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Article *in* Intelligent Buildings International · February 2013

DOI: 10.1080/17508975.2013.778192

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Intelligent Buildings International
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/tibi20

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Version of record first published: 08 Apr 2013.

To cite this article: Jori Reijula, Rauno Holopainen, Erkki Kähkönen, Kari Reijula & Iris D. Tommelein (2013): Intelligent HVAC systems in hospitals, Intelligent Buildings International, DOI:10.1080/17508975.2013.778192

To link to this article: http://dx.doi.org/10.1080/17508975.2013.778192

Intelligent Buildings International, 2013
http://dx.doi.org/10.1080/17508975.2013.778192

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REVIEW ARTICLE

Intelligent HVAC systems in hospitals

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(*Received 7 August 2012; final version received 17 February 2013*)

Increasing interest has been expressed towards intelligent heating, ventilation and air conditioning (HVAC) systems in hospital environments. This article presents a literature review of intelligent HVAC systems used in hospitals. First, we discuss the current state of HVAC systems and common ventilation issues regarding modern hospitals. Second, we describe hospital airflow modelling using computational fluid dynamics. We then define 'intelligent HVAC systems' and address challenges concerning their design and implementation. Lastly, possibilities for HVAC system optimization and energy conservation are presented.

Keywords: energy conservation; hospital; HVAC; indoor air quality; infection control; intelligent

Background

Hospitals require efficient heating, ventilation and air conditioning (HVAC) systems to maintain good indoor air quality (IAQ), aseptic conditions, and to secure healthy, safe and suitable indoor thermal conditions (i.e. temperature, humidity, air quality and airflow) for the hospital personnel and the patients (Kalliokoski, Luscuere, and Streifel 2003; Balaras, Dascalaki, and Gaglia 2007). Owing to various types of facilities, delicate nature of hospital work and infection-prone patients, hospitals require more specialized, state-of-the-art HVAC solutions than most buildings (Hellgren et al. 2011). For example, hospital operating theatres (OTs) have very strict IAQ requirements, while, by contrast, hospital offices have practically the same requirements as any regular offices. Factors such as low ventilation rate, inadequacy of building HVAC systems, use of certain building materials and overcrowding, may result in indoor air pollution (Yocum, Cote, and Benson 1977). Standards for hospital indoor air have not been established in most countries (Tang et al. 2009), but for example in Europe, standards for hospital indoor air are currently being developed.

Hospital ventilation must be effective for controlling airborne transmission and preventing outbreaks of infectious diseases (Wehrle et al. 1970; Li et al. 2004; Qian et al. 2006). A correlation exists between ventilation, air movements in buildings and the transmission of infectious diseases (Mendell et al. 2002; Li et al. 2007). Poorly designed, maintained (i.e. contaminated) and used HVAC systems are common in hospitals and often lead to poor IAQ (Hellgren and Reijula 2006). This may cause sick building syndrome (SBS), various occupational hazards and hospital-acquired infections such as SARS, tuberculosis, chickenpox, smallpox, varicella, influenza and measles (Seltzer 1994; Kumari et al. 1998; Li et al. 2004; Li et al. 2007; Wan, Chung, and

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Tang 2011). Hospital-acquired infections, in turn, are associated with increased mortality, length of hospital stay and costs (Jarvis 1996; Mathieu et al. 2001).

Most modern HVAC systems have the ability to control IAQ by detecting certain parameters of indoor air such as air temperature, carbon oxide (CO_2) concentration, humidity or air flow rate and adjusting it to match a predefined, ‘optimal’ value. This makes indoor air pleasant for the hospital staff and patients and also creates energy savings as excessive heating/cooling can be avoided. However, many modern HVAC systems only respond to a single IAQ parameter (i.e. air temperature or CO_2) while disregarding others. This may be partly due to a lack of feasible HVAC optimization techniques and advanced HVAC sensors. Rapidly advancing technologies have, however, enabled new systems capable of detecting several air quality parameters simultaneously – like the human nose or body – and optimizing them to suit the needs of hospital users. HVAC systems should be developed towards more adaptive and user-centric ones; to take users’ needs and preferences into account and adjust the room temperature, humidity and airflow rate to meet these preferences (Wong and Li 2010).

Designing and implementing these ‘intelligent’ HVAC systems for hospitals is an enormous challenge for several reasons. In this article we aim to describe the current state of HVAC systems used in hospitals and the definition of ‘intelligent’ HVAC systems. We also discuss some basics of airflow modelling using computational fluid dynamics (CFD). Furthermore, we review some challenges posed on the design and implementation of intelligent HVAC systems, and present some solutions for enhancing hospital IAQ, infection control and energy conservation.

Present situation in hospitals

The facilities management commonly has the final say on HVAC system implementation. They value the financial aspect, which may mean saving money by choosing cheaper alternatives for hospital HVAC solutions. However, needs of the facilities management often contradict needs of the actual users of the hospital – the patients and the physicians. They value a comfortable environment to be treated or treat patients (Fransson, Västfjäll, and Skoog 2007). The focus of value should thus be shifted from financial considerations towards those of user-centricity (Figure 1).

