ABSTRACT
In recent years, in the quest focused about energy conservative building design, as a high efficiency air conditioning scheme, the variable air volume (VAV) systems owe their growing popularity in heating, ventilation and air conditioning (HVAC) applications. This paper reports the simulation study to investigate the inherent operational characteristics of direct expansion (DX) VAV air conditioning (A/C) unit when the supply air fan and compressor speeds are varied based on the thermal load persisting in the conditioned space. Based on the Matlab-Simulink environment, a new fuzzy based simulation model of the DX VAV system has been developed and the energy utilization of the air conditioning system is investigated by incorporating the concept of combined economizer cycle (EC) and demand controlled ventilation (DCV) techniques into the simulated model. Indoor air quality (IAQ) is addressed under DCV and combined DCV-EC modes of ventilation. Simulation results obtained for the DX VAV A/C system are compared with the conventional constant air volume (CAV) system. The results infer that the fuzzy control methodology and algorithm developed are feasible with a proper control of IAQ being achieved. Variation of refrigerant mass flow rate corresponding to the variation of supply air flow rate is also investigated.

KEYWORDS
Energy conservation, fuzzy logic, IAQ, VAV, variable speed compressor

INTRODUCTION
The variable refrigerant volume (VRV) systems that vary refrigerant volume are basically large-capacity versions of ductless multisplit air conditioning systems. The revolutionary variable refrigerant volume systems first appeared in Japan in 1982 and are now used throughout the world. VRV systems circulate refrigerant directly to multiple evaporator units, rather than using water, as in contrast to conventional HVAC systems, to achieve heat transfer to the conditioning space. Energy savings can be achieved with a VRV system and it can be attributed to the system high part-load efficiency. Increased number of high rise apartment buildings and rapid increase in land cost paved way for variable refrigerant volume (VRV) technology to become increasingly attractive. It is fast replacing the traditional chilled water systems owing to its waterless operation, absolute flexibility and energy saving features. The VRV system modulates refrigerant volume according to capacity requirements. Many researchers have discussed the concept of fuzzy logic control dedicated to solve many real world applications. The effective utilization of fuzzy logic control for refrigerant distribution for multiple evaporating units of an air conditioning system was well expressed (Burn et al. 1999). Research on the cold store analysis was performed, making use of a variable speed compressor for refrigeration purpose, in which the speed of the compressor was modulated by employing the fuzzy logic control (Aprea et al. 2004). Performance prediction of a vapor compression heat pump using different ratios of refrigerant mixtures of R12/R22 was determined by utilizing fuzzy logic instead of expensive experimental study (Akcayol et al. 2004). Performances of variable refrigerant flow systems through an
experimental analysis in which a calorimetric test methodology was adopted for the VRF equipment to identify the heating or cooling emission of each indoor unit was estimated (Georges et al. 2004). A new variable refrigerant flow (VRF) module based on the Energy Plus simulation was developed and elucidated about the energy usage of VRF system (Wu et al. 2006). The retrofit capability of variable refrigerant volume system features enabling its integration into virtually any building, old or new, with the minimum of structural alteration was well described by (Brodrick et al. 2004). The dynamic modeling of individual components present in the DX VAV air conditioning system was explained and demonstrated (Shiming Deng and Wu Chen 2006).

SYSTEM DESCRIPTION

In order to develop and test the variable refrigerant volume system, a fuzzy controlled simulation model has been developed under Matlab-Simulink environment. The compressor speed can be modulated for varying condition of the suction pressure and supply air temperature. For a quite fluctuation in thermal load observed in the space to be cooled, the refrigerant suction enthalpy gets modulated and for this variation in enthalpy the corresponding mass flow rate of refrigerant supplied to the evaporator through EEV can be varied. For the combined DX VAV air conditioning system the set point temperature of supply air was determined to be 13°C and by utilizing a fuzzy logic controller the set point temperature of supply air was maintained precisely. The schematic representation of the energy efficient inverter DX VAV air conditioning (A/C) system equipped with fuzzy logic control unit is shown in Figure 1.

