EFFECTS OF LOW HUMIDITY ON COMFORT, HEALTH, AND INDOOR ENVIRONMENTAL QUALITY: LITERATURE REVIEW

by

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Abstract

This study was conducted to investigate the effects of humidity on comfort, health, and indoor environment quality (IEQ) using a comprehensive literature review. Published papers were obtained from keyword and citation searches from bibliographic databases (i.e., PubMed, Scopus, and Google Scholar), including papers from 1985 to 2015. Over 600 papers were identified and classified based on topic area; from these papers, seven were chosen as case studies for this report.

The seven papers represent studies on various topics, including bacteria, influenza/virus transmission, elderly subjects, indoor air quality, effects on eyes and skin, dust mites, and asthma. Theunissen et al. (1993) showed bacteria (gram positive and gram negative) do not act the same in low or high humidity conditions. Lowen et al. (2007) studied influenza transmission. Sunwoo et al. (2006) used elderly subjects to study eyes, skin, and comfort. Reinikianen et al. (1992) and Nordström et al. (1994) surveyed a large number of subjects, controlled humidity, and assessed multiple factors regarding indoor health and comfort. Arlian et al. (2001) implemented dehumidifier as a way to reduce house dust mites. Kaminsky et al. (1995) tested asthmatic subjects and healthy subjects to compare the effects of dry air on asthma. From these case studies low humidity appeared to have a variety of effects on health and comfort; however, no precise and defined borderline exists to distinguish acceptable low humidity. Acceptable low humidity levels depend on many factors, including building location and purpose, age of occupants, and climatic conditions.

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Dedication

Dedicated to my lovely Family.

تقدیم به خانواده عزیزم.

Chapter 1 - Introduction

Many people in North America spend about 90% of their time indoors [1]. As a result, investigation of indoor building environments has become important. Residential and commercial buildings consume 40% of the total energy in the United States (Figure 1) [2]. Energy is required to meet heating and cooling demands depending on the climate. In addition to minimizing energy consumption, buildings must be healthy and comfortable for occupants. Humidity level is a primary factor affecting building human comfort, health, and indoor environmental quality (IEQ). IEQ is related to lighting, air pollutants, and health and well-being of occupants. Many studies have been conducted to determine effects of high humidity on building occupants, including negative effects of high humidity in kitchens and bathrooms [3-5]. However, with the exception of the literature review by Sterling et al. [6], few in-depth case studies have focused on impacts of low humidity. Therefore, effects of low humidity on health, comfort, and IEQ must be studied.

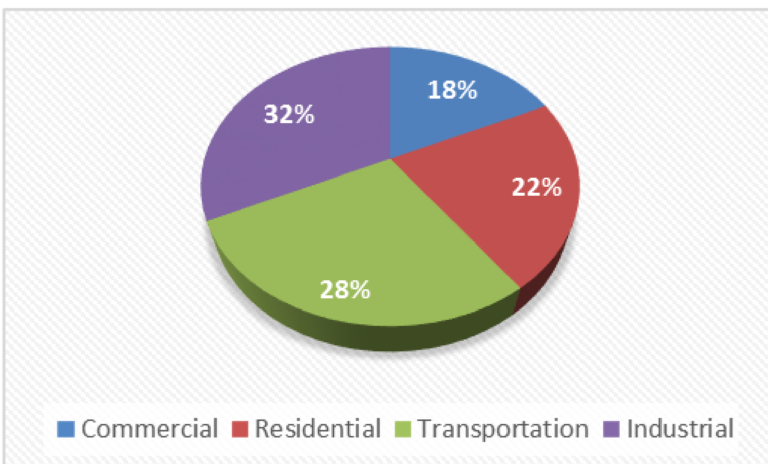

Figure 1: Total US energy consumed by major sectors of the economy. Data were obtained from the U.S. Energy Information Administration [7]

1.1 Humidity definitions

Humidity describes the water content in air. Definitions of humidity, including relative, absolute, and specific humidity are presented in the following sections. Definitions were obtained from the ASHRAE Fundamentals Handbook [8].

Relative humidity (Φ) or RH is the ratio of the mole fraction of water vapor X_w in a given moist air sample to the mole fraction X_{ws} in the air sample saturated at the same temperature and pressure (eqn 1). Relative humidity can also be defined as the ratio of partial pressure (P_w) to saturation pressure (P_{ws}).

$$\Phi = \frac{X_w}{X_{ws}} = \frac{P_w}{P_{ws}} \tag{1}$$

Absolute humidity (d_v) is the ratio of the mass of water vapor (M_w) to total volume of the sample (V) :

$$d_v = \frac{M_w}{V} \tag{2}$$

$$dv = \left(\frac{\gamma}{1-\gamma}\right)\left(\frac{1}{V_g}\right) \tag{3}$$

where V_g is saturated vapor and ɣ is the specific humidity.

