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Original Research Paper

Effects of CO_2 Exhaled and Human Metabolism on Comfort Conditions in Air-conditioned Indoor Environment

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ABSTRACT

Thermal and atmospheric conditions in an enclosed space are usually controlled to ensure the health and comfort of the occupants, and proper functioning of sensitive electronic equipment such as computers, etc. The former is referred as comfort conditioning and the latter is called process air conditioning. The conditions required for optimum operation of machinery may not coincide with those conductive to human comfort. Process air-conditioning requirements are highly specific to the equipment or operation. Once the necessary condition for process or machinery is established, attention must be paid to the acceptable human comfort. Although human beings can be considered very versatile machines having the capacity to adapt the wide variations in the working environment, their productivity depends on the immediate environment. This paper discusses about the CO_2 generation of the human beings based on their working environment, activity, metabolism and its effects inside the indoor environment. The indoor pollutants created by the human beings and the rate of ventilation required to dilute the pollutant levels to meet ASHRAE standards is also discussed.

INTRODUCTION

Comfort is best defined as the absence of discomfort. People feel uncomfortable when they are in too hot or too cold, and when the indoor air is odorous and stalled. Positive comfort conditions are those do not distract by causing unpleasant sensation of temperature, drafts, humidity or other aspects of the environment. Ideally, in a proper conditioned space, people should not be aware of equipment noise, heat or air motion. The feeling of comfort or discomfort is based on a network of sense organs: the eyes, ears, nose, tactile sensors, heat sensors and brain. Thermal comfort is the state of the mind that is satisfied with the thermal environment; it is thus the minimal stimulation of the skin's heat sensors and of the heat sensing portion of the brain (EBRG, Ver.1.1 2008)

For comfort and efficiency, the human body requires a fairly narrow range of environmental conditions compared with full scope of those found in nature. The factors that affect humans pleasantly or adversely include temperature of the surrounding air, radiant temperatures of the surrounding surfaces, humidity of the air, air motion, odours, dust, aesthetics, acoustics and lighting. The first four relate to thermal interaction between people and immediate environment. The odour and man-made air pollutants like CO_2, dust, radon, dander, etc. can be diluted by the fresh air ventilation.

MATERIALS AND METHODS

Body temperature control: Human beings are essentially constant temperature mammals with a normal internal body temperature of 98.6°F (37°C). Heat is produced in the body as a result of metabolic activity. So its production can be controlled to some extent by controlling metabolism. Given a set of metabolic rate, the body must reject heat at the proper rate in order to maintain thermal equilibrium with the surrounding environment.

The body is in a state of thermal equilibrium with environment when it loses heat at exactly the same rate as it gains heat. The relation between body's heat production and all its heat gains and losses is:

$$M = E \pm R \pm C \pm S \qquad ...(1)$$

M = metabolic rate (kJ/sec)
E = Rate of heat loss by evaporation, respiration and elimination (kJ/sec)
R = Radiation rate (kJ/sec)
C = Conduction and convection rate (kJ/sec)
S = Body heat storage rate (kJ/sec)

When body temperature rises above normal, the blood vessels in skin dilate, bringing more heat-carrying blood to the surface. This results in higher skin temperature which results in increased heat loss. At the same time sweat glands are stimulated, opening the pores of the skin to the passage of body fluids which evaporates on the surface of the skin and thereby cooling the body. During high heat loss people experience a feeling of lassitude and mental dullness brought about by the fact that an increased amount of the blood pumped by the heart goes directly to the skin and back to the heart bypassing the brain and other organs. A hot environment also increases the strain on the heart (ASHRAE Hand Book of Fundamentals 1989).

If the body loses more heat to a cold environment, it decreases heat loss by constricting the outer blood vessels thus reducing the flow of blood to the outer surface of the skin. This will convert skin surface in to a layer of insulation between interior body and environment. Within limits, the body can acclimate itself to thermal environmental change. Humans feel discomfort when the body has to work too hard to maintain thermal equilibrium.

For calculating the optimum environmental conditions for comfort and health, metabolic levels should be ascertained during the course of routine physical activities, since body's heat production increases in proportion to the level of exercise. When the activity level shift from sleeping to heavy work, the metabolism varies accordingly as listed below. Table 1 presents average metabolic rates for a variety of steady activities in *met* units.

