6th International Quality Conference
June 08th 2012
Center for Quality, Faculty of Engineering, University of Kragujevac

ESTIMATING THE INDOOR AIR QUALITY IN BUILDINGS WITH HEAT RECOVERY MECHANICAL VENTILATION SYSTEMS

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Abstract: *Today, the buildings sector represents more than 40 % of the total energy consumption in the European Union. A significant part of energy consumption in buildings relates to building ventilation. Heating, ventilating and air conditioning systems (HVAC) are essential for the maintenance of a comfortable and healthy indoor environment for building occupants. In order to reduce energy costs, the mechanical ventilation systems with heat recovery are designed. Ventilation is one method to maintain good indoor air quality. The primary functions of mechanical ventilation systems include the delivery of outdoor air to the occupants, the removal of indoor contaminants and the maintenance of thermal comfort conditions in the occupied zones. This paper presents a method of mechanical ventilation systems modeling in buildings by using software EnergyPlus, with the special attention to the indoor air quality (air temperature, relative air humidity, CO_2 concentration).*

Keywords: *Buildings, Mechanical ventilation, Indoor Air Quality, software EnergyPlus*

1. INTRODUCTION

Heating, ventilating and air conditioning systems (HVAC) are essential for the maintenance of a comfortable and healthy indoor environment for building occupants. In developed countries the HVAC systems consume around a third of the total energy consumption of the whole society. In hot and humid countries, the energy consumption to cool and dehumidify fresh ventilation air constitutes between 20% and 40% of the total energy consumption by HVAC systems [1].

On the other hand, energy saving in buildings is being strictly regulated by official requirements and local authorities. Nowadays, the role of heat gains in the energy balance of a building is becoming more and more important. The advances in thermal insulation and air-tightness of buildings' envelopes, which greatly reduce thermal losses and air infiltrations, increase ventilation requirements and, consequently, raise the thermal losses associated with the ventilation system. In a modern building, the ventilation losses may become more than 50% of total thermal losses [2]. Taking into account the above facts, the improvement of the efficiency in buildings ventilating systems to reduce their environmental impact constitutes a key issue.

The primary purpose of ventilation is to create optimal conditions, in terms of air quality and thermal comfort in indoor environments, for people living or working there, taking into account their health, comfort and productivity. The role of ventilation in residential buildings is mainly to maintain good air quality by diluting air pollutants. Today there is a variety of ventilation strategies in various

European countries. In some countries, uncontrolled air infiltration and window opening is often the only ventilation, while in others, passive stack ventilation systems are more or less used. In countries with colder climates, mechanical systems have been installed, which are with or without heat recovery units. The latter mode has been widely implemented since the energy crisis of 1973 [3]. Each system has its advantages, disadvantages and applications. The choice of ventilation system ultimately depends on indoor air quality requirements, heating and cooling loads, outdoor climate, cost and design preference.

Ventilation is required in buildings to provide fresh air to the occupants, avoid condensation due to a high indoor air humidity level and remove pollutants due to occupants or building materials. The traditional approach to ventilation is to provide a fixed minimum ventilation rate per person based on the maximum occupancy of a facility. To provide air quality guidelines, ASHRAE Standard 90.1 specifies the minimum ventilation rate of 2.5 l/s per person, while ASHRAE Standard 62-2004 has been revised to the minimum ventilation rate of 10 l/s per person [4]. The number of occupants in any facility varies over time, and it is rare that the facility is fully occupied. This provides a good opportunity to save energy by ventilating facilities on demand. Thus, the demand-control ventilation (DCV) is a commonly used strategy in HVAC systems based on signals from the indoor sensors, e.g., a CO2 sensor. Other sensors like the VOC (volatile organic compound) sensor, occupancy sensor, humidity sensor, particle sensor, and so on, are used to modulate the ventilation rate over time under various conditions.

Mechanical ventilation systems are widely used to maintain thermally comfortable environment and with satisfactory indoor air quality (IAQ) for the occupants [5]. In common practice, a certain percentage of recycled air is recirculated into the mechanical ventilation system and its particle concentration level is related to the couple effect of the particle deposition in ventilation ducts and dispersion inside rooms. On the other hand, the inlet particle concentration depends on both indoor particle generation rate and also the atmospheric particle coming in with the fresh air. These complex relations make it very difficult to compute the particle concentration in each part of the system. In order to simplify the calculation, most of the existing studies. Like the EnergyPlus software, used zero inlet particle concentration as the boundary conditions for indoor particle distribution calculation.