The age and condition of hospital buildings often closely correlates with the quality of the hospital’s HVAC systems. Twentieth century saw quick development in medical technology and after the Second World War, a period of intense hospital construction and renovation began. Many of today’s hospitals and their HVAC systems have been built during that era and are now approaching the end of their life-cycles and are in dire need of a major repair or renovation (Bartley, Olmsted, and Haas 2010; Hellgren et al. 2011). As a consequence, the quality of HVAC systems is not as high as it should be and the prevalence of indoor air-related problems (temperature, humidity, infection control, etc.) has been high worldwide (Nordstrom, Norbäck, and Akselsson 1995; Hellgren et al. 2008) (Figure 2).

Hospitals have a diverse indoor environment due to the different comfort and health needs of its occupants (Yau, Chandrasegaran, and Badarudin 2011). Ventilation studies mostly revolve around specialized areas such as operating and isolation rooms (Yau, Chandrasegaran, and Badarudin 2011). These areas are briefly discussed below.

Airborne infection isolation rooms

Airborne infection isolation rooms (AIIRs) are used to prevent infectious airborne diseases and other pathogens from spreading from patients via small particles originating from mucus and skin (Hyttinen et al. 2011b). The AIIRs are single-patient rooms isolated from adjoining areas

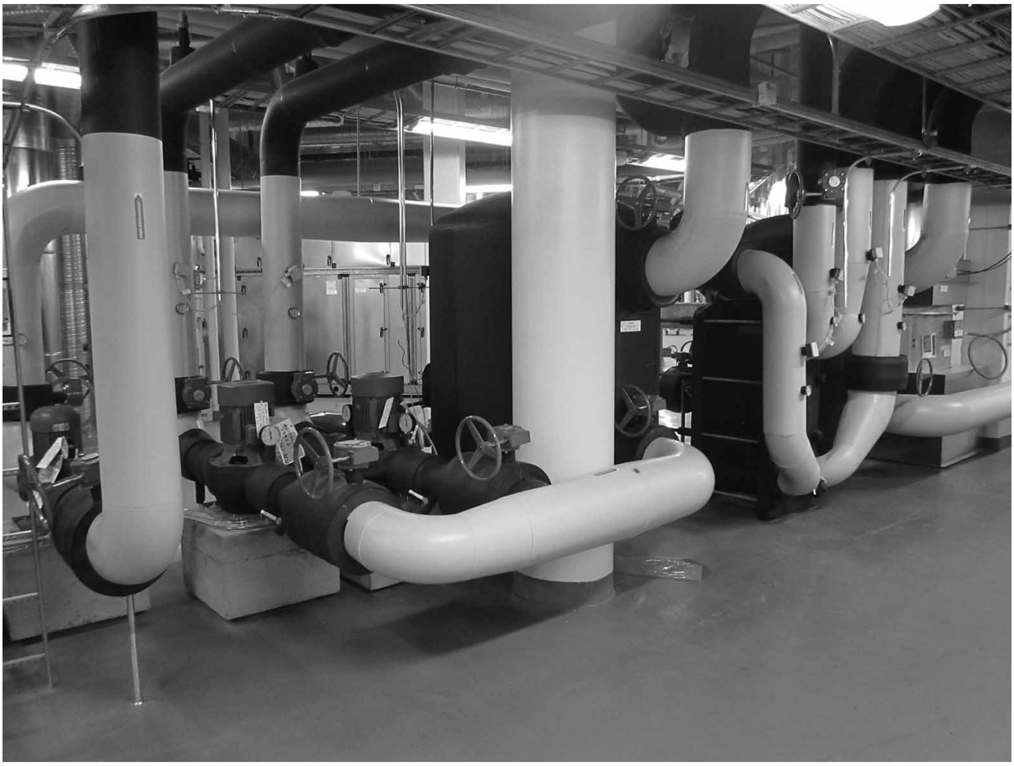

Figure 1. A cooling system in 'triangle-hospital' in Helsinki, Finland.

using a negative pressure differential (Hyttinen et al. 2011b). The exhaust air flow rate must be greater than the supply air flow rate in order to maintain the negative pressure, and air leakage must be minimized (Hyttinen et al. 2011b). The ventilation system can be simple (and even inexpensive) as long as it generates air flow patterns to protect the hospital staff inside the AIIR and reduces the spread of airborne infectious diseases between wards through leaking doors and windows (Booth et al. 2009; Tung et al. 2009; Hyttinen et al. 2011a). Furthermore, German ventilation guidelines recommend changing the room air as fast as possible in order to decrease the concentration of germs (VDI 2007).

It is difficult to achieve an absolutely airtight envelope in the design of a negatively pressurized isolation room and thus many AIIRs fail to provide sufficient isolation (Pavelchak et al. 2001; Tung et al. 2009; Hyttinen et al. 2011a). For instance, the New York State Department of health reported that half of the studied hospital isolation rooms failed to provide negative pressures (Pavelchak et al. 2000). This poses a major infection risk both to the hospital staff and patients (Walker et al. 2007) and is often due to the old age and poor condition of the HVAC systems. Air tightness of new isolation rooms is better than old isolation rooms (Salmi 2012). However, several leakages such as unsealed cables and tubes, windows, door frames and surroundings, wall sockets, switches and old seals have been found in new isolation rooms, all of which reduce the rooms' air tightness (Salmi 2012). Adding insult to injury, hospital employees have also mistakenly opened the isolation room windows and thus helped spread infectious diseases (Salmi 2012). There is also a need for more careful calibration and maintenance of isolation room pressure gauges (Salmi 2012). Saravia et al. found recently that only 32% of the 672 AIIRs investigated achieved the recommended pressure difference of -2.5 Pa relative to surrounding areas (Saravia, Raynor, and Streifel 2007).