Specific humidity (ɣ) is the ratio of the mass of water vapor (M_w) to total mass of the moist air sample:

$$\gamma = \frac{M_w}{M_w + M_a} \tag{4}$$

where M_a is the mass of dry air. Specific humidity is related to humidity ratio (W):

$$\gamma = \frac{W}{W+1} \tag{5}$$

At low relative humidity, ɣ ≈ W.

Humidity ratio (W) is the ratio of the mass of water vapor in the air to the mass of dry air:

$$W = \mathbf{M_w} / \mathbf{M_a} \tag{6}$$

It can also be expressed as

$$W = 0.622 \frac{\mathbf{P_w}}{\mathbf{P - P_w}} \text{ , where } \mathbf{P_w = \Phi P_{ws}} \tag{7}$$

Dew point temperature is another metric used to assess humidity. It is defined as "temperature of moist air saturated at pressure *P* with the same humidity ratio *W* as that of given sample of moist air."[9]

1.2 Relationship between humidity parameters

The relationship between humidity parameters is illustrated for three different temperatures (i.e., 15°C, 20°C, and 25°C) in Figures 2, 3 and 4 respectively. At low RH, temperature is less important. As shown in the figures, the slope of each curve differs for each temperature and RH. Absolute humidity is inversely proportional to specific humidity.