Indoor air quality is an important factor for every person living in a building. IAQ depends on the different parameters such as the outdoor air, the building location, number of people, and the ventilation system in the building. The ventilation system in the building improves the indoor air quality and at the same time it increases the cost of power consumption. The optimum ventilation level depends on the source strength of the air pollution [6]. The mechanically induced ventilation rate also depends on the number of people living in the building. Indoor air relative humidity level (RH) is also a measure of indoor air quality. By definition, higher relative humidity means higher moisture content (MC). Moisture in building envelopes can cause numerous problems, including the indoor air quality, of mold/fungi and bacteria growth, various health hazards for the occupants, infestation by insects, and deterioration of the building components.

The efficiency of HVAC systems may achieve an improved heat recovery (HR) by using the special type of heat exchangers (HEs) - air-to-air HR HEs. These units transfer energy from the exhaust air to the supply air and are applicable in both heating and cooling

situations. In air-to-air plate HEs, (discussed in this paper) the exhaust air from the building passes through one side of the HE while the fresh air from outside the building flows in a cross or counter-current flow through the other side of the HE. On that way, the outdoor fresh air can be heated by exhaust, inside air heat. The possible sensible and total HR depends on the properties of the plate material, as well as the climate and the operating period.
This paper analyze building ventilation system with HRunit - flat plate HE with the special attention to the indoor air quality (air temperature, relative air humidity, CO_2 concentration).

2. SIMULATION SOFTWARE - *ENERGYPLUS*

In this study, the simulation software EnergyPlus (Version 7.0.0) was used. EnergyPlus is made available by the Lawrence Berkley Laboratory in USA [3]. Its development began in 1996 on the basis of two widely used programs: DOE-2 and BLAST. The software serves to simulate building energy behavior and use of renewable energy in buildings. Other simulation features of EnergyPlus include: variable time steps, user-configurable modular systems, and user defined input and output data structures. The software has been tested using the IEA HVAC BESTEST E100-E200 series of tests [7].
EnergyPlus uses weather data from its own data base with weather files. Weather files have hourly or sub-hourly data for each of the critical elements needed during the calculations (dry-bulb temperature, dew-bulb temperature, relative humidity, barometric pressure, wind direction, wind speed, etc.) as well as some auxiliary data such as that for rain or snow.

To model the mechanical ventilation system in EnergyPlus environment, models of different components are used that are embedded in EnergyPlus such as ducts, fan, exhausts fan, flat-plate HE, mixer, splitter, air loop, outdoor air mixer, controller, exhausts air and fresh air.

3. MATHEMATICAL MODEL

3.1 EnergyPlus Model for ventilation system

A special part of EnergyPlus contains the airflow network model, which may simulate the performance of an air distribution system, including supply and return leaks, and calculate multizone airflows driven by outdoor wind and forced air during HVAC system operation. This detailed model is used to simulate thermal conduction, and air leakage losses for constant volume air distribution systems in either residential or light commercial buildings [8]. The airflow network model can simulate the heat and moisture gains or losses from the air distribution system itself (ductwork). The airflow network model consists of three sequential steps: (1) pressure and airflow calculations, (2) node temperature and humidity calculations, and (3) sensible and latent load calculations.

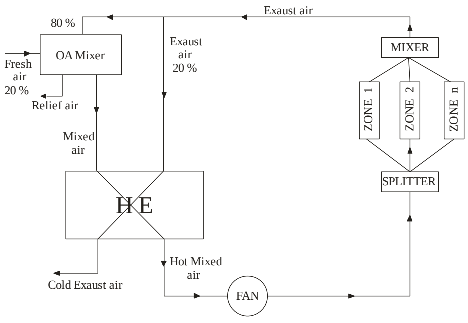

Figure 1 *- Simplified mechanical ventilation system with HR unit*

Fig. 1 represents a simplified schematics of the mechanical ventilation system with the HR unit.

Heat Exchanger. The airflow network

model may also have a HE component. The HE component models an energy transfer between the supply air stream and the exhaust air stream. The energy transfer is guided according to the effectiveness values that are specified by the user in the input data file. The air-to-air flat plate HE is an HVAC component typically used for exhaust or relief air HR. At this HEs, the exhaust air from the building passes through one side of the HE while the fresh air from outside the building flows in a cross or counter-current flow through the other side of the HE. On that way, the hot preheated fresh air in the rooms is obtained according to the user requirements.

