4713

Development of Energy-Efficient Single-Coil Twin-Fan Air-Conditioning System with Zonal Ventilation Control

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ABSTRACT

Indoor air quality (IAQ) is strongly affected by the various sources of indoor pollutants and the efficiency of the ventilation system. Higher ventilation demands pose an enormous energy penalty, particularly in the tropics, and this paper presents a new method of air conditioning that addresses both IAQ and energy issues. The newly developed energy-efficient method of air conditioning involves the independent control of temperature and humidity of two different airstreams. It is further enhanced to incorporate a new method of air distribution for independent control of ventilation air quantity at acceptable temperature and humidity conditions in congruence with the overall environmental conditions in the indoor space so that the desired setpoint conditions in the occupied space are achieved at all times of operation. Recent findings are encouraging, and adequate ventilation provision in different zones based on respective demand is observed with a potential to save energy up to 12% in the tropics.

INTRODUCTION

The quality of air in the indoor environment is strongly affected by the various sources of indoor pollutants and the ability of the ventilation system in diluting the indoor air of these pollutants. Although health and thermal comfort issues usually can be addressed by attempting to eliminate the various sources of indoor pollutants, it is almost impossible to totally eliminate them. It is thus inevitable that ventilation with outdoor air should play an important role in the eventual quality of the air in the indoor environment, and ANSI/ASHRAE Standard 62-2001 specifies a minimum ventilation provision of 10 Lps per person at all times of operation (ASHRAE 2001). Several studies involving the role of ventilation in ensuring good IAQ have been done in the past, and clear associations between the two have been established (Seppanen et al. 1999; Wargocki et al. 2000). The importance of effective ventilation distribution has also been investigated in the context of the outdoor air being available at the occupied breathing zone (Sekhar et al. 2000). In certain climatic conditions, such as the tropics, air conditioning is dictated by the stringent requirements of cooling and dehumidification, which becomes a challenge to the designer who is usually confronted with cost-effective design criteria to address thermal comfort, indoor air quality (IAQ), and energy issues. The high energy penalty of cooling and dehumidification associated with ventilation in the tropical context is apparent from the large enthalpy difference that exists between the outdoor air and the indoor air conditions (Luxton and Marshallsay 1998). Inadequate ventilation would almost invariably lead to a deterioration of the indoor air quality due to a buildup of indoor pollutants, and adequate ventilation with poor dehumidifying performance of the cooling coil would be even worse, as it is likely to result in elevated humidity levels in the air distribution systems and the occupied zones (Sekhar et al. 1989). This phenomenon could be considered in the context of humidity as an "indoor" pollutant, which propagates the origin and sustenance of microbial contamination. The issue of high indoor humidity levels in tropical buildings originates from the high ambient humidity levels in the ventilation air (outdoor air) and the need to provide adequate ventilation to avoid problems associated with "sick building syndrome." Therefore, the fundamental objective is to provide an air-conditioning system with superior indoor environmental performance that is achieved in an energy-efficient manner.

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In the design of ventilation systems, it is not sufficient to ensure an adequate provision of total outdoor air quantity at the outdoor air intake of an air-handling unit (AHU), but it is equally important to consider the related ventilation characteristics. It is essential that the outdoor air reach the localized "breathing zone" of the various occupied zones served by the particular AHU in the correct proportion and maintain the desirable local air exchange effectiveness characteristics at all times. As the occupancy profile in the various localized zones of an indoor environment can change quite significantly during the course of operation of an AHU on a daily basis, it becomes necessary to incorporate the response of ventilation systems to such dynamically changing profiles to ensure adequate ventilation provision at all times without excessive energy consumption. Conventional designs of air-conditioning and mechanical ventilation systems resort to mixing of the centralized outdoor air intake and the recirculated air before being treated by the cooling coil and subsequently distributed to the various occupied zones as "mixed air." The disadvantage of such designs, particularly with VAV systems, is fairly well established, resulting in complaints of inadequate ventilation, leading to perceptions of staleness and stuffiness. Such complaints are inevitable due to the inability of these typical designs of VAV systems to maintain adequate outdoor air distribution to the dynamically changing occupancy and "other" space load profiles, as any reduction of total supply air flow results in a reduction of outdoor air quantity.