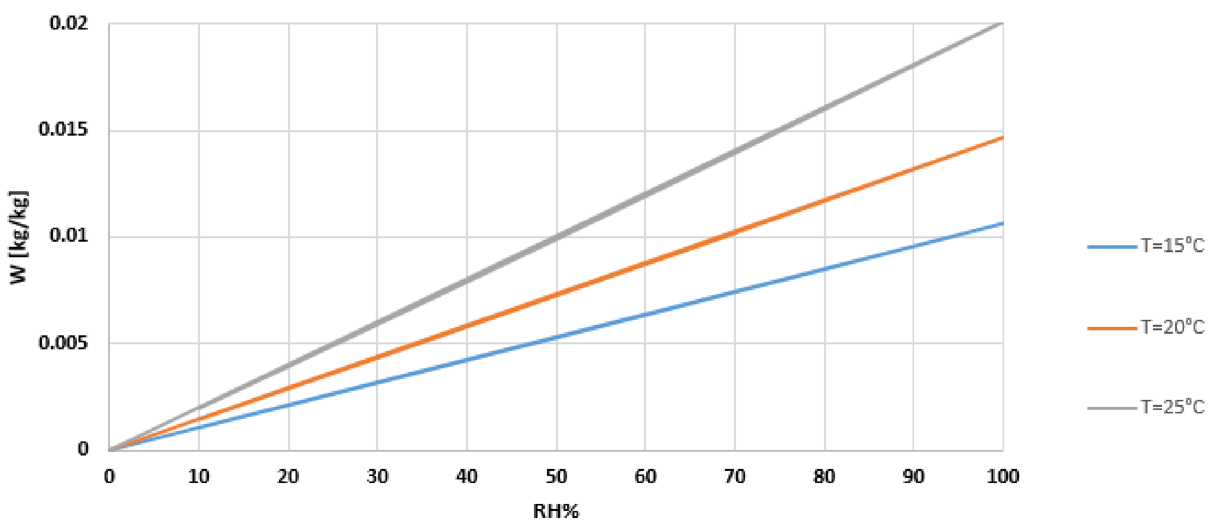

Figure 2: Relationship between relative humidity and humidity ratio

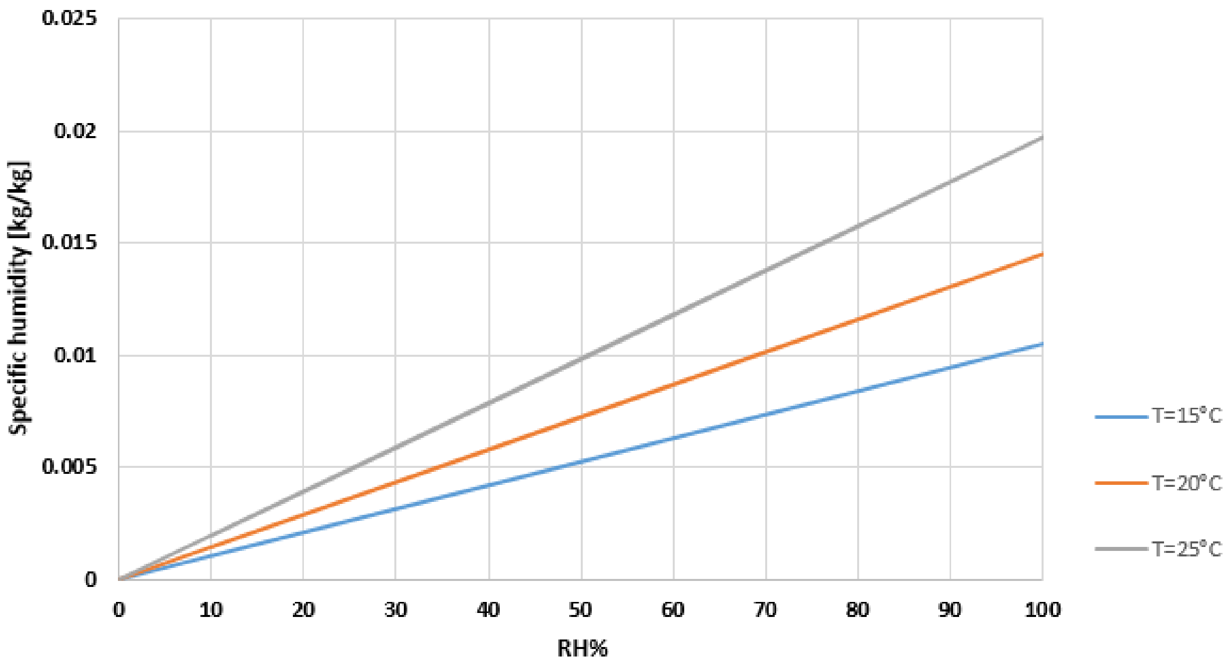

Figure 3: Relationship between relative humidity and specific humidity

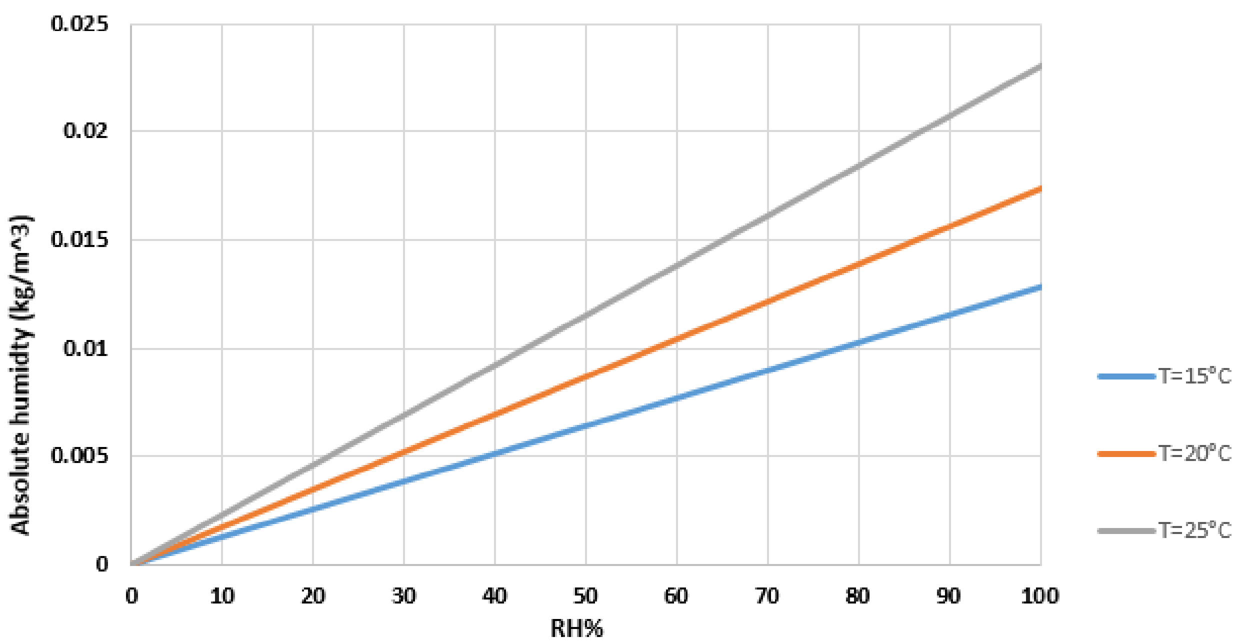

Figure 4: Relationship between relative humidity and absolute humidity

1.3 Objectives

The objectives of this study are to review the effects of low humidity on health, comfort and indoor environmental quality (IEQ); and identify papers for case studies in the different categories. A detailed survey of the technical literature to determine effects of low humidity in occupied buildings was conducted. The survey focused on health, comfort, and IEQ aspects of low humidity.