Outdoor Air Mixer. The outdoor air mixer is the most common component used in an outdoor air system. The outside air mixer splits the return air of primary air system into relief and re-circulated air streams. Then, it mixes the outside air stream with the re-circulated air stream to obtain the mixed air stream. The outdoor air mixer has 2 inlet flow nodes: the return air node and the outside air node. It has 2 outlet flow nodes: the relief air node and the mixed air node. This is a passive component.

Air Loop. In EnergyPlus, an air loop is a central forced air HVAC system. The term “loop” is used because in most cases some air is re-circulated so that the air system forms a fluid loop. The air loop is just the “air side” of a full HVAC system. For simulation purposes the air loop is divided into 2 parts: the primary air system (representing the supply side of the loop) and the zone equipment (representing the demand side of the loop). The primary air system includes the following components: the supply and return fans, central heating and cooling coils, outside air economizer, and any other central conditioning equipment and controls. The zone equipment side of the loop contains the air terminal units as well as fan coils, baseboards, window air conditioners, and so forth.

Splitter. The splitter divides an inlet air stream into multiple outlet streams. The outlet air streams have the humidity ratio, pressure, enthalpy, and temperature set to that of the inlet air stream. The inlet air stream has the air mass flow rate set to the sum of the outlet air mass flow rates.

Mixer. The mixer combines multiple inlet air streams into a single outlet air stream. The air mass flow rate calculation is done for the maximum and minimum available mass flow rates.

3.2 Characteristics values

Pressure calculations. Newton’s method is used to solve node air pressures and it requires an initial set of values for the pressures. These initial values may be obtained by including in each airflow component a linear approximation relating airflow to the pressure drop:

$$\dot{m}_i = c_i \rho \frac{\Delta p_i}{\mu}$$

where $\dot{m}_i$ =air mass flow rate at i-th linkage (kg/s), c_i=air mass flow coefficient (m^3), Δp_i=Pressure difference across the i-th linkage (Pa), μ = Air viscosity (Pa·s).

Node Temperature Calculations. The following equation is used to calculate temperature distribution across a duct element at the given airflow rate and inlet air temperature:

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

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 element (°C) and U=overall heat transfer coefficient (W/m^2K).

Since the inlet temperature at one linkage is the outlet temperature for the connected linkage, the outlet air temperatures at all nodes are solved simultaneously. A square linear system assembled by the airflow network model is expressed below:

$$\{M\}[T] = [B]$$

where {M} = airflow matrix, [T] = temperature vector and [B] = given boundary conditions.

Node Humidity Ratio Calculations. The following equations is used to calculate humidity ratio distribution **at the given airflow rate and inlet air humidity ratio:**

$$\dot{m}\frac{dW}{dx} = U_m P(W_\infty - W)$$

Where $\dot{m}$ =air flow rate (kg/s), P=perimeter of a duct element (m), W = humidity ratio (kg/kg), W_∞ = humidity ratio of air surrounding the duct element (kg/kg) and U_m = overall heat transfer coefficient (kg/m^{2}s).

Since the inlet humidity ratio at one linkage is the outlet humidity ratio for the connected linkage, the outlet air humidity ratio at all nodes are solved simultaneously. A square linear system assembled by the AirflowNetwork model is expressed below [9]:

$$\{M_m\}[W] = [B_m]$$

where $\{M_m\}$ = airflow matrix, [W] = humidity ratio vector and $[B_m]$ = given boundary conditions.

Zone Air Carbon Dioxide Concentration The EnergyPlus as a report variable give us the Air Carbon Dioxide Concentration which represents the carbon dioxide 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 [9].

Sensible, total and latent HR rates. These values can be obtained by using next equations:

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

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

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 psychrometric routine. Latent HR can be obtained from upper equations:

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

4. RESULTS AND DISCUSION

Mechanical ventilation with a HR unit is modeled by EnergyPlus software. The mechanical ventilation is used in a house shown in Fig.2.

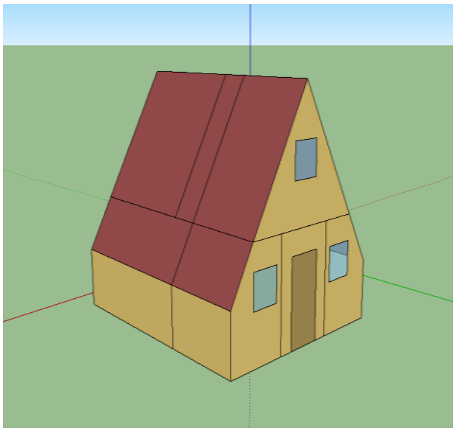

***Figure 2** – Modeled residential house*

The house consists of living room (DS), kitchen (KUH), bathroom (KUP) and anteroom (HOD1) at the first floor (Fig.3), and two bedrooms (SS1 and SS2), and anteroom (HOD2) at the second floor.