One *met* is defined in terms of body surface area as,

18.4 Btuh/ft^2 = 58.2 W/m^2 = 50 kcal/m^{2}hr

For an average-size man, the *met* unit corresponds to 360 Btuh = 100 W = 90 kcal/hr

Heat is generated within the human body by the combustion of food. The heat is lost from the body by means of conduction and convection (25%), radiation (43%), evaporation and moisture (30%) and exhaled air (2%). Evaporation prevails at high ambient temperatures. Conduction and convection prevails at low ambient temperatures. Heat is liberated in a rate maintaining the internal body temperature at 37°C. The total heat loss from an adult at normal activity is approximately 118W (2 *met*) in room with temperatures between 19°C and 34°C.

Air movement: Air motion significantly affects the body heat transfer by convection and evaporation. Air movement results from natural or forced convection as well as from the occupant's movements. When ambient temperature is within the acceptable limits, there is no requirement of air movement to achieve thermal comfort. The natural convection of air over the surface of the body allows for the continuous dissipation of body heat. Artificial air movement is required when ambient temperature rise and natural air movement is insufficient to provide thermal comfort. Human response to the air velocity is listed in the Table 2.

A noticeable air movement across the body when there is perspiration on the skin may be regarded as a pleasant cooling breeze. When the surrounding surface and room air temperatures are cool, it will result in chilly draft. The neck, upper back and ankles are most sensitive to drafts, particularly when entering cool air is 1.5°C more or below normal room temperature. Every 0.15 m/s increase in air movement above the velocity of 0.3 m/s is sensed by the body as a 1°C temperature drop. Air systems are usually designed for a maximum of 0.25 m/s in the occupied zone (Roonak Daghigh et al. 2009).

Cool air can impinge on an occupant in two general cases: Air that is warm when introduced into the room may cool off before reaching the occupant, or the air is intended to cool the occupants under overly warm ambient conditions. In both the cases, if the temperature of the air impinging on the occupant is below the ambient temperature, the individual becomes more sensitive to air motion and may complain of drafts. Therefore, careful attention must be given to air distribution as well as velocity. Besides the removal of heat and humidity, another function of air motion in alleviating stuffiness is the dispersion of body odours and air contaminants.

Indoor air contaminants: Air conditioning rooms are usually constructed tight and leak proof to save energy cost. These tight buildings combined with inadequate fresh air ventilation produce an indoor environment with higher levels of chemical contaminants, bacteria, fungi and dust (Table 3). The people spend 85 to 90% of their time in this larger concentration of indoor air pollutants make them susceptible to illness related to these airborne contaminants (WHO 2001).

The indoor air contaminants, which can be hazardous to health include environmental tobacco smoke (ETS), formaldehyde, radon, asbestos, volatile organic compounds (VOC), paints, and varnishes, carpets causing long term or short term illness. Biologicals like bacteria, viruses, fungus due to presence of high humidity, directly affect the health of the occupants. Odours and dust can cause significant discomfort and unpleasantness (WHO 2001).

The various sources of air contamination are found in commercial/office buildings are in the following average proportions: human - 13%, smoking - 25%, vapours from the materials in the room - 20%, and ventilation air conditioning systems - 42%. The poor indoor air quality in work environment will affect health of the individual, subsequent economic effect by loss of productivity and increased absenteeism (Levente Herczez et al. 2000).

These pollutants can be controlled by two methods, namely source control and removal. Source control method, though the preferred approach, may not be often practical. Source control method is pollutant specific and may include use of low formaldehyde emitting materials, banning of cigarette smoking, preventing radon entry by sealing of foundations, eliminating use of asbestos and storing paints and solvents outside the occupied space. Controlling the humidity will prevent microbial contamination.

Removal of contaminants from a building or reducing its concentration within a work space can be accomplished by passive or active ventilation. Passive ventilation refers to air exchanged through doors, windows or other openings by natural forces. In most of the air conditioned buildings, these openings are limited to reduce the cooling load thereby saving energy cost. Active ventilation systems provides continuous ventilation to which passive ventilation may add but not subtract when pollutants are evenly mixed throughout a space and the source rate is constant; the concentration of airborne pollutants will be inversely proportional to the ventilation rate, i.e., doubling the ventilation will result halve the concentration.

RESULTS AND DISCUSSION

Respiration and CO_2 exhaled: Humans need fresh air for respiration and for transport of heat and vapour emitted from the body. An adult at rest breathes 16 respirations per minute, approximately 5 m^3/h (lung volume 4-6 L), with harder work the respiration rate is 3 to 6 times more i.e., 15-30 m^3/h. The average composition of exhaled air is: oxygen 16.5%, carbon dioxide 4.0% and nitrogen and argon 79.5%. The quantity of carbon dioxide exhaled in 24 hrs is about 1 kg. CO_2 emission from persons based on their activity is given in Table 4.