1.4 Literature review process

This report discusses the effects of low humidity in occupied buildings. It focuses on studies that have appeared in the technical literature, beginning with Sterling et al. [6] until studies in 2015. A few studies prior to 1985 are included due to the importance of the data and referencing of the data by current literature.

Literature review search was conducted to find relevant literature using keyword and citation searches. Keywords, as shown in Table 1, were combined with “low humidity” and “dry air.” For citation searches, important papers were identified (Table 2). Databases such as PubMed, Scopus, and Google Scholar were searched. Keyword combinations used are shown in Table 2.

Several approaches were used to conduct an exhaustive search. One method was to search references of retrieved articles, determine which articles were relevant, find those, read their references, and repeat the process until no new articles were identified.

The papers were sorted and placed in folders for various categories (i.e., health, comfort, and IEQ) and subcategories. When searches were completed, the list of references was shared with experts in the field to detect any missing articles, and additional references were added to the database.

Table 1: Keyword search terms

Category	Search terms
Comfort	Low humidity, Impact, Comfort , Skin Dryness, Thermal comfort, Comfort, Eye Irritation, Static Electricity, Low Moisture, Occupied Building, Home, School, Hospital, Indoor Environment, Humidity Ratio,Water Loss, Absolute Humidity
Health	Health Effects, Bacteria, Virus, Influenza, Pneumonia, Asthma, Allergy, Mites, Infections, Respiratory Infections, Fungi, Allergic, Rhinitis, Physiological Effects, Eukaryote, Eukarya, Fungal, Metagenomics, Microbes, Microbial, Microbiota, Microbiome, 16 S RNA, Disease Transmission
IEQ	Bioaerosol, Ozone Generation, Particulate Level, Particulate Generation
Population	Adolescents (<18), Adults, Adults over 65 old, Young, Elderly

When data collection was completed, obviously irrelevant articles were identified and discarded. Discarded articles included studies that focused only on high humidity, studies that did not provide data for RH less than 40%, or studies that were conducted on non-human subjects (except for disease transmission). Then, determination was made as to which of the remaining articles were relevant. The criteria for selecting relevant articles included use of control group, study occurrence within a desired year range, measurements and reporting of temperature and RH, use of human subjects, and study of low humidity (RH≤40%). The articles were classified as literature review, experiments, or modeling. The type of data and the process used were also documented. Tables were generated for recorded data for each article, including variables such as humidity level or percentage, temperature, location, year, country, age, and data analysis procedures as well as the types of experimental controls, and other data that helped track the extraction of research outcomes.

Papers were classified according to the following factors that affect building occupants:

- Health: asthma, allergies, bacteria, influenza, mite, pneumonia, virus
- Comfort: eye irritation, skin dryness, thermal comfort, static electricity
- Indoor environment quality: indoor air quality (IAQ), ozone generation, particulate generation, particulate level.

