Improvement of Indoor Air Distribution by Utilizing Small Fans Powered by Solar Energy

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Abstract: A pilot-scale HVAC system is constructed to study the performance of air quality inside the comfort-zone when small fans are utilized to perform the air circulation. The research investigates the impact on energy consumption when the fan of the coil is eliminated from the fan coil unit (FCU). This would improve access to separate comfort zone controls and positively affect thermal comfort in those areas. In the study, the comfort room temperature variation is measured during 15 minutes in four cases, namely: all fans ON, all Fans OFF, 1-Fan ON, and 2-Fans ON. Optimization of the fan location that forces the zone temperature to stabilize around the set-point value in shorter time is recorded. Observation of the results indicates that the position of the fan does affect the time elapsed to reach the set-point as it affects the inside-air turbulence. Comparison of the four cases shows that the All-Fans-ON case cools down the zone temperature faster than other cases in entire space. In return, the space has fluctuated temperature in the cases of the 1-Fan and 2-Fans ON. This is due to the reduction in the turbulence intensity of the air near the Fan(s)-OFF region.

Keywords: HVAC, Renewable energy, FCU, Indoor-Air quality.

1 Introduction

Despite the negative effect of fossil fuel on the environment, it still monopolizes the global energy utilization. However, many countries seek alternative non-polluted sources to sustain the rapid demand for energy. The world primary energy demand will increase by almost 60% from 2002 to 2030, and the average annual increase percentage is 1.7% per year [1-4]. Such energy demands are mainly consumed by HVAC systems. Recent data obtained from Saudi Electricity Corporation has shown that HVAC systems in residential and commercial buildings consume about 65% of total power production [1].

The overall energy efficiency and indoor environmental quality of new and existing buildings are significantly influenced by the effective operation of the building’s heating, ventilating and air conditioning (HVAC) system. Achieving high performance in today’s buildings requires HVAC systems to operate under optimal conditions and with minimal energy consumption. The need of energy management to reduce the energy consumption in such buildings becomes crucial not only because of the end-of-the-month bill, but also for risk-free environment issues.

Although a robust renewable energy, solar power is currently supplying merely a small portion of global energy demands. Its use can be expanded to power specialized air conditioning systems which could replace current systems that consume a significant amount of electricity and are environmentally unsustainable. Using solar as an alternative power source will decrease electricity requirements, lower operational costs, and reduce the GHG (greenhouse gas) emissions [5].

Numerous technologies using renewable energies have been employed, and several dissimilar prototypes have been tested for this purpose, however, marketing these technologies is still a challenge due to economical, unpractical, or unreliable reasons [6,7]. Since fan coil units (FCUs) in air conditioning systems are the main sources of energy consumption in HVAC systems, it becomes essential to wisely manage the unit for minimal operation and energy consumption [8, 9, 10]. The traditional system could even comprise two or three individual fan coil units and as many as a few thousand individual units. These FCUs, normally installed above the false ceiling, and distributed around the building contribute to high energy consumption as well as increased noise levels [1]. Each provides air conditioning to the particular area of the building in which they are located.

The study experimentally investigates the impact on energy consumption when the large fan of the fan coil unit (FCU) is eliminated. Instead of large central fan, indoor air is distributed using small fans powered by solar energy mounted inside each interior comfort zone. This would improve access to separate comfort zone controls and positively affect thermal comfort in those areas. Enhancement of the heat transfer between the circulated water and the air in the zone is also of interest.

The proposed technology will not only substantially reduce energy consumption and alleviate greenhouse gas emissions caused by fossil fuel use; it should also reduce the noise produced by the fan of the unit that shares the same space.

The factors affecting indoor environment mainly include temperature, humidity, air exchange rate, air movement, ventilation, particle pollutants, biological pollutants, and gaseous pollutants. The small individually spaced fans enhance the turbulence in the zone, speed up the reduction in zone temperature as well as the air exchange rate, and reduce the resident time of fine and ultrafine particles that are released by indoor pollution.

2 Pilot-Scale mini-System

Preliminary research using a small scale building equipped with simplified unit has been completed at Prince Mohammed bin Fahd University (PMU), Figure 1. We successfully developed the experimentation, collected necessary data, and performed comparative analyses.