Carbon dioxide concentration in a room with people can be used as an indication of the indoor air quality. It is desirable to design ventilation system capacity to the number of people and their activity by measuring the CO_2 concentration in the air (Leephakpreeda et al. 2001). The conversion factor of CO_2 concentration from ppm to L/m^3 is 0.001013439 (Leephakpreeda et al. 2001). CO_2 concentration in a room with persons can after a time "t" can be expressed as:

$$C = (q/nV)\,[1-(1/e^{nt})] + (c_o-c_i)\,(1/e^{nt}) + c_i \quad ...(2)$$

Where,

C = CO_2 concentration in the room (m^3/m^3)
q = CO_2 supplied to the room (m^3/h)
V= volume of the room (m^3)
e = constant 2.718
n = number of air shifts per hour
t = time in hour
c_o = CO_2 concentration in the room at the start (m^3/m^3)
c_i = CO_2 concentration in the ventilation air (m^3/m^3)

Even though CO_2 not dangerous in normal concentrations, it is frequently used as a reference indicator for indoor air quality, and therefore, ventilation performance. That is due to the fact that the people, when they exhale CO_2, even exhale and emit many other contaminants including microorganisms. These may be gases, odours, particles and germs. When the concentration of these, as a result of bad ventilation, is permitted to increase in a room, occupants complain tiredness, headache, and even feeling of sickness. CO_2 concentration and human responses are given in Table 5.

CO_2 measurement inside a building dynamically measures the relation between CO_2 generated by people, and the dilution effect given by the mechanical ventilation or draught. If the difference between indoor and outdoor concentration is known and the indoor concentration is stable, it is possible to relate the CO_2 concentration to the ventilation system performance. Ventilation rates for indoor air quality (ASHARE 62-1989)

Workplaces and offices need higher ventilation and fresh air needs along with other issues like ergonomics, light, noise, decoration and ambience (Table 6). ASHRAE 62-1989 recommends fresh air intake of 15 to 20 cfm per person where 5 cfm was considered adequate by the industry (Deepak Pahwa 2004). CO_2 levels, which have been recognized by ASHRAE as the surrogate ventilation index (being the only economically and practically measurable variable), should not exceed 1000

Table1: Metabolic rate for different activities.

Activity	Metabolic rate in *met* units	Activity	Metabolic rate in *met* units
Resting		**Carpentry**	
Sleeping	0.7	Machine sawing, table	1.8 to 2.2
Reclining	0.8	Sawing by hand	4.0 to 4.8
Seated, Reading	0.9	Planning by hand	5.6 to 6.4
Office work		**Vehicle Driving**	
Seated, writing	1.0	Car	1.5
Seated, typing/talking	1.2 to 1.4	Motorcycle	2.0
Seated, filing	1.2	Heavy vehicle	3.2
Standing, talking	1.2	Aircraft flying	1.4
Drafting	1.1 to 1.3	Instrument Landing	1.8
Miscellaneous office work	1.1 to 1.3	Combat flying	
Standing filing	1.4		
Walking (On level Ground)		**Miscellaneous work**	
2 mph (0.89 m/s)	2.0	Watch repairing, seated	1.1
3 mph (1.34 m/s)	2.6	Lifting/Packing	1.2 to 2.4
4 mph (1.79 m/s)	3.8	Garage Work	2.2 to 3.0
Domestic Work		**Leisure Activities**	
Shopping	1.4 to 1.8	Stream Fishing	1.2 to 2.0
Cooking	1.6 to 2.0	Golf swinging & walking	1.4 to 2.6
House cleaning	2.0 to 3.4	Dancing	2.4 to 4.4
Washing by hand and ironing	2.0 to 3.6	Tennis singles	3.6 to 4.6

Table 2: Human response to the air movement.

Air velocity in m/s	Occupant's Reaction
0 to 0.05	Complaints about stagnation
0.05 to 0.25	Generally favourable (Air outlet devices normally designed for 0.25 m/s in the occupied zone.
0.25 to 0.51	Awareness of air motion. But may be comfortable, depending on moving air temperature and room conditions.
0.51 to 1.02	Constant awareness of air motion, but can be acceptable if air supply is intermittent and if moving air temperature and room conditions are acceptable
1.02 and above	Complaints about blowing of papers and hair and other annoyances.

ppm. The following are the standards in force for ventilation rates for buildings.