Demand-controlled ventilation (DCV) strategies are potential solutions in addressing issues related to inadequate ventilation. One of the studies has shown that energy savings from DCV control approaches ranged from 5% to 80% in comparison to fixed ventilation strategy (Emmerich and Persily 1997). A CO_2 sensor will consider the contribution of infiltration in a space and only require the mechanical system to make up what is necessary to meet the required ventilation, and this would add on to the savings (Schell and Int-Hout 2001). Under unpredictable and varying human occupancy conditions, CO_2 sensor-based DCV strategy has been shown to have an energy savings potential of up to 50% (Fisk and Almeida, 1998).

Proper distribution of ventilation air to the space is a function of VAV boxes' minimum settings, space sensible loads, local exhaust and exfiltration, short circuiting paths, and interzonal air transfer (Mumma and Lee 1998). When the multiple spaces equation of ASHRAE Standard 62-2001 is used, generally 20% to 70% more outdoor air is required in an effort to ensure proper ventilation air distribution in all air systems than is required with dedicated outdoor air systems (ASHRAE 2001). The inability to decouple the space sensible and latent loads to high space relative humidity at low sensible loads in the occupied spaces is yet another concern in any typical conventional system. These inabilities found their solution through having separate outdoor air systems to handle space latent loads as well as the varying ventilation requirements. Research attempts on the use of a separate outdoor air system started with Meckler in 1986, and subsequent works were carried out by Scofield and Des Champs (1993), Brady (1997), Mumma and Lee (1998), and others. A dedicated outdoor air system (DOAS) is a 100% outdoor air, constant volume system designed to deliver the volumetric flow rate of ventilation air to each conditioned space. It is used to place the required and conditioned ventilation air directly into the space without first mixing it with stale building air as is the current practice, thus always meeting the requirements of ASHRAE Standard 62. A general layout of the DOAS, consisting of a preheat coil, an enthalpy wheel, a deep cooling coil, a sensible heat exchanger, and the prime movers, has been discussed by Mumma and Shank (2001).

Conventional air conditioning and air distribution systems seldom consider the relative importance of the following two components of the conditioned air:

- the primary outdoor air required for ventilation
- the secondary recirculated air required for offsetting thermal loads

As the function of each of the above two components is quite different from each other, and as each component is affected by different factors, it is logical to treat them as two separate airstreams. The notion of separate airstreams involving dual-duct concept typically consists of hot and cold airstreams. The concept of dual-duct air-conditioning systems is well established from the perspective of better thermal conditions in the occupied zones. Simulation results of a large retail store using a dual-duct system in comparison with a conventional single-path system showed that the dual-path system provided 14% to 27% annual energy savings and 15% to 23% smaller equipment tonnage (Khattar 2002).

Research attempts on dual-duct systems showed improved air quality by providing needed ventilation to the space while maintaining desired temperature and excellent indoor humidity control at all part-load conditions (Khattar 2002). A ventilation air-conditioning (VAC) system proposed by Coad (1999) is a 100% outdoor air system, and it would provide all the ventilation air required. In combination with this, a space temperature control (STC) system was designed for sensible cooling and for control of the thermal comfort aspects of the space except the humidity level. It has been shown that properly designed systems based upon the concept would provide an extremely high degree of indoor air quality and thermal comfort for general space conditioning (Coad 1999).

The single-coil twin-fan (SCTF) system proposed in this paper is a dual-duct system employing a unique compartmented coil that has the capability of simultaneously and independently controlling the "off-coil" temperatures of the outdoor air and the recirculated airstreams and thereby maintaining a fixed supply air temperature at all times.

In typical cooling and dehumidifying coil designs, an airstream at certain operating conditions passes over the tubes and fins of the coil, and chilled water passes through the tubes of the coil, each pass of the chilled water entering at a certain supply temperature and leaving at a certain recirculated temperature. The psychrometric performance of the cooling coil results in a certain leaving air condition. In the event of two different airstreams being conditioned, two separate coils would typically be employed with either *parallel* or *sequential* feed of chilled water. Efforts have been directed in the past to achieve energy-efficient dehumidifying performance by addressing the air velocity across the coil, the chilled water velocity through the tubes of the coil, and various configurations of the physical geometry of the coil (Shaw and Luxton 1988; Sekhar et al. 1989; Luxton and Marshallsay 1998).