The system (illustrated in Figure 2) consists of: i) 5.25 ft x 5.25 ft x 4.27 ft (1.6 m x 1.6 m x 1.3 m) glass-made box, ii) radiator coil, iii) refrigeration system, iv) pump, v) Solar system with Dc/AC convertor, and vi) three small fans. The box is covered by a wood-made plate. The thickness of the glass is 1 cm while the covering wood is 2 cm. The solar system provides power to the fans as well as the pump. The pump circulates the chilled water throughout the radiator which in turns supplies cold air to offset the load of the box. Three temperature measurements with ±1 ºC precision are mounted on the inner walls near the fans to detect the air temperature and optimize the fan speed.

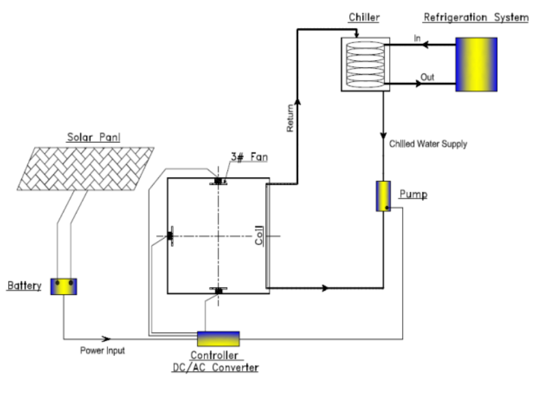

Figure 1. Laboratory-Scale system

Figure 2. Experimental Test Rig

External pipes are connected to the coil with straight joints at the two ends. Other than the radiator coil, insulation was applied to the external pipes to avoid any heat gain/loss from the surroundings. Thermal insulation material covers the top of the box to minimize the heat transfer with the surroundings.

The pump and the ball-valve regulate the flow of fluids inside the coil. The ball-valve is specifically designed to maintain a particular flow rate of fluid flowing within the coil when the pump is under operation.

During the experiment, the fluid flowing inside the radiator coil absorbs heat energy from the interior air of the box. The inlet/outlet water temperatures are measured using the installed digital thermometers. Similarly, the inlet/outlet pressures were also measured using installed pressure transducers. Important data were captured after every moment and recorded for 15 minutes or until steady state occurs.

3 Tests Implementation

The integrated system has first been tested for inspection. Pump/pipes water leakage is checked. Water circulation, A/C temperature controller, and coil inlet/outlet temperature sensors are monitored. Having completed system inspection with no malfunction, the first test is conducted for the case of “ALL-FANS ON”. Time/temperature data are recorded for each fan per minute using the digital screen attached to each fan. Once the fan temperature sensor reads the set point, the fan will automatically be switched off for optimization purpose. Each fan has its own sensor, which measures the air temperature nearby the fan. As the fan turned off, the internal and/or external heat load will force the temperature of the air adjacent the fan to cross the set-point limit. Hence, a signal will be sent to the fan motor to switch ON.

Three more tests are also conducted for other cases: i) Two-Fans under operation; ii) One-Fan under operation, and iii) ALL-FANS OFF. Recorded data are then tabulated and analyzed to demonstrate the time span required to reach the comfort set point.

4 Coil Sizing and Rating

An actual thermal analysis is performed by theoretical approach for the following requirement. Heat transfer requirement is decided as per room specification, atmospheric conditions and Cooling load estimation. Cooling system design should fulfill all these requirements.

The ultimate purpose of the thermal analysis of heat exchanger is to determine heat transfer surface area (sizing) and performance calculation to determine heat transfer rate (rating). It is necessary to find out the amount of heat transfer, outlet temperatures of both fluids. ε-NTU method is based on the concept of heat exchanger effectiveness. Here approximate size is assumed according to the space availability. Based on this size heat transfer rate is calculated which should fulfill the requirement. Radiator coil size and heat transfer rate are finalized accordingly.