The ventilation load can be determined by,

$$E = m\,(h_o - h_i) \quad ...(3)$$

Where, E is the ventilation load

m = rate of ventilation

$h_o - h_i$ = enthalpy of outdoor air - indoor air

The influence of air distribution on IAQ: Through utilizing the hydro-mechanical theory, the indoor air distribution can be calculated quite accurately according to the modern theory. Parameters like uneven coefficient, air distribution performance index, etc. are introduced to appraise air distribution performance. Inside the air conditioned room few positions give blowing sense. Pollutant will stay and gather when the return air is unable to reach or the air velocity is small, influencing indoor air quality seriously. The larger amount of fresh air, the less risk sick building syndrome will take place (Thirumal & Saraswathy 2010).

Increased ventilation rates and energy management: Introduction of even small amount of fresh air will increase the air conditioning energy cost. As the recommended levels of outside air brought into conditioned space has been increased by 4 times to 20 cfm from 5 cfm per person, much higher latent and sensible loads imposed on the cooling/heating equipment. This translates in two ways: an improved IAQ and significantly higher energy cost. This increase in energy can be reduced by recovery devices like rotary energy exchangers, coil energy recovery loop, twin tower enthalpy recovery loop, heat pipe heat exchangers, fixed plate exchangers and thermosyphon heat exchangers (Deepak Pahwa 2004).

Table 3: Classification of air contaminants.

Contaminants	Main sources
Gases & Vapours	Human beings
CO_2	Cigarette smoke
Butyric acid	Road & Highways
Carbon monoxide	Adjacent parking lots and garages
Nitrogen dioxide	Industrial area
VOCs	Paints, wood panelling, air freshener, pesticide sprays and cleaning agents
Inert particles	Man made fibres, dust etc.
Microorganisms	Damp corners,
(Fungus	Behind insulation,
Bacteria, Viruses,	Under carpets,
Moulds)	Evaporative/desert/swamp coolers, cooling towers, air washers, human beings

The volume of fresh air required for proper ventilation is determined by size and use of the space. Air change rate is expressed as:

$$N = 3600\, q/V \qquad ...(4)$$

Where, N = air change rate per hour
q = fresh air (make up air) flow through the room (m^3/s)
V = volume of the room (m^3)

CONCLUSION

A sufficient outside air ventilation rate is necessary to provide a healthy indoor environment. The potential increase in energy cost to heat, cool and dehumidify the ventilation air can be greatly moderated by control systems and energy recovery.

Demand controlled ventilation reduces the fresh air flow to match the building occupancy levels using carbon dioxide and potentially VOC sensors to control dampers and ventilation fans.

Cleaning and removing contaminants in the filters and return air path will improve the quality and quantity of recirculated air suitable for the occupied space. Energy recovery systems such as heat wheels, desiccant wheels, heat pipes and run around loops to recover energy from the exhausted air. It is feasible to increase the building air quality even in hot humid climates without a large increase in utility costs. Careful analysis of the above relations and design along with system commissioning is required to assure comfort and efficient conditions.

Table 4: CO_2 emission from persons based on their activity.

Activity	Respiration per person (m^3/h)	CO_2 emission per person (m^3/h)
Sleep	0.3	0.013
Resting or low activity work	0.5	0.02
Normal work	2-3	0.08-0.13
Hard work	7-8	0.33-0.38

Table 5: CO_2 concentration and human response.

CO_2 concentration in ppm	Human response
400 (4%)	Fresh air (Normal outdoor air)
1000 (10%)	Recommended indoor limit value
5000 (50%)	Hygiene limit value
15000 (150%) (Common pre alarm)	Shortness of breath and increased heart frequency
30000 (300%) (Common main alarm)	Muscular pain, unconsciousness, convulsions and risk of death
80000 (800%)	Convulsions, immediate paralysis and death

Table 6: Ventilation rates (in cubic feet metre).

Application	Ventilation rate/person	Application	Ventilation rate/person
Office space	20 cfm	Smoking lounge	60 cfm
Restaurants	20 cfm	Beauty saloon	25 cfm
Bars/Cocktail	30 cfm	Supermarkets	15 cfm
Hotel rooms	30 cfm/room	Auditorium	15 cfm
Conference rooms	20 cfm	Classrooms	15 cfm
Hospital rooms	25 cfm	Laboratory	20 cfm
Operating rooms	30 cfm	General retail	15 cfm

Source: ASHRAE standard 62-1989

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