Figure 2. An air-conditioning and heat recovery system in 'T-hospital' in Turku, Finland.

Several guidelines recommend using downward ventilation systems in isolation rooms (ASHRAE 2003; CDC 2003). AIIR control efficiency can also be enhanced by using auxiliary devices, such as portable air cleaners and ultraviolet germicidal irradiation (UVGI) systems (Hyttinen et al. 2011a). UVGI and ionization are low-cost control methods that provide realistic remedies to alleviate spreading of diseases such as tuberculosis (Hyttinen et al. 2011a). Supply and exhaust units should be arranged to allow air flow from the cleanest zone (i.e. health-care worker) to the most contaminated zone (i.e. patient with an infectious disease) and extract contaminants efficiently from the room (Cheong and Phua 2006). Exhaust air units should also be located at a low level and near the infectious source (Cheong and Phua 2006).

Operating theatres

Hospital OTs require special HVAC design. OT ventilation, air cleanliness, temperature and humidity are controlled using a dedicated air conditioning device. Indoor air in the surgical operation area must be aseptic and at a constant temperature and humidity. OT air cleanliness can be improved using a high-efficiency particulate arresting or an ultra-low penetration air supply air filtering and laminar air distribution. Operations that require an especially high level of sterility should be carried out in an OT equipped with a laminar flow ceiling with low velocity in order to avoid drafts and swirls that promote the recirculation of microbes and may disrupt the procedures during an operation. Local exhaust ventilation is being used to some extent for removal of anaesthetic gases.

British Medical Council has recommended the following ventilation objectives for an OT: To dilute the bacteria generated by the operating team and patients in the theatre by appropriate air volume changes, to prevent less clean air from other rooms entering the OT by using different air pressures, to create an air flow pattern that carries contaminated air away from the operating table, and to provide a comfortable environment for the operating team and patients with controlled temperature, humidity and ventilation (Rao 2004). Ho, Rosario, and Rahman (2009) recommend positioning supply grilles as close to the centre of the room as possible in order to maximize the performance of the room on both contaminant removal and thermal comfort.

Commonly encountered HVAC problems in the OTs include insufficient indoor air exchange, poor control on indoor thermal conditions, bad space ergonomics that influence the ventilation system operation, poor maintenance of technical installations, understaffed technical departments and energy-efficient HVAC systems (Balaras, Dascalaki, and Gaglia 2007; Yau 2008). In a study carried out by Wan, Chung, and Tang (2011) the IAQ in OTs varied significantly from month to month.

Intensive care units

The IAQ is of great importance for intensive care unit (ICU) patients. Severely ill patients in ICUs frequently require invasive devices, which may increase the risk of airway infections (Tang et al. 2009). The incidence of these infections is especially high in the ICU (Tang et al. 2009). Also, the probability of cross-infection among patients increases with the use of an HVAC system or from contacts between patients and health-care personnel (Tang et al. 2009). In addition, patient-visiting activity impacts the IAQ of the ICU environment, and affects coarse particle concentrations (Tang et al. 2009). Periodic monitoring of ventilation system efficiency is needed to ensure optimal IAQ (Tang et al. 2009). In case an ICU patient suffers from infectious diseases that can be communicated via the air, isolation for that patient is recommended (VDI 2007).

Patient wards

The HVAC systems in today's hospital patient wards are inherently quite similar to those of office buildings. However, due to infection-prone patients, the wards must be well ventilated to prevent contagious diseases (such as tuberculosis) from spreading from one patient to another. Additionally, patient wards are occupied and thus in use throughout the entire day. The patient ward air is usually supplied using ceiling or corridor wall blasting with mixing ventilation, but displacement ventilation is becoming increasingly popular (Guity, Gulick, and Marmion 2009). Patient ward ventilation is commonly enhanced by using window ventilation during impurity and temperature peaks. In all hospital areas – but especially in patient wards – exhalation flow from a patient with airborne infectious diseases can impose health risks to caretakers and visitors. By using local exhaust ventilation, the possibility of health risks could be decreased.

Laboratories

Hospital laboratories require efficient IAQ control. Local exhaust ventilation is being used in laboratories to prevent indoor air contaminants from spreading. In addition, fume cupboards should provide high enough face velocities (approx. 0.4–0.6 m/s) to prevent chemical or microbial substances from spreading around in the hospital (Ruys 1990). Unfortunately, this is often not the case, that is, due to hospital staff mistakenly unbarring the fume cupboard door too wide open, which results in insufficient airflow by the fume cupboard. Additionally, laboratories frequently suffer from poor ventilation and the HVAC systems in laboratories are in poor condition, creating occupational safety hazards.

