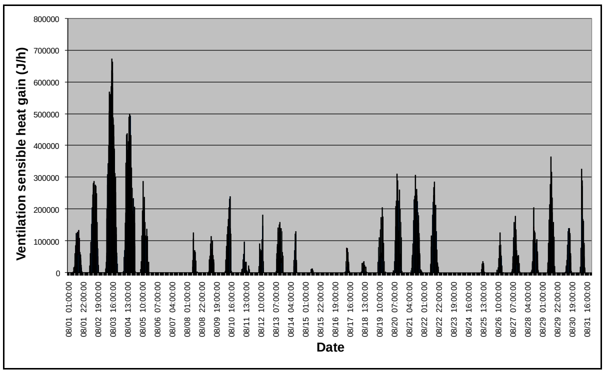


Figure 4. Sensible heat gains in the building due to natural ventilation, during August

Figure 5 represents the sensible heat losses due to natural ventilation, calculated by EnergyPlus during November. The highest values of sensible heat gain are during the final days of November when the outdoor dry bulb temperature has the lowest values. Heat losses must be compensated with additional energy for heating, in order to maintain thermal comfort in the building at the desired level.

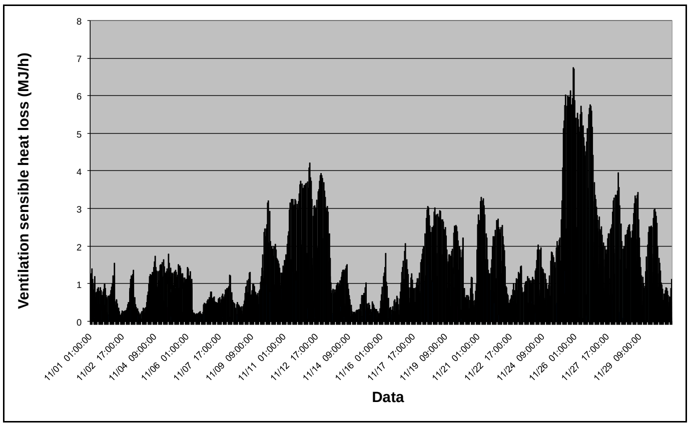


Figure 5. Sensible heat losses in the building due to natural ventilation, during November

Figure 6 represent the zone air temperatures obtained by EnergyPlus software, in the building modelled with mechanical ventilation. Simulations were done from January 1st-5th. The biggest temperature fluctuations were in HOD1 and SS2, because these zones are most exposed to the penetration of cold air or the surrounding unheated zones.

Figure 6. Zone air temperatures calculated by EnergyPlus from January 1st-5th

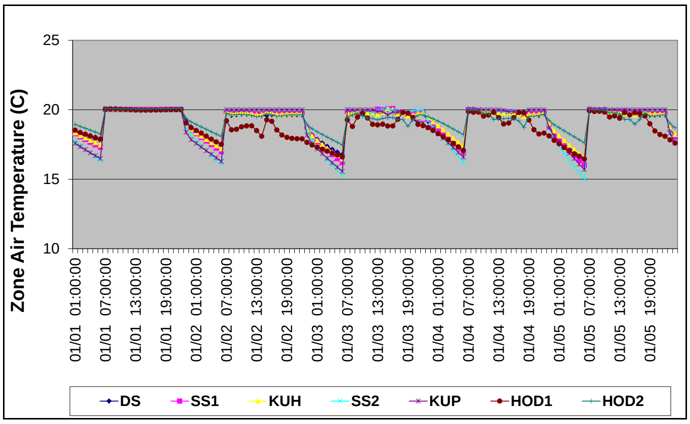


Figure 7 shows the total heating energy exchanged at heat exchanger (HE) during a simulation month – January. It can be concluded that the highest total heating energy is achieved during daily hours, when HVAC system operates.

Figure 7. Air Carbon Dioxide concentration (ppm) per hour calculated by EnergyPlus on January 1 st

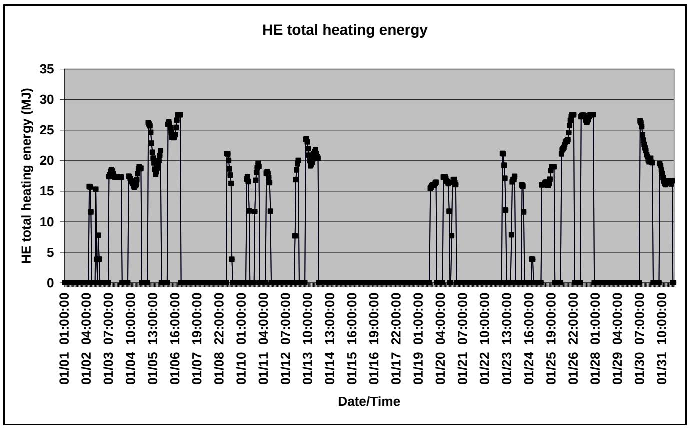
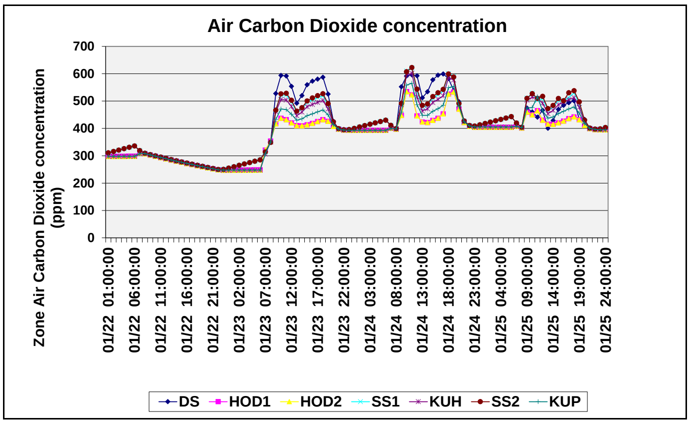


Figure 8 represent the Air Carbon Dioxide concentration (ppm) per hour, by mechanical ventilation in each simulated zone calculated by EnergyPlus on January 1st. The higher concentration of air carbon dioxide is for living room at the first floor and for the bedroom at the second floor, which have more occupants during the simulation period. But, the air carbon dioxide concentration is within the permissible limits (5000 ppm).

Figure 8. Total heating energy of Heat Exchanger during simulation month January



5. Conclusion

This paper represents the modeling of natural ventilation and HR mechanical ventilation system in residential building, by EnergyPlus software. EnergyPlus has great capabilities for modeling buildings energy behavior. Using EnergyPlus for modeling natural ventilation, it is possible to determine heat gains and heat losses during the ventilation, and also, to reduce these values by varying different parameters. Implementation of mechanical ventilation system with heat recovery is modelled, with the special attention to indoor air quality IAQ. Obtained results show that the performances of the ventilation systems, the ventilation design and the weather condition affect to the characteristics of the ventilation and the indoor air quality. Using HR in a ventilation system, the energy used for ventilation and space heating can be reduced and very good indoor air quality can be achieved.

Today, modern energy-efficient buildings require the installation of modern HVAC systems, and the use of heat recovery units is preferable because of the greater energy savings.

6. Acknowledgement

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