Table 2: List of papers that were identified

Category	Subcategory	Key papers	Papers found
Comfort	Eye irritation	McCulley et al. [10]	Abelson et al. [11], Abusharha and Ian Pearce [12], Arciniega et al. [13], Borchman et al. [14], González-García et al. [15], Mathers and Daley [16], Mathers et al. [17], McCulley et al. [18], Ousler et al. [19], Tomlinson et al. [20], Viso et al. [21]
	Skin dryness	Sunwoo et al. [22]	Alikhan et al. [23], Andrasko and Schoessler [24], Chou et al. [25], Hashiguchi and Tochihara [26], Hurlow and Bliss [27], Llamas-Velasco and García-Díez [28], Mercke [29], Su et al. [30], Wan et al. [31]
	Skin dryness	Reinikainen et al. [32]	Andersson et al. [33], Angelon-Gaetz et al. [34], Bakke [35],Fang et al. [36], Gavhed and Toomingas [37], Höppe [38], Huang et al. [39], Mendell and Mirer [40], Nguyen et al. [41], Nordström et al. [42], Reinikainen et al.[43], Wang et al. [44]
	Thermal Comfort	Berglund et al. [45]	Atmaca and Yigit [46], Backman and Haghighat [47],Chen and Horton [48], Chinevere et al. [49], Fischer et al.[50], Fischer and Bayer [51], Ho and Young [52], Howell [53], Khodakarami et al. [54], Khodakarami and Nasrollahi [55], Lück [56], Olesen and Parsons[57], Olesen et al. [58], Olesen [59], Palonen et al. [60], Simonson et al. [61], Skoog [62]
Health	Asthma	Bundgaard et al. [63]	Anderson et al. [64], Bethel et al. [65], Hayes et al. [66], McFadden and Gilbert [67], Pavilonis [68], Singh et al. [69], Soter et al. [70]
	Asthma	Strauss et al. [71]	Douglas et al. [72], Gilbert et al. [73], Noviski et al. [74], Stone et al. [75], Strauss et al. [76], Thomachot et al. [77]
	Bacteria	Dunklin et al. [78]	Awad [79], Bateman et al. [80], Berendt [81], Cox [82], Ehrlich et al. [83], Ko et al. [84], Lester [85], McDade [86], Songer [87], Tang [88], Wathes et al. [89], Won and Ross [90], Wright et al. [91]
	Influenza	Shaman et al. [92]	Airoldi and Litsky [93], Barreca and Shimshack [94], De la Noue et al. [95], Huang et al. [96], Koep et al. [97], Lowen et al. [98] Schaffer et al. [99], Shaman and Kohn [100], Shaman [101], Yang and Marr [102]

	Mite	Howieson et al. [103]	Allinson and Hall [104], Arlian et al. [105], Arlian [106], Gunnarsen et al. [107], Harvie-Clark and Siddall [108], Hobday[109], Hobday [110], Howieson [111], Luczynska et al. [112], Pretlove et al. [113]
	Pneumonia	Theunissen et al. [114]	Cox [82], Hatch and Dimmick [115], Karim [116]
	Virus	Akers et al. [117]	Donaldson [118], Hermann et al. [119]
Population	Elderly	Chou et al. [120]	Alikhan et al. [23], Collins et al. [121], Diaz et al. [122], Garcia [123], Hashiguchi et al. [124], Hurlow and Bliss [27], Inbar et al. [125], Mäkinen et al. [126], Pfluger et al. [127], Rocklöv and Forsberg [128], Rudge [129], Salah et al. [130], Seyfarth et al. [131], White-Chu and Reddy [132]
IEQ	Ozone generation	Grøntoft. and Raychaudhuri [133]	Altimir et al. [134], Grøntoft [135], Nicolas et al.[136], Uhde and Salthammer [137], Vibenholt et al. [138], Weschler [139]
	Particulate generation	Hitzenberger et al. [140]	Airoldi and Litsky [93], Galadanci and Tijjani [141], Hänel [142], Kreisberg et al. [143], Li-Jones et al. [144], McMurry and Stulzenberg [145], Mølhave and Pedersen [146], Rood et al. [147]
	IAQ	Fang et al. [148]	Goyal et al. [149], Olesen [150], Schnell et al. [151] Šeduikyte and Paukštys [152], Skov et al. [153]
	IAQ	Nordström.et al. [42]	Fiedler et al. [154], Green [155], Hodgson [156] Norbäck et al. [157], Reinikainen [43], Reinkainen et al. [158], Skov et al.[159]
	IAQ	Wolkoff,et al. [160]	Bornehag et al. [161], Cain et al. [162], Fang et al. [163], Geving and Holme [164], Hersoug [165], Undin et al. [166], Mlakar and Strancar [167], Rani et al. [168], Weschler [139], Wilkins et al.[169], Woloszyn et al. [170]

Case studies

The papers selected as case studies for this report fit a majority of the desired criteria, and they generally showed more than one aspect. Number of selected papers are listed in Table 3. Theunissen et al. [112] showed bacteria (i.e., gram positive and gram negative) do not act the same in low or high humidity. Lowen et al. [171] studied influenza transmission. In terms of pathogen, there were two papers, one selected paper studied influenza and another paper studied pneumonia. These two papers were chosen for this report because they investigated very common pathogens and important for IEQ. Sunwoo et al. [22] was the only paper that studied the elderly, and studied eyes, skin, and comfort, and this advantage made this paper a good choice. Reinikianen et al. [158] and Nordström et al. [42] had large number of subjects, and controlled humidity. Also they had questionnaires and assessed multiple factors regarding indoor health and comfort. Arlian et al. [172] implemented dehumidifying as a nonchemical way to reduce dust mites. Kaminsky et al. [173] compared asthmatic subjects and healthy subjects. Selected case studies are listed in Table 4.