Airflow modelling using CFD

Various computer-based models are being used to predict air movement, temperature and contaminant distribution, as well as several other parameters of room air distribution (Nielsen et al. 2007a). Most popular methods for predicting or evaluating ventilation performance include analytical models, empirical models, small-scale experimental models, full-scale experimental models, multi-zone models, zonal models and CFD models (Chen 2009). Below, CFD – the most popular method of modelling air movement – is briefly presented.

CFD is computational modelling of fluid (gas, liquid or their combination) flow. The flow can be laminar, transitional or turbulent. Usually the air flow in a room is more or less turbulent, which makes modelling challenging. There are three types of basic tools which are used in the solution of CFD. Historically, finite difference methods (FDMs) have been the dominant method of performing CFD due to its simplicity in formulations and computations (Ferziger and Peric 1999). Finite element methods (FEMs) on the other hand has been known for more complicated formulations and more time-consuming computations (Pepper and Heinrich 1992). However, this is no longer the case in many of the recent developments in FEM applications, and many examples of superior performance of FEM have been demonstrated (Chung 2002). Also, FINITE volume methods (FVMs) have become increasingly popular in recent years because of their simple data structure (Chung 2002). FVM formulations are related to both FDM and FEM (Chung 2002).

In a hospital room, CFD is used as a tool for modelling airflows created by both the air distribution devices and their placement in the room, and for developing air distribution. The application of CFD is useful to help understand the appropriateness of the ventilation design (Chow and Yang 2003). In practice, obstructions such as furniture, heat sources (i.e. humans) and other distractions have a significant effect on airflows in a room (Cheong and Phua 2006). For example, a light source above the operating table and movement in the operating room may cause undesired effects on the laminar flow in the OT (Chow and Yang 2003). CFD modelling can also be used to assess spreading of indoor air contaminants in the OT, ICU or in the whole hospital building.

Yam et al. used CFD analysis to simulate and compare the removal of microbes using a number of different ventilation systems (Yam et al. 2011). Instead of the conventional corridor air return arrangement used in most hospital wards, air return was rearranged so that ventilation was controlled from inside the ward cubicle (Yam et al. 2011). The CFD results revealed improved air ventilation rate, improved ventilation performance and also significantly improved microbe removal (Yam et al. 2011). Yam's proposed improvements enable matching the standards maintained in a properly constructed isolation room at a significantly lower cost. This ventilation system can also be applied in existing hospital general wards with far less disruption and cost than a full-scale refurbishment.

What is an intelligent HVAC system?

An 'intelligent HVAC system' is a broad term meaning many things. More discussion is needed in the community to reach a common definition. Reijula et al. (2011) have defined an intelligent work environment to be able to: sense the interaction between users and space, process this information and understand the context data, react in a way that adjusts to users' needs and enhances their endeavours in the environment, be active and autonomous, omnipresent and enhance the worker's flow of work and perception of their physical and psychological well-being. The same is also required from HVAC systems in an intelligent hospital environment. It is also proposed that in addition to serving users' needs an intelligent hospital HVAC system should take into account local climate and facility type of the hospital, conserve energy, increase safety, decrease the number of indoor air symptoms and improve the work atmosphere and efficiency (Niemelä et al. 2002; Seppänen and Fisk 2006; Wong and Li 2010; ASHE 2011; Hellgren et al. 2011).

Challenges concerning intelligent HVAC systems

Although a growing amount of research is put into development and implementation of intelligent HVAC systems, several challenges have been encountered along the way. Below, we present some of the most relevant ones.

Poor hospital design

Despite extensive knowledge on the mechanisms of infection spread in hospitals, little has been done to radically redesign hospitals with an emphasis on contamination control (Clark and de Calcina-Goff 2009). New hospitals are often designed by architects who lack knowledge of the function of contamination control (Clark and de Calcina-Goff 2009). Designers may also be hampered by being unable to implement radical features; those that do not appear in national guidelines or are outside nationally accepted norms (Clark and de Calcina-Goff 2009). Furthermore, once a hospital has been built on traditional lines, a retro-fit for greater patient protection is seldom a viable option (Clark and de Calcina-Goff 2009).

Lack of adequate sensors

Many IAQ sensors have not achieved commercial success in the past years (BCS Partners 2002). Ihasalo has also identified a problem with a lack of adequate sensors installed with HVAC systems (Ihasalo 2012). Although a variety of sensors are becoming commercially available, more work could be carried out in sensor development as well as establishing common interfaces for them. BACnet is a viable data communication protocol for building automation and control networks (ISO/IEC 16484-5 2003). It has been developed since 1987 and has had some remarkable results. The developed HVAC sensors and devices must be simple, feasible and functional with a common interface or they will not be adopted by hospitals.

Poor data collecting, archiving and visualization by building automation systems

Current building automation systems – used to manage and control HVAC equipment – have a limited ability to collect, archive and visualize data (Brambley et al. 2005; Haves and Hitchcock 2008). They are usually capable of real-time monitoring of only temperature and humidity, while several important parameters of air quality are left unmonitored. The visualization of building automation system programs has been mainly created for adjusting system parameters and for system monitoring. Each program developer has their own program, which causes challenges for the user. Thus the functionality and feasibility of building automation system programs should be improved. Although it is possible to simulate building automation systems in order to improve their feasibility, it is currently only performed rarely (because this requires special expertise in building automation systems). It is likely that future generations will capitalize on building automation systems much better.