The convection heat transfer coefficient of the chilled water side is calculated pursing the following mathematical expressions:

1. Hydraulic Diameter

$$D_{h(w)} = \frac{4A_p}{P_p} \quad (1)$$

2. Reynolds Number

$$Re_{(w)} = \frac{V_{av} D_h}{\nu_w} \tag{2}$$

3. Nusselt Number

$$Nu_{(w)} = 0.023 Re_w^{0.8} Pr_w^{0.4} \tag{3}$$

4. Heat Transfer Coefficient

$$h_{(w)} = \frac{Nu_w k_w}{D_{h(w)}} \tag{4}$$

Indoor air side heat transfer coefficient, however, is determined using the following steps:

1. Hydraulic diameter

$$D_{h(a)} = \frac{4C_d A_{r(a)}}{A_a} \tag{5}$$

2. Reynolds number

$$Re_{(a)} = \frac{V_a D_{ha}}{\nu_a} \tag{6}$$

3. Colburn factor

$$J = \frac{0.174}{Re_a^{0.383}} \tag{7}$$

4. Heat transfer coefficient

$$h_{(a)} = \frac{J \times V_a \times Cp_{(a)}}{Pr_a^{2/3}} \tag{8}$$

Heat rejection calculations:

1. Factor to calculate fin efficiency

$$mL = \left(\frac{2h_{(a)}}{k_{fin} \times t_{fin}}\right)^{0.5} \left(\frac{H_{fin}}{2}\right) \tag{9}$$

2. Fins efficiency

$$\eta_{fin} = \frac{\tanh(mL)}{mL} \tag{10}$$

3. Total surface temperature effectiveness of fins

$$\varepsilon_{(fin)} = 1 - (1 - \eta_{fin}) \times \frac{A_{fin}}{A_a} \tag{11}$$

4. Overall thermal resistance

$$R = \frac{1}{\varepsilon_{(fin)} h_{(a)}} + \frac{1}{\left[\left(\frac{A_p}{A_a}\right) * h_{(w)}\right]} + \frac{t_{pipe}}{k_{pipe}} \tag{12}$$

5. Overall heat transfer coefficient

$$U = \frac{1}{R} \tag{13}$$

6. Indoor air stream thermal capacity

$$C_{(a)} = \dot{m}_a \times Cp_a \tag{14}$$

7. Water thermal capacity

$$C_{(w)} = \dot{m}_w \times Cp_w \tag{15}$$

8. Heat capacity ratio

$$c = \frac{\text{minimum}\ \left(C_{(a)}, C_{(w)}\right)}{\text{maximum}\ \left(C_{(a)}, C_{(w)}\right)} \tag{16}$$

9. NTU

$$NTU = \frac{U * A_a / 2}{\text{minimum}\ \left(C_{(a)}, C_{(w)}\right)} \tag{17}$$

10. Coil effectiveness

$$\varepsilon_{coil} = 1 - \exp\left\{\frac{NTU^{0.22}}{c}\left[\exp\left(-c * NTU^{0.78}\right) - 1\right]\right\} \tag{18}$$

11. Total heat transfer rate

$$Q = \varepsilon_{coil} \times \text{minimum}\ \left(C_{(a)}, C_{(w)}\right) \times \left(T_{i(a)} - T_{i(w)}\right) \tag{19}$$

12. Chilled water outlet temperature

$$T_{o(w)} = T_{i(w)} + \frac{Q}{C_{(w)}} \tag{20}$$

13. Anticipated outlet temperature for indoor air

$$T_{o(a)} = T_{i(a)} - \frac{Q}{C_{(a)}} \tag{21}$$

5. Results Analysis

Transient response of the system is the prominent of the study. Four cases are compared regarding the elapsed time required to reach the comfort set-point.

5.1 Case-I All Solar Fans ON

Figure 3 illustrates the temperature variation in the comfort zone as a function of time for the three mounted sensors at different locations. The set-point temperature is adjusted to be 73.4°F (23°C) while the initial temperature is set to be 104°F (40°C). The time interval is chosen to be 2 minutes for recording the zone temperature.

As expected, the zone temperature drops exponentially to reach the set point for all sensors. It can also be concluded that no time-lag has occurred among the three locations as all sensors are read same values every time interval. The temperature decreases periodically and after 12 minutes the temperature of all fans became 73.4°F (23°C). As such, all the fans switch to OFF mode automatically. The situation lasts 4 minutes before one of the sensors has ordered its corresponding fan to switch to ON as the air-temperature there passed 77°F (25°C) (the upper range of the set-point).