A variable air volume (VAV) air conditioning software laboratory building situated at Anna University, Chennai city in India, was considered for the simulation. The building zone was decided to be 33m x 8.5m x 2.9m of dimensions. The building has seven windows at each side and door with dimensions 0.91m x 1.83m and 0.91m x 2.13m. Cooling load calculations have been carried out for solving the heat load in the model. The construction materials and properties were selected according to the ASHRAE (American Society of Heating Refrigeration and Air Conditioning Engineers) handbook. The zone has 45 computers on each side and total occupancy of 95 people and lightning load was taken as per the ASHRAE Standards. A scale model (1.48 m x 1.75 m x 0.6 m) for the building and air handling system with fuzzy logic controller unit have been constructed in the refrigeration and air
conditioning laboratory at Anna University that confines to the numerical values obtained for the building. Due to the symmetry of the room, only a portion was considered for the analysis. This model is geometrically similar to full scale in all details that are important for the volume flow, the energy flow and the contaminant flow. The key components present in the scale model are thermally insulated air conditioned room model, inverter driven variable speed rotary compressor, electronic expansion valve (EEV), cooling coil, supply air fan, return air fan, velocity sensor, silicon-based NDIR CO₂ sensor, temperature sensor, fuzzy logic controller, fresh air damper, return air damper, exhaust damper and actuators.

FUZZY LOGIC CONTROLLER DESIGN

Fuzzy logic controller (FLC) a kind of Fuzzy Rule-Based System composed of a knowledge base (KB) that contains the information used by the proficient operator in the form of linguistic control rules. In Fuzzification process, the crisp values of the input variables are transformed into fuzzy sets that will be used in the fuzzy inference process. The inference system uses the fuzzy values from the fuzzification interface and the information from the KB to perform the reasoning process. The fuzzy-inference process essentially operates on IF-THEN rules that define the system behavior. Defuzzification takes the fuzzy action from the inference process and translates it into crisp values for the control variables. The structure of the fuzzy logic controller is shown in Figure 2. The fuzzy logic controller design utilized in this work included multi input and multi output parameters to control the DX VAV A/C system effectively. The error in supply air temperature and suction pressure of compressor were considered to be input variables that constitute for output variable in the form of modulated compressor speed.

![Figure 2. Structure of fuzzy logic controller](image)

a) Error in supply air temperature  
b) Suction pressure plot
Similarly, the duct static pressure and error in room temperature were another set of input parameters considered that corresponds to the varied fan speed that was obtained as the output from the FLC. In order to have a better control over proper ventilation air requirements, the FLC was tuned effectively by mapping the input variables like outdoor temperature and CO2 concentration over the damper opening position and that was the desired output required from FLC. Graphical illustration of the membership functions and their ranges for the input and output variables are shown in Figure 3. The range of the membership functions were selected according to the minimum and maximum values occurred. These ranges are defined in the interval of -25ºC to 5ºC for error in supply air temperature, 640kPa to 680kPa for suction pressure, 2000rpm to 6000rpm for compressor speed, 15ºC to 40ºC for outdoor air temperature, 300ppm to 2100ppm for CO2 concentration, and 0% to 100% for damper opening position. FLC was utilized to vary the compressor speed according to the room cooling load fluctuations. The process for determining the rules is to track the set point temperature with a minimum steady-state error. Fuzzy rules were generated for the DX VAV air conditioning system. For instance, when error in temperature is very high negative (VHN) and suction pressure is high then the compressor speed is maintained at high speed (HS). By using Matlab-Simulink environment, the designed FLC can be linked with the simulated model to evaluate the system performance. Centroid method was used to convert the fuzzy variable back to the output variable that can be varied according to the rules. Mathematical relation behind the centroid method is given by:

\[
Z^* = \frac{\int \mu(z)z \, dz}{\mu(z) \, dz} \quad (1)
\]
HVAC SYSTEM SIMULATION

The MATLAB-SIMULINK software package was used for the simulation purpose. The outdoor temperature variation is taken as per the meteorological department for the month of May and December, since May month and December month records maximum average and minimum average temperatures throughout the year. The summer and winter outdoor air temperature variation for 24 hours and the occupancy load pattern for the software laboratory is represented in Figure 4. The load pattern is noted for the real building and the pattern is drawn in terms of percentage, so that the pattern can be followed for both building and scale model. Figure 5 represents the schematic diagram of the Simulink model of DX VAV A/C system for the scale model developed.

![Image](image_url)

**Figure 4.** Outdoor temperature variation and occupancy load pattern

**Figure 5.** Simulink model of DX VAV A/C system based on FLC
Mathematical models
The mathematical models considered for simulation work are given below.