Complexity of airborne infection spread prevention

The generation of infectious aerosols from infectious human pathogens can occur in many ways, and in many settings in a hospital environment (Tang et al. 2006). For instance, droplets generated by talking, laughing, coughing and sneezing may lead to the generation of an infectious aerosol (Tang et al. 2006). The environmental conditions (i.e. temperature and humidity) determine the survival of these pathogens (Tang et al. 2006). However, they vary with the season and the indoor building environment. The aerosols can also be transmitted over short distances (large droplet aerosols) or long distances (small droplets) (Tang et al. 2011). Thus, it is very difficult to prepare for an airborne infection outbreak.

Investigations have suggested that ventilation systems may possess microbial contamination (Garrison et al. 1993; Rose and Hirsch 1979), which may also be a source of pollutants (Ohsaki et al. 2007). Humidifiers, dirty air ducts and dirty filters could all be sites for amplification and dissemination of indoor fungi (Ohsaki et al. 2007). It is important to make sure no humidity condenses into the HVAC system and proper sewage systems are installed for water condensing into coolers, humidifiers, etc.

Morawska has identified experimental complexity of simultaneous characterization of the microbiological and physical nature of virus-containing particles as well as a lack of scientific methods and techniques for accurate quantification of virus particles in the air (Morawska 2005). Advanced techniques such as polymerase chain reaction, which can be used in a quantitative way in the application to the types of viruses selected for investigations, became available only recently. Also, a lack of realization exists of the importance of the dynamics of virus spread (Morawska 2005). Because of the complexity of the mechanisms involved in ward ventilation, the exact level of ventilation required to prevent hospital acquired infections is still unknown (Beggs et al. 2008).

There are also remarkable differences between infection isolation practices in different countries and even within different regions of countries (Humphreys et al. 2009). In addition, there is no generally accepted definition of the term ‘isolation’ in the infection prevention and control community (Dettenkofer et al. 2011). Some institutions interpret ‘isolation’ as a ‘quarantine-type’ separation of the patient, who is not allowed to leave the isolation room. Others separate the patient within a multi-bed room; yet some even allow the patient to move around freely, with only health-care workers encouraged to wear gloves and gowns during patient care.

There are new innovations and technologies that support infection control, including the reduction of surgical site infections by use of minimally invasive procedures (Dettenkofer et al. 2011). However, advanced devices such as robots used in surgery may pose a relative risk of pathogen transmission if not designed and maintained properly, and such developments are a challenge for today’s infection control personnel (Dettenkofer et al. 2011).

Conflicting indoor air preferences between patients and staff

According to Skoog et al. the hypothesis that staff and patients can be treated as one coherent group of hospital users with the same needs and preferences is incorrect (Skoog, Fransson, and Jagemar 2005). For instance, the patients accept the thermal climate in a higher degree than the staff – possibly because the patients will leave the hospital in foreseeable time (Skoog, Fransson, and Jagemar 2005). Also, the patients’ and physicians’ preferences for indoor temperature and humidity differ between summer and winter seasons (Skoog, Fransson, and Jagemar 2005). Good mental and physical health speeds up the recovery of the patients and enhances the work efficiency of physicians (Wells-Thorpe 2000). It is thus important to pay attention to the indoor air needs of each hospital user individually.

Insufficient knowledge on HVAC systems

Lack of good instructions for ventilation design and maintenance and improper HVAC system use have resulted in infections inside the hospital (Hellgren et al. 2011). In many cases, the provisions for contamination control, particularly in relation to HVAC systems, do not operate as designed (Clark and de Calcina-Goff 2009). The hospital staff has usually not been trained to monitor such systems and as a result often report faults and are confused with the over-complex and unreliable engineering controls (Clark an de Galcina-Goff 2009).

HVAC energy conservation in hospitals

Based on a survey from 2008, health-care designs aimed at environmental sustainability and energy efficiency are being used in over 80% of active projects and this trend is likely to continue in the future (Bartley, Olmsted, and Haas 2010). However, HVAC systems are the biggest consumer of energy in hospital buildings (Singer, Coughlin, and Matthew 2009) and account to approximately 30% of the total building energy consumption (Perez-Lombard, Ortiz, and Pout 2008). Furthermore, the energy intensity of hospital HVAC systems is more than five times that of dwellings (Perez-Lombard et al. 2011). A considerable body of research has been carried out in order to find reliable solutions to decrease their energy consumption. The climate of the hospital plays a major role when deciding energy-conserving HVAC systems for a hospital and some of the aforementioned solutions are specifically designed for certain climates (Ozyogurtcu, Mobedi, and Ozerdem 2011).

Radio frequency identification (RFID)-based system for occupancy monitoring

Li et al. have proposed an RFID-based system to measure and monitor building occupancy (Li, Calis, and Becerik-Gerber 2012). The proposed system estimates the thermal zone where each occupant is located, and reports the number of occupants for each thermal zone in real time (Li, Calis, and Becerik-Gerber 2012). The system enables energy-saving strategies that can be carried out in response to real-time occupancy changes.