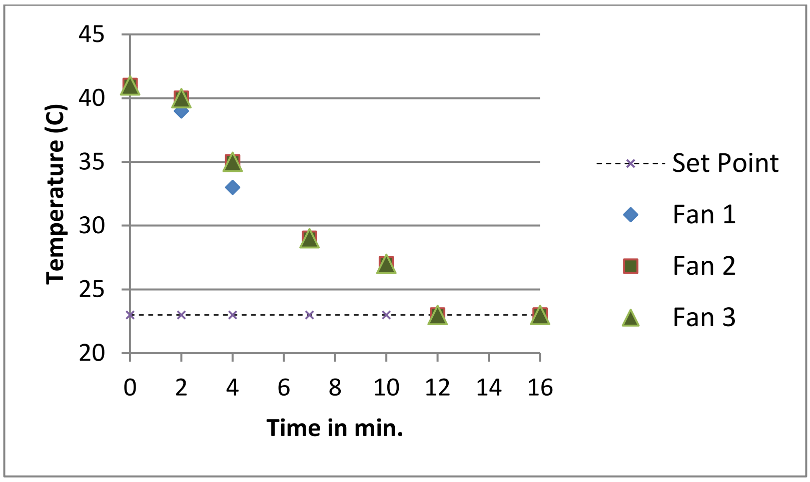

Figure 3. All Fans ON

5.2 Case II One-Fan OFF

By setting one of the fans to OFF-mode permanently, the elapsed time required to reach the set point has increased (Figure 4). In fact, after the same period of the case I (i.e., 12 minutes), the zone temperature has barely dropped the thirties. Figure 4 illustrates the temperature variation for the first 16 minutes. Since FAN-2 is mounted at a distance from the coil farther than FAN-1, the air temperature near FAN-2 drops slower. This is attitude to the reduction in air turbulence as a result of switching FAN-3 off.

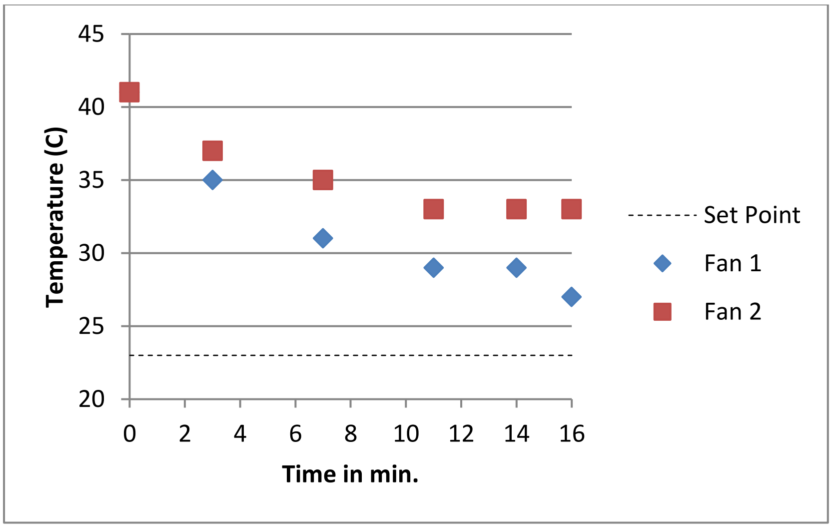

Figure 4. One Fan OFF

5.3 Case III One-Fan ON

Figure 5 depicts the condition of the comfort zone when two of the three fans have switched to OFF. The situation becomes worst as the major part of the zone didn't pass 86°F (30°C). The temperature of the room after 16 minutes sets only at 84.2°F (29°C) while at the other previous cases were 73.4°F (23°C) and 80.6°F (27°C) respectively.