Variable speed rotary compressor (VSC)
The mass flow rate of refrigerant is represented by the equation,
\[ m_{\text{com}} = \lambda \frac{V_{\text{th}}}{V_{\text{vsuc}}} \] ---- (2)
The theoretical volumetric flow rate is found using the equation,
\[ V_{\text{th}} = 60 \times N \times \pi \times R^2 \times L \times e \left( \frac{2 - e}{R} \right) \] ---- (3)
where, \( h_1, h_2 \)– enthalpy of refrigerant, \( W_{\text{com}} \) – Compressor work.

Electronic expansion valve
The mass flow rate of refrigerant flowing through EEV is given by
\[ m_{\text{ev}} = A_{\text{ev}} \times \xi \times \left( \frac{P_c - P_e}{v_c} \right)^{0.5} \] ---- (5)

Building model
Mathematical Energy balance equations were framed for all the heat load components in the zones. The overall heat transfer coefficient, \( U \) and thermal capacitance \( C \) were taken from the building standards as per ASHRAE. All the energy balance equations were simplified in order to make the equations in matrix form under State-Space notation. The notation for State-Space model is presented by:
\[ \frac{dT}{dt} = AT + Bu \] ---- (8)
where \( A, B \) are matrices of coefficients, \( u \) is the input vector, \( T \) is the matrix of temperatures.

Well mixed model
To dilute sources from both the building and its occupants, the design ventilation rate (DVR) equation that contains people and floor area components is given by,
\[ \text{DVR} = V_{p} + V_{f} \] -----(11)
Based on the well mixed condition and applying the mass balance on the contaminant, the differential
equation relating contaminant concentration and time is given by,

\[ N(t) = G \cdot P(t) \quad -----(12) \]
\[ \frac{dC}{dt} = \left( C_S - C \right) Q_S v/v + G \cdot P(t)/v \quad -----(13) \]

where, \( v \) - Volume of the room; \( Q \) - Ventilation quantity; \( N \) - Contaminant concentration rate; \( P \) - Occupancy

RESULTS AND DISCUSSIONS

Simulink allows creating a block diagram representation of the system under study and running simulations very easily. Since MATLAB and SIMULINK are integrated, the mathematical model can be simulated, analyzed and revised in either environment at any instant. The outdoor temperature variations were taken as per the meteorological data pertaining to Chennai, India. A series of simulation were implemented for the performance comparison of the combined DX VAV systems and the simulation results presented involves the parameters that influence greater on the system operating conditions.

Figure 6. Variation of refrigerant mass flow rate

Figure 6 shows the influence of modulated refrigerant mass flow rate on compressor speed for the varying air flow rates. The mixed air from the mixing plenum imposed direct cooling load on the cooling coil and as the thermal load in the conditioned space gets changed the air flow rate corresponding to the cooling load was varied by the variable speed supply air fan. Based on Figure 6, it is observed that, as the air flow rate requirement varied between 7.93 cmm to 15.03 cmm, the refrigerant to be pumped by the compressor was modulated between 0.031 kg/s to 0.067 kg/s with compressor speed varying from 2510 rpm to 5190 rpm. This is because of the mass flow rate of refrigerant having a direct relation with compressor speed. A similar trend is observed when the load on the cooling coil is declined, the compressor speed gradually reduces and the mass flow rate of refrigerant requirement is also decreased. It is obvious that varying compressor speed would significantly change the power input to compressor. By varying the speed of supply air fan would also influence compressor power input since the fluctuated cooling load imposed on the cooling coil would alter refrigerant mass flow rate passing through the evaporator. Figure 7 shows the supply air temperature varying with respect to time and that is directly related to the cooling load prevailing on the cooling coil for the respective time interval considered. The supply air temperature was effectively maintained around 13°C using the fuzzy logic controller. As the supply air temperature is maintained almost constant, based on the simulation result, it inevitably express that, the cooling load prevailing in the building model is also controlled satisfactorily.