Run-around membrane energy exchanger system

Run-around membrane energy exchanger (RAMEE) system pre-conditions the outside air using the exhaust air before it enters the HVAC heating/cooling unit (Mahmud et al. 2010). The system can achieve a maximum total effectiveness of 55% (Mahmud et al. 2010). The system performs slightly better in the winter season than the summer session, making it especially appealing for countries in the northern climate (Mahmud et al. 2010). The RAMEE system could prove to be a viable alternative for the existing emergency room devices.

Combined generation of heat, cooling and power

Combined generation of heat, cooling and power (CHCP) is a system optimal for Mediterranean climates. Absorption cooling is used to increase the heat demand, improve the overall heat recovery utilization and to make electric and thermal loads more simultaneous (Pagliarini, Corradi, and Rainieri 2012). CHCP can be more efficient than combined generation of heat and power only (Pagliarini, Corradi, and Rainieri 2012). Arcuri et al. applied a mixed integer programming model to the design optimization of a CHCP plant for a hospital (Arcuri, Florio, and Fragiacomo 2007). They concluded that a CHCP plant configuration utilizing heat pumps directly fed by a co-generator, greatly improves energy management and achieves significant economic, energy and environmental benefits (Arcuri, Florio, and Fragiacomo 2007).

Double heat pipe heat exchanger system

Today's hospitals use indirect heat recovery systems due to hygienic reasons. The systems can be improved with a double heat pipe heat exchanger (HPHX) system (Yau 2008). A heat pipe allows very high rates of heat transfer over medium distances with low levels of thermal resistance and relatively low-temperature differences (Yau 2008). The benefits of HPHX systems over conventional heat exchangers are lower initial cost (because of higher effectiveness per unit area of heat exchanger), reduced air-side pressure drop (fewer rows), lower maintenance costs (no moving parts) and lower operating costs (no external power) (Shirey 1993). HPHX systems are recommended for conventional HVAC systems to significantly improve humidity control and decrease fungus growth and energy consumption in hospitals located in hot and humid areas (Yau 2008; Yau and Ng 2011).

Aquifer thermal energy storage system

An aquifer thermal energy storage system was monitored in combination with a heat pump for heating and cooling of the ventilation air in a Belgian hospital (Vanhoudt et al. 2011). Groundwater flows and temperatures were monitored as well as the energy flows of the heat pumps and the energy demand of the building (Vanhoudt et al. 2011). The resulting energy balance of the building showed that the primary energy consumption of the heat pump system was 71% lower in comparison with a reference installation based on common gas-fired boilers and water cooling machines (Vanhoudt et al. 2011).

Adaptive variable air volume system

Despite having an energy-saving feature, currently installed variable air volume (VAV) systems in hospital isolation rooms often run at constant air volume, which lead to inefficient fan energy consumption (Kim and Augenbroe 2009). The adaptive VAV mode consumes significantly less energy compared to the current VAV systems (Kim and Augenbroe 2009). Despite its energy savings, these two systems do not exhibit a noticeable difference in the potential spread of contaminant and thermal comfort (Kim and Augenbroe 2009). The challenge, however, lies in the high repair and maintenance costs of VAV systems.

Demand-controlled ventilation

Demand-controlled ventilation (DCV) is a ventilation rate control strategy to provide exact amount of ventilation air to each space based on the real-time ventilation demand (Jeong, Choi, and No 2010). A simple and inexpensive closed-loop control system for DCV consists of CO_2 or occupancy sensors, programmable controllers and ventilation damper actuators, which can be either pneumatic or electric (Jeong, Choi, and No 2010). The several proposed DCV approaches thus far include approximate occupant scheduling (for buildings with predictable occupancy patterns), use of infrared sensors to sense whether the space is occupied or not, CO_2-based approach, and direct measurement of the number of occupants (Jeong, Choi, and No 2010). As the airflow rate is continuously adapted to the actual load condition, considerable energy savings can be achieved.

Natural ventilation

Although natural ventilation (NV) decreases the energy consumption in hospitals and there are several studies supporting its use in hospitals (WHO 2009; Qian et al. 2010), it is unlikely that it will be utilized in developed countries such as US's acute care facilities because it compromises building envelope integrity, allowing in non-filtered air with outdoor air contaminants such as fungal spores (Bartley, Olmsted, and Haas 2010). In addition, NV is not compatible with modern life safety and infection prevention principles (Bartley, Olmsted, and Haas 2010).

HVAC simulation and monitoring

Integrated dynamic HVAC simulation in hospitals could prove to be useful in improving energy utilization and systems maintenance (Mathews and Botha 2003). Also, HVAC system monitoring using building management systems has been shown to provide energy savings (Masoero, Silvi, and Toniolo 2010).

HAMLab (Heat, Air and Moisture simulation Laboratory) is a collection of tools developed for programs such as MatLab, Simulink or COMSOL. HAMLab enables dynamic calculation and optimization of buildings and systems. Van Schijndel (2007) has assessed the use of HAMLab in a hospital power plant.

HVAC system improvement proposals

Although energy conservation has thus far been the most active area of intelligent HVAC systems research, it is also vital to emphasize other areas, especially in a hospital environment. Here are some improvement proposals for hospital HVAC systems.