Table 3: Categories and number of relevant papers

Category	Keyword	Total number of papers found	Number of selected papers
	Eye irritation	23	6
Comfort	Skin dryness	32	7
	Static electricity	6	3
	Thermal comfort	49	3
	Allergy Mite Rhinitis	12 35 5	5
Health	Asthma Respiratory effects	36 19	7
	Bacteria Infection	16 7	7
	Fungi	25	3
	Influenza Virus	32 52	13
	Pneumonia	8	0
IEQ	IAQ Ozone generation	61 19	11
	Particulate generation	26	0
	Particulate level	23	0
Population	Adolescent	3	2
	Elderly	32	2
		521	

Table 4: Selected case studies

Category	Selected paper
Influenza/ Virus	Lowen et al. (2007)
Elderly	Sunwoo et al. (2006)
IAQ	Reinikainen et al. (1992)
Eye/Skin	Nordström et al. (1994)
Mite	Arlian et al. (2001)
Bacteria	Theunissen et al. (1993)
Asthma	Kaminsky et al. (1995)

Chapter 2 - Case Studies

2.1 Sunwoo et al. (2006)

Sunwoo, Y., Chou, C., Takeshita, J., Murakami, M., and Tochihara, Y. (2006). Physiological and subjective responses to low relative humidity in young and elderly men. Journal of Physiological Anthropology, 25(3), 229-238.

Objective

Determine effects of low humidity on people's eyes, skin, and mucous membranes, and determine whether these effects vary according to age.

Test conditions

In order to determine the effects of age on response to low humidity, eight young (mean age=21.7 years) and eight elderly men (mean age=71.7 years) were selected for the study. The subjects wore standardized clothing and sat in a pretest room for 50 minutes which had humidity of 50% and temperature of 25°C for all tests. Initial measurements such as weight and body temperature were taken and then, the subjects were transferred to a test room at 25°C temperature, and RH of 10%, 30% or 50%, for 180 minutes. The subjects were asked about their response to thermal, dryness and comfort sensations with the help of a rating scale. Saccharin clearance time (SCT) was measured to understand low humidity effects on mucous membrane and blinking frequency for eye dryness. Sebum level recovery, transpidermal water loss (TEWL), hydration state for face and hands, and mean skin temperature were used to determine the effects on skin. In addition to these measurements, the subjects were asked regarding thermal comfort and feeling of dryness.

Results

An undesirably high SCT was found in the elderly group at humidity of 10%. For SCT, which is a measure of mucocillary clearance, RH did not affect the young men or elderly men at

30% and 50% RH. In addition, time and RH did not significantly influence the perception of nasal dryness for the young or elderly subjects. In general subjects in the young group felt drier throat at RH of 10%, but the conditions did not strongly impact the sensation of skin dryness for all subjects.

The young group demonstrated an increase in blinking frequency between pre-test room and tests at 10% and 30% RH. For eye dryness, the young men reported drier eyes than the elderly group even though blinking frequency was identical. Hydration state for the face was lower for both groups at 10% and 30% RH compared to the hydration at 50% RH. Similarly, hand hydration was lower at 10% for both groups. Researchers found higher TEWL on the face for the young and elderly groups, although age did not strongly affect TEWL. The largest changes in TEWL occurred at the beginning of the test, in the first 30 minutes, but after that it was mostly constant. Based on a thermal comfort surveys, the subjects did not perceive dryness on faces and hands in all test conditions. At low humidity (10% and 30% RH) only the initial change from the pretest humidity to room humidity affected thermal comfort.

Discussion

This study by Sunwoo et al. [22] utilized unique testing conditions, including three RHs and test subjects of approximately 50 years old. Many studies do not consider elderly subjects, making this inclusion advantageous to the study. In addition, the authors considered parameters related to mucous membranes, eyes, and skin. The strength of the study also includes the wide range of parameters and unique ages of subjects. However, limitations of the study include the small sample size of subjects (N = 8) and limited exposure time of 3 hours when, in reality building occupants may be exposed to low RH over days or months. Although the authors measured multiple parameters, it is not clear how those parameters directly link to mucous, eye dryness, and skin dryness. For example, blinking frequency was used to determine eye dryness. Additional study could determine how a subject's vision changes with low humidity, and what adaptations or problems may occur over time.