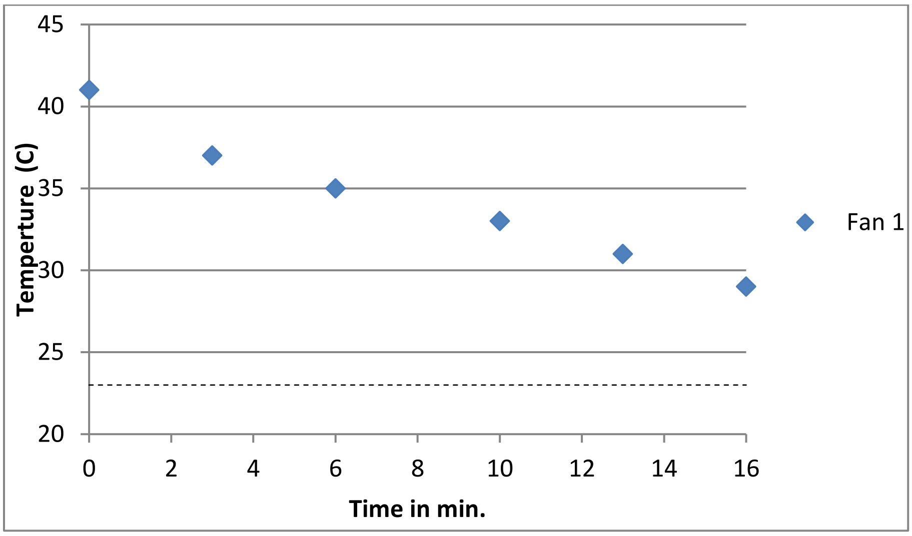

Figure 5. Two Fans OFF

5.4 Case IV All-Fans OFF

Switching to natural convection mode by turning all fans OFF causes insignificant drop in the zone temperature. As shown in Figure 6 the temperature decreases by only two degrees after 16 minutes of operation.

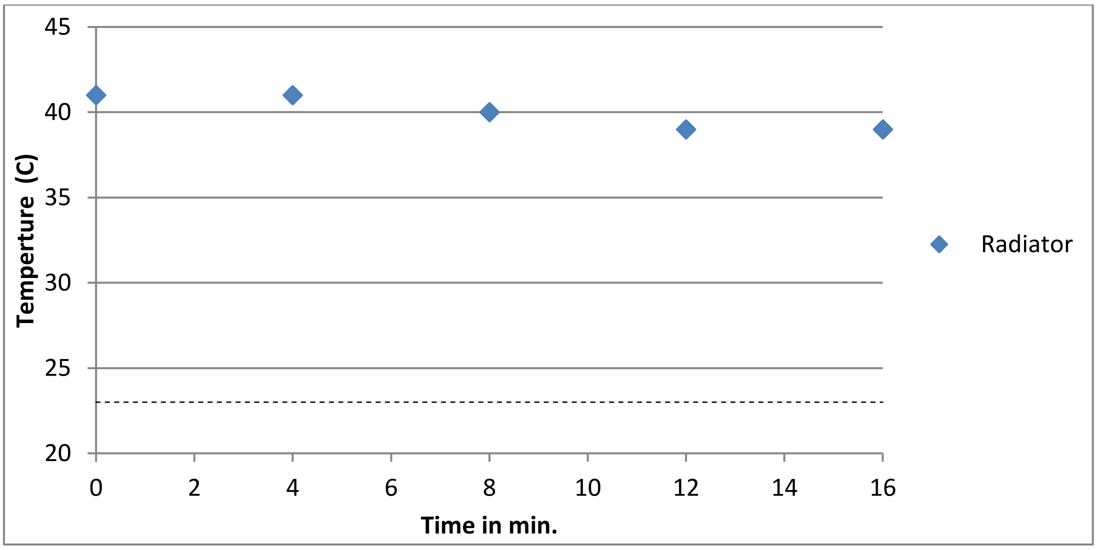

Figure 6. All Fans OFF

6 Conclusion

An experimental study is conducted to enhance the indoor air quality of a comfort zone using small solar-powered fans instead of the large central fan. The coil unit is designed to condition the interior zone of a pilot scale room and utilizes three small, solar-powered, fans to achieve the task. The small fans are installed on the interior walls facing the coil unit. The separated fans provide complete air circulation which would improve indoor air quality.

Observing the experiment outcome, the system was shown to be energy efficient since the air turbulence achieved by the solar fans has proved to be sufficient to drop the zone temperature by 17°C after only 12 minutes of operation. Optimization of the number of the fans has shown that three-fans mounted on each of the side walls facing the coil are the minimum to avoid any temperature fluctuating. Otherwise, instability in the zone temperature will be occurred. Also, operating the system with no-fan ON (i.e. natural convection) leads to very slow dropping in the room temperature.

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