Figure 7. Variation of supply air temperature
In order to acquire a better indoor air quality, the carbon dioxide concentration present inside the conditioned space, due to change in occupancy levels, has to be controlled to a particular value, such that the fresh air delivered into the conditioned space will dilute the CO2 contaminant concentration and bring it to the permissible level. Figure 8 refers to the CO2 contaminant concentration observed from the conditioned space for varying occupancy levels. The simulation result infers that the CO2 concentration was maintained between 950ppm to 1040ppm under demand controlled ventilation technique and the CO2 concentration was maintained between 350ppm to 950ppm under DCV combined with economizer cycle ventilation scheme. Both the results suggested that, the CO2 concentration was observed to be under the permissible levels for the corresponding change in occupancy levels. The fuzzy logic controller maintained the CO2 concentration within the permissible limits by introducing the corresponding ventilation air quantity required to flow into the conditioned space through the control action given to the supply air fan. The variation of fan power and compressor power observed based on the simulation performed are depicted in Figure 9 and Figure 10 respectively. For the proposed DX VAV A/C system, under demand controlled ventilation scheme, both fan power and compressor power achieved the maximum value of 442W and 3.8kW respectively. During the demand controlled ventilation scheme, the variable speed compressor (VSC) consumed reduced power while compared with the constant speed compressor (CSC). This occurred because, during the DCV mode, only the required quantity of ventilation air based on the occupancy level and
CO₂ concentration persisted inside the conditioned space would be delivered into the mixing plenum, and this amounts for the net decrease of fan power consumption and cooling coil load compared to fixed ventilation. On the other hand, since the mass flow rate of refrigerant pumped by the compressor substantially reduced because of reduced cooling load, the input energy spent for compressor found to be declined and attributed towards energy conservation. Similar but enormous energy conservation potential was achieved under the DCV combined with economizer cycle ventilation scheme by the proposed fuzzy based DX VAV A/C system. In the combined DCV and economizer cycle ventilation scheme, the variable speed compressor was totally turned OFF during the economizer cycle, since the outdoor air temperature was found around the comfort conditions level and thus only the fan input energy would prevail.

CONCLUSIONS

The variable refrigerant volume system has been identified as one of the most promising energy saving technologies having abundant research and development opportunities. Computer simulation is regard to be a viable tool of appraising the building energy performance, refrigeration and air conditioning system features, and system operational strategies. It permits the users to validate their model and give a better idea of the operational characteristics of individual components present in the system. In this study, a new control technique for the building scale model considered was developed that utilized fuzzy logic concept incorporated into the Matlab-Simulink environment in order to assess the benefits of the DX VAV A/C system under cooling condition in terms of IAQ and energy conservation. Simulation results from the operational features of combined DX VAV system imply that the proposed DX VAV A/C system was the most energy efficient, compared with the conventional CAV A/C system. Simulation result also suggested that with the application of fuzzy logic, the supply air temperature was maintained precisely around 13°C by modulating the speed of compressor that greatly influenced the system performance. It is pertinent to note that by employing a variable speed compressor driven by inverter technology, much of the energy consumption can be reduced since compressor is the major component consuming enormous energy. Based on simulation, it is observed that the indoor air quality was well addressed that during demand controlled ventilation (DCV) mode the concentration level of contaminant CO₂ was maintained between 950ppm to 1040ppm and while economizer combined DCV mode was activated, the concentration of CO₂ was maintained between 350ppm to 950ppm. The simulation results exhibits that in both the modes of ventilation, the CO₂ level was well maintained below the permissible level as per the ASHRAE standard. Although the results presented were based on simulation, they were considered to be typical and representative for the operating strategy considered that was exhibited by varying both compressor speed and supply fan speed. This strategy may be preferably adopted for environmental control in places subjected to variable latent loads, such as the residential buildings located in hot and humid subtropical regions.

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NOMENCLATURE

\begin{align*}
A & \quad \text{heat transfer area, m}^2 \\
e & \quad \text{eccentricity, m} \\
h & \quad \text{enthalpy, kJ/kg} \\
L & \quad \text{axial length of cylinder, m} \\
m & \quad \text{refrigerant mass flow rate, kg/s} \\
N & \quad \text{rotational speed of compressor, r/s} \\
P_c & \quad \text{condenser pressure, Pa}
\end{align*}
P_e  Evaporator pressure, Pa
R  radius of cylinder, m
U  overall heat transfer coefficient, kW/m² K
v  specific volume, m³/kg
V  volume flow rate, m³/s
W  specific work, kJ/kg
\lambda  volumetric efficiency
\xi  valve flow coefficient
C_p  specific heat, kJ/kg K
C_d  coefficient of airflow
\rho  density, kg/m³

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