Results indicated that eye dryness may occur at 10%-30% RH. Moreover, SCT was higher for elderly men at 10% RH, possibly indicating reduced mucous transport and leaving subjects more at risk for respiratory infections. In addition, some indications of skin dryness were evident at 10% and 30% RH compared to 50% RH. For all test cases, 50% RH was very comfortable but subjects experienced effects below 50% RH. For building conditions, if possible 50% RH is a good target.

A majority of the behavior related to mucous membrane, eye, and skin dryness for subjects was similar in the elderly and young subjects for 3 hours low humidity exposure. However, the elderly subjects had a harder time sensing dryness. Elderly patients may be unable to realize dry conditions. This lack of sensitivity should be considered for hospitals and nursing homes. The human body seems to adapt partially for skin dryness, at lower RH, future study could determine if it continues long-term. A long- term study of effects of low RH on elderly subjects, including physiological health and illness, would be beneficial in order to draw stronger conclusions related to indoor conditions in hospitals and skilled nursing facilities.

2.2 Reinikainen et al. (1992)

Reinikainen, L. M., Jaakkola, J. J., and Seppänen, O. (1992). The effect of air humidification on symptoms and perception of indoor air quality in office workers: a six-period cross-over trial. Archives of Environmental Health, 47(1), 8-15.

Objective

Study the effects of air humidification on dryness of the skin and mucosa, on allergic and asthmatic reactions and perception of indoor air quality.

Test conditions

The researchers surveyed office workers regarding perceptions of low humidity. Responses from 290 subjects (148 males and 142 female) were drawn from 362 office workers in a building in Helsinki, Finland. The study was conducted in winter. The building had two similar wings: one used a steam humidifier to maintain RH in the range of 30% – 40 %, and the other wing used only natural conditions with a humidity range of 20%-30%. Due to the warm outdoor weather conditions, the humidity was higher than expected. Indoor air temperature ranged from 21.3°C to 23.9 °C during the humidified period and was 0.5°C higher than the reference phase without supplemental humidification. In the humidified wing, RH was 30%-35%. The two wings had different humidities for three weeks but equal humidities during the last week of the study. The study was conducted as a six-week cross-over trial. No supplemental humidification was added during the first week of the study. The humidifiers were switched on and off during the weekend, so wing B had humidification during the second week of the study and wing A used natural nonhumidified conditions. Each wing experienced three weeks with humidification and three weeks without humidification. None of the subjects knew the time of alteration, so it was a blind trial. Each subject recorded his/her daily perception of indoor air and symptoms.

Results

Seventy-two percent of the workers in the study experienced humidified and nonhumidified conditions and recorded the daily diary at least for two weeks. Symptoms are shown in Table 5. Allergic and asthmatic symptoms were less common when using humidifier although the decrease in asthma scores was not statistically significant. Single symptoms of the dryness score were observed less often in the humidified phase than the reference phase (non-humidified period), with the exceptions of nasal and throat dryness. For mean general symptoms, no considerable differences were observed for headache, weakness, nausea and lethargy. Conversely, sensation of dryness was much more common in the non-humidified phase, but perception of stuffy air increased significantly with humidification (Table 5).

Table 5: Means of health scores used in the experiment. Data from Reinikainen et al. 1992 [158]

Health Parameters	Symptoms	Humidification phase	Reference Phase
Dryness symptom	Skin symptoms	0.38	0.42
	Eye symptoms	0.35	0.39
	Nasal dryness	0.49	0.48
	Pharyngeal dryness	0.26	0.30
Allergic reactions	Nasal congestion	0.36	0.39
	Nasal excretion	0.15	0.17
	Sneezing	0.17	0.16
	Eye symptoms (as above)		
Asthma symptom	Cough	0.08	0.10
	Wheezing	0.01	0.02
	Breathlessness	0.02	0.03
General symptom	Headache	0.15	0.14
	Lethargy	0.13	0.13
	Weakness	0.02	0.03
	Nausea	0.03	0.03
Perception of indoor air quality	Sensation of dryness	3.35	3.43
	Unpleasant odor	0.31	0.27
	Stuffiness	0.74	0.62
	Dustiness	0.46	0.50
	Draft	0.47	0.50

Discussion

This study investigated the effects of humidification on symptoms of sick building syndrome (SBS). The authors provided a case study of office workers to investigate the effects of low humidity on these symptoms. They stated that proper humidification can positively affect human health factors such as dryness of skin and mucosa, allergic reactions and the sensation of dryness. Skin dryness, eye dryness stuffiness and allergic symptoms showed the most significant differences between humidified and non-humidified environments. Increased skin and eye dryness was observed for the non-humidified wing compared to the humidified wing and a decrease in the allergic reaction score was observed for the humidified wing. Moreover, in the humidified wing the air was perceived to be stuffier. In contrast, no statistical differences were evident in nasal dryness and pharyngeal dryness, asthma scores, odor or draft perception between the two wings. Daily assessment of the feeling of dryness revealed that people did not feel strong differences. Based on results of this study 20%-30% RH is acceptable for many people.