HVAC optimization techniques

Optimization techniques are being used increasingly for the design of HVAC systems (Pantelic, Raphael, and Tham 2012). However, most of them only focus on the optimization of a single objective, which has most often been minimizing energy consumption (Huh and Brandemuehl 2008; Wemhoff 2010; Kämpf and Robinson 2010). Sub-optimization, such as improving energy performance at the expense of indoor conditions, must be avoided in hospitals (Ihasalo 2012). Thus a need exists for research on multi-criteria optimization tools that optimize several parameters, including IAQ (i.e. air particles (dust, smoke, etc.), carbon dioxide levels, airflow rate), lighting, acoustics and energy consumption and balance them to create optimal circumstances for the patients and the staff.

Pantelic et al. have developed a multi-criteria decision-making tool, an algorithm named RR-PARETO2 (Pantelic, Raphael, and Tham 2012). It makes trade-offs between power consumption, thermal comfort, risk of airborne infection of influenza and tuberculosis and effective differential temperature of body parts in order to provide an optimal air exchange rate for users of the building (Pantelic, Raphael, and Tham 2012). The algorithm was successfully used in an influenza outbreak scenario to prevent the spread inside the building.

Performance monitoring and management systems (PEMMS)

In his doctoral thesis, Ihasalo proposes PEMMS, a system that utilizes automation data from real buildings (Ihasalo 2012). PEMMS is capable of presenting building performance from energy, indoor conditions and HVAC system perspectives and visualizing the performance metrics in an easy and intuitive manner: PEMMS provides high-level performance reports which enable the overall building performance to be assessed at a glance, drill-down capabilities to view detailed information behind each metric, and information that can be utilized by the whole building operation and maintenance organization in both building performance management and monitoring (Ihasalo 2012).

Organizational simulation

Li, Heo, and Augenbroe (2009) used organizational simulation (OS) to test the feasibility of the HVAC system in the hospital design phase. It can be used to provide HVAC designers with the information that is needed and to reduce the risk that HVAC system is poorly designed (Li, Heo, and Augenbroe 2009). The implementation by Li et al. can directly calculate HVAC load in the OS model, feed dynamic occupancy information into a dynamic building simulation tool and check how HVAC system performs in different operational situations (Li, Heo, and Augenbroe 2009). The cost/benefit analysis shows that the approach is attractive and potentially even mandatory in dynamic organizational processes (Li, Heo, and Augenbroe 2009).

Perceived indoor environment

Psychosocial factors have influence on the perceived indoor environment (Lahtinen, Huuhtanen, and Reijula 1998). Welling et al. have gathered positive results by adapting temperature adjustment according to the feedback received from the users of the building (Welling 2000). By allowing patients' and hospital personnel control the IAQ parameters for hospital rooms – or at least the space they are occupying – positive results could follow (Kostiainen et al. 2008). Dascalaki et al. found that when hospital personnel perceived satisfactory indoor environmental quality conditions (satisfactory thermal, visual and acoustical comfort conditions and acceptable IAQ), it significantly decreased the average number of symptoms among them (Dascalaki et al. 2009).

Personalized ventilation

Studies by Nielsen et al. have suggested using a separate diffuser or diffusers integrated into hospital beds to provide personalized ventilation (PV) (Nielsen et al. 2007b) and to minimize the possibility of cross-infection (Nielsen et al. 2008). By using PV, that is, receptionists working at the hospital counter can also be protected from infections transmitted by patients. PV can significantly improve occupants' comfort, decrease SBS symptoms and reduce the risk of transmission of contagion between occupants in comparison with total volume ventilation as long as the design is carefully considered together with type of occupant activity (Melikov 2004).

The RFID-based system by Li, Calis, and Becerik-Gerber (2012) (discussed in 'HVAC Energy Conservation in Hospitals') could also be used for PV in hospital wards. Personal preferences for each patient/staff member could be saved into the system database and IAQ – parameters could thus be adjusted accordingly in real-time depending on the person's location inside the hospital.

Enhanced infection prevention

The airborne transmission of diseases may be restricted in three ways: control the source of infection by quarantine and the use of isolation facilities; control airborne transmission routes by the use of negative pressure ventilation systems, sliding doors instead of hinged doors and improving seals around doors and windows; and protect exposed susceptible individuals from both aerosol and contact transmission of infection by the use of personal protective equipment (Tang et al. 2006).

The risk of airborne infection can be minimized in hospital wards by using a high air change rate. Nielsen et al. (2010) recommend using a ceiling-mounted low-velocity diffuser that generates vertical ventilation and vertical displacement flow in a room when it is used together with a high location of distributed return openings. This type of flow can produce a personal exposure index larger than that produced when the supply temperature is less than the room air temperature (Nielsen et al. 2010). The system can handle a high flow rate without causing high velocity, and it is therefore appropriate for ventilation in a hospital ward (Nielsen et al. 2010).