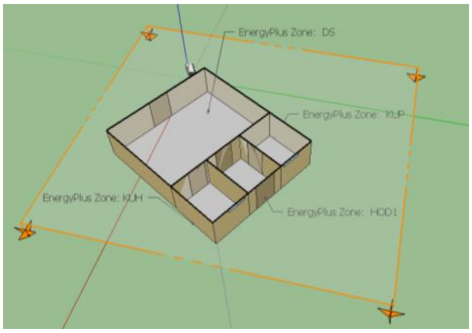

Figure 3 *– The intersection of the first floor*

Figure 4 represent the outdoor dry bulb temperature and zone air temperatures by mechanical ventilation with heat recovery, in each simulated zone calculated by EnergyPlus from January 1st-5th, as a functions of time. The thermostats in each zone regulates the temperature by their own schedules (20 ^{0}C).

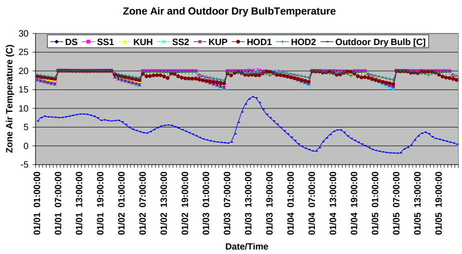

Figure 4 *– Outdoor dry bulb temperature and air temperatures calculated by EnergyPlus from January 1st-5th*

Figure 5 shows the air relative humidity in each simulated zone per hour by mechanical ventilation, calculated by EnergyPlus in 1st January, as a functions of time.

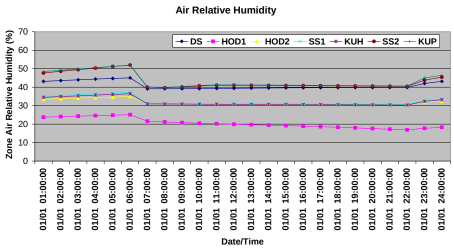

Figure 5 *–Air relative humidity calculated by EnergyPlus from January 1st*

It can be concluded that the smaller air relative humidity is achieved during daily hours, when HVAC system operates. Then, the need to deliver fresh air inside the house and for space heating is greater and than that during night.

Figure 6 represent the Air Carbon Dioxide concentration (ppm) per hour, by mechanical ventilation in each simulated zone calculated by EnergyPlus in 1st January as a function of time. The higher concentration of air carbon dioxide is for livingroom 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).

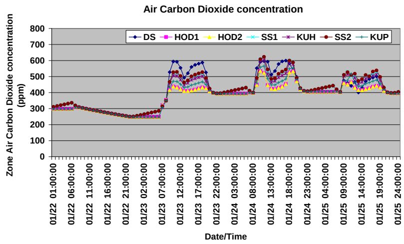

Figure 6 *–Air carbon dioxide concen–tration calculated by EnergyPlus from January 22nd-25th*

Figure 7 shows the total heating energy exchanged at 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.

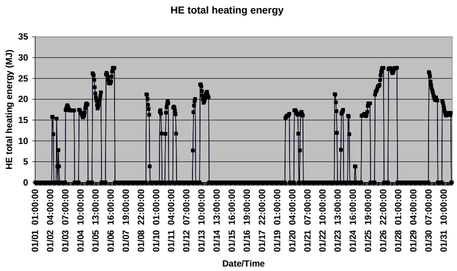

Figure 7 *– Total heating energy of HE during simulation month - January*

5. CONCLUSION

This paper represents the modeling of a HR mechanical ventilation system in commercial and residential buildings by EnergyPlus software, with the special attention to indoor air quality IAQ. These 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 indoor air quality is very good.

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Acknowledgment: This investigation is a part of the project TR 33015 of Technological Development of the Republic of Serbia and the project III 42006 of Integral and Interdisciplinary investigations of the Republic of Serbia. We would like to thank to the Ministry of Education and Science of Republic of Serbia for the financial support during this investigation.