This paper describes the development of a new method of *conditioning* and distributing air through the multiple zones of an air-conditioned building such that adequate ventilation and, consequently, acceptable indoor air quality (IAQ) is ensured throughout the operating range of a variable air volume (VAV) air-conditioning system. It is also aimed at providing the necessary ventilation while optimizing energy consumption, realizing the complete energy-saving potential of a VAV system.

CONCEPTUAL FRAMEWORK

The new method of air conditioning involves the cooling and dehumidification of the outdoor and the recirculated airstreams separately through separate compartments of a single cooling coil without mixing them during their flow through the coil, and the new method of distribution involves transmitting the two airstreams separately until they reach a modified VAV box in the occupied zone. The conceptual framework of the newly developed single-coil twin-fan (SCTF) air-conditioning and air distribution methods is presented in Figure 1 and is now described in detail. The psychrometric performance of the compartmented coil of an SCTF air-conditioning system is presented in Figure 2.

SCTF Air-Conditioning Method

The SCTF air-conditioning method is a method of air-conditioning in which the temperature and humidity of the outdoor and the recirculated airstreams are independently controlled while passing through the compartmented cooling and dehumidifying coil. This naturally implies that the compartmented coil encounters two distinctly different streams on the air-side, while being provided with the same flow on the coolant-side. The SCTF system is composed of an air-handling unit consisting of two separate sections for the flow of air on either side of the coil so that the two airstreams are always maintained separate and unmixed. It has a single cooling coil located in the air-handling unit between the upstream and downstream of the two different airstreams, as illustrated in Figures 3a and 3b. A thermally insulated sheet metal barrier is to be provided to separate the two airstreams and, in particular, suitably modified to interface with one of the plate fins of the coil to maintain the independent and unmixed characteristics of the two airstreams through the coil. The compartmented coil configuration provides flexibility in employing different numbers of rows in the two compartments, as shown in Figures 3a and 3b, a feature that is envisaged to play an important role in design flexibility and in the selection of coil to address the two distinct loads that are encountered. The two different airstreams are operated by their respective VAV fans, thereby decoupling the operation and control of the outdoor air fan from that of the recirculated air fan. The various components of the SCTF air-conditioning system are presented in Figures 4 and 5, and a working model of the system is presented in Figure 6. The cooling coil, being common to both airstreams albeit separated on the air-side, is controlled by a modulation of the coolant flow rate based on a signal from either of the outdoor airstream or the recirculated airstream. The coolant flow through the common compartmented coil is such that both the outdoor and the recirculated airstreams encounter each pass of the coolant feed. However,

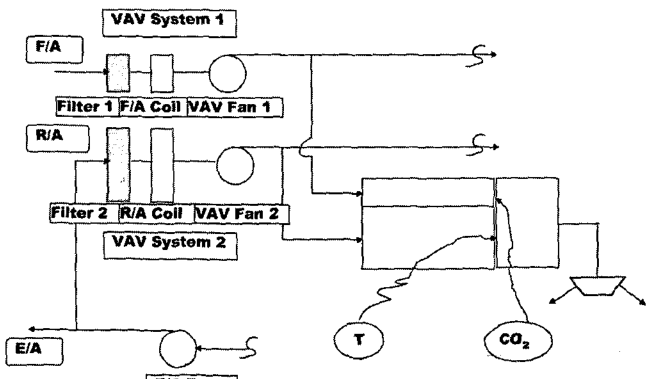

Figure 1 *Compartmented coil in a single-coil twin fan (SCTF) system with zonal ventilation control.*

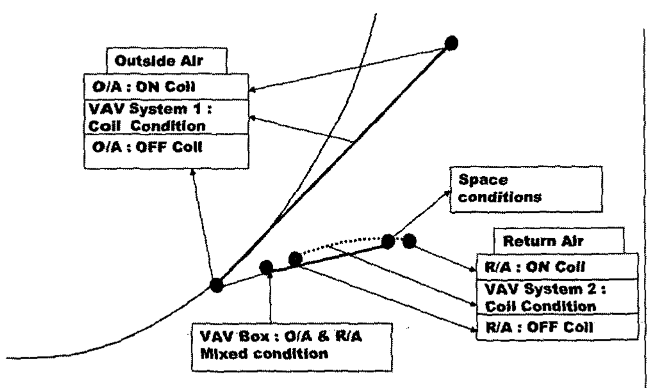

Figure 2 *Psychrometric performance of the compartmented coil in a single-coil twin fan (SCTF) system with zonal ventilation control.*