Lim et al. have studied high-rise hospital buildings and noted the increased risk of airborne infection due to stack effect among these buildings (Lim, Cho, and Kim 2010, 2011). In order to minimize the spread of air flow movement due to the stack effect, an additional plan for the frequently used entrances of the hospital to be made more airtight is required (Lim, Cho, and Kim 2011). Also, efforts are needed to minimize the influence of supply air volume to other spaces by balancing it with the return air volume (Lim, Cho, and Kim 2010). Moreover, a zoning plan could be considered where the wardrooms for patients with a possible infectious disease are placed in the upper floors above the neutral pressure level (NPL) (Lim, Cho, and Kim 2011). For example, the clinics can be located on levels that are higher than the NPL, or patients suspected of having respiratory diseases need to be accommodated on the upper levels (Lim, Cho, and Kim 2010). However, in Finnish hospitals, isolation rooms have often been built on the lower levels. One reason for this might be getting patients quickly into isolation in case of an epidemic. Morawska (2005) recommends taking an interdisciplinary approach to help prevent infection spread.

Improved emission control

Environmental concern for sustainable development has prompted for procedures for controlling greenhouse gases using HVAC systems. Commercial solutions are available for, that is, catalysing nitrous oxides in hospitals. Local exhaust ventilation is often used to catalyze greenhouse gases before they are released into outdoor air. Hospital emission control is largely dependent on the hospital, and much work remains to be done to improve this issue worldwide.

Wireless sensor networks

Modern hospitals have an interface challenge with various brands of sensors measuring different IAQ parameters. There is a need to develop both sensor hardware and sensor information technology software in order to develop a functional and feasible system for hospital HVAC systems. Wireless sensor networks reduce the need for cabling and enable placed sensors where cabling is not appropriate, enable better indoor conditions and energy savings through improved sensor location, and can be quickly and effortlessly reconfigured and extended (Arens et al. 2005; Reinisch et al. 2007; Österlind et al. 2007). Below, a couple of wireless sensor network protocols are presented for wireless sensor networks that could prove to be useful in hospital HVAC systems.

Breath is a new protocol for control applications, where sensor nodes transmit information via multi-hop routing to a sink node (Park 2011). The protocol is based on the modelling of randomized routing, medium access control (MAC), and duty-cycling (Park 2011). Analytical and experimental results have shown that Breath is reliable, has low delay, and exhibits virtually uniform distribution of the work load (Park 2011).

SERAN is a two-layer semi-random protocol that specifies a routing algorithm and a MAC layer for clustered wireless sensor networks (Bonivento et al. 2005). It combines a randomized and a deterministic approach: The former provides robustness over unreliable channels and the latter reduces the packet collisions (Bonivento et al. 2005). SERAN has shown excellent performance for low data rate transmissions with low average node duty cycle, which yields a long network lifetime.

Conclusions

Intelligent HVAC systems have been increasingly implemented into hospital buildings. The definition of intelligent HVAC systems itself has been used by various researchers to mean different things. Thus far, most of the intelligent HVAC research has focused on energy conservation issues. Although this is an important topic – especially with increasing energy demand worldwide – the focus of modern day HVAC systems design should be shifted towards user-centric design. The well-being of hospital users should be the top-priority in intelligent HVAC system design and implementation.

There are several challenges to intelligent HVAC system implementation. First of all, the delicacy of the hospital environment leaves little space for system failures: Especially infection control must be top-notch to prevent and control epidemic outbreaks. Limitations in airborne infection control may cause serious health hazards for hospital users. This issue should thus not be overlooked but instead paid increasing attention to in the near future. Second, as user-centric HVAC system design in hospitals is a relatively new topic, little is known about the causal connection of intelligent HVAC system implementation and there has been some uncertainty among the hospital users on how to use the new systems. Furthermore, some hospitals may be poorly designed and the designers may lack knowledge on how to implement intelligent HVAC systems into these hospitals. Furthermore, lack of adequate sensors has posed a challenge for HVAC design in the past, but the situation is gradually improving due to new technological innovations in sensor technology. Also, poor data collecting, archiving and visualization by the building automation systems, and conflicting indoor air preferences between patients and staff have created problems for the hospital designers.

Based on a wide survey of intelligent HVAC literature, many systems have been designed to conserve energy in hospital ventilation. In this article, the benefits and limitations of RFID-based system for occupancy monitoring, RAMEE system, HPHX system, aquifer thermal energy storage system, adaptive VAV system, DVC, CHCP, HVAC simulation and monitoring methods and NV are briefly discussed.

Also, many solutions have been presented to enhance hospital HVAC systems – especially for improving IAQ parameters and infection prevention, and also to enhance the user-centric functionality. Some examples of these include HVAC optimization techniques such as RR-PARETO2 algorithm, PEMMS, organizational simulation, improved perceived indoor environment, personalized ventilation, enhanced infection prevention, improved emission control and enhanced wireless sensor networks. A fully automated, intelligent HVAC system which covers an entire hospital and adjusts optimal IAQ parameters for each individual hospital user is yet to be developed, but would greatly benefit all users of the hospital.

Acknowledgements

Jori Reijula is grateful to The Finnish Work Environment Fund, K.V. Lindholm heating-, ventilation- and air conditioning-technology foundation, KAUTE Foundation, the Association for Promotion of Occupational Health and the Miina Sillanpaa Foundation for funding his research.

Research for this article was supported in part by gifts made to the Project Production Systems Laboratory (http://p2sl.berkeley.edu/). All support is gratefully acknowledged. Any opinions, findings, conclusions or

recommendations expressed in this article are those of the author and do not necessarily reflect the views of contributors to the Project Production Systems Laboratory.

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