The strength of this study is that it included a large number of subjects thereby providing a good sample size for statistical analyses. In addition, authors studied multiple health factors which is helpful. One limitation of the study was the lack of control of the office environment for the non-humidified period control. Due to the unseasonably warm temperature for winter, the non-humidified space humidity approached humidified section humidity. In this study the researchers surveyed the subjects about 21 symptoms. The survey results were added up to provide composite dryness, allergic, asthma and perception of indoor air quality scores. However, the scales differed and, although perception of indoor air quality is statistically meaningful, how people perceive air quality differs. In addition, the subjects were exposed to this condition for one week, but the researchers did not include time as a variable. For example, they did not compare first day to last day. Future work could investigate how people adapt to the new conditions. Because the

Scandinavian climate often experiences indoor conditions of 10%-20% RH, it would be interesting to repeat the test on a different population.

In conclusion, although the experiment occurred during a mild winter and humidity conditions were the same in the last week of the study because the weather was warm, the factors mentioned above led to the conclusions that dryness symptoms can occur when indoor RH is 20% - 30% and that skin and mucosa of the eye and respiratory tract are affected by dry air. Results showed that a drawback of increased humidification is the feeling of stuffy air; however, the effects on the office workers seemed modest.

2.3 Lowen et al. (2007)

Lowen, A. C., Mubareka, S., Steel, J., and Palese, P. (2007). Influenza virus transmission is dependent on relative humidity and temperature. PLoS Pathogens, 3(10), e151.

Lowen, A. C., and Steel, J. (2014). Roles of humidity and temperature in shaping influenza seasonality. Journal of Virology, 88(14), 7692-7695.

Objective

Study the effect of humidity on virus influenza transmission with a guinea pig model

Test conditions

Researchers used a guinea pig model to study influenza transmission. Tests were conducted at three temperatures (i.e. 5°C, 20°C and 30°C) and five relative humidities (i.e.,20%, 35%, 50%, 65% and 80% RH). Four of eight guinea pigs were infected by the influenza virus, the remaining exposed pigs were placed in an environmental chamber separate from the infected pigs. The only way for transmission of influenza virus was through air flow since direct contact between animals was not permitted. Four possible instances of transmission at each temperature and humidity condition were possible, a transmission rate of 0% meant no transmission (0 out of 4 exposed guinea pigs were infected), and a transmission rate of 100% meant all four exposed guinea pigs were infected with influenza.

Results

The behavior of the guinea pigs did not change at different RHs. When the temperature changed from 5°C to 20°C, they also did not act differently; however, when the temperature rose to 30°C, the authors observed that the guinea pigs "consumed more water and seemed to be more lethargic." No obvious symptoms of diseases were observed in the guinea pigs. At a room temperature of 20°C, influenza transmission rates were high (75%-100%) at 20% RH and 35% RH. At 50% humidity, transmission rates dropped to 25%. As RH increased to 65% and 80%, influenza transmission rates were 75% and 0%, respectively. Lower transmission rates (0-25%) were found at an intermediate RH (50%) and very high RH (80%). Regarding the effects of temperature, at 5°C transmission rates were higher than at 20°C. However no transmission occurred at 30°C, although tests were only conducted at 35% RH.

Due to the temperature dependence of influenza transmission and interest in absolute humidity in the field, Lowen and Steel (2014) converted the data from RH to absolute humidity. They hypothesized that absolute humidity is a better metric than RH, because increased transmission was observed at 5°C. They hypothesized that absolute humidity is more important for influenza transmission. Saturation pressure, and subsequent relative humidity, changes with temperature while absolute humidity is the mass of water per unit volume of air, and it is not dependent on temperature. The researchers reanalyzed the data, and results showed no significant relationship between absolute humidity and virus transmission. For example, at an absolute humidity of 6 g/m^3 and 11 g/m^3 influenza transmission rates of 0-100% were plotted. At high absolute humidities (20-25 g/m^3), no transmission occurred, but that corresponded to a temperature of 30°C (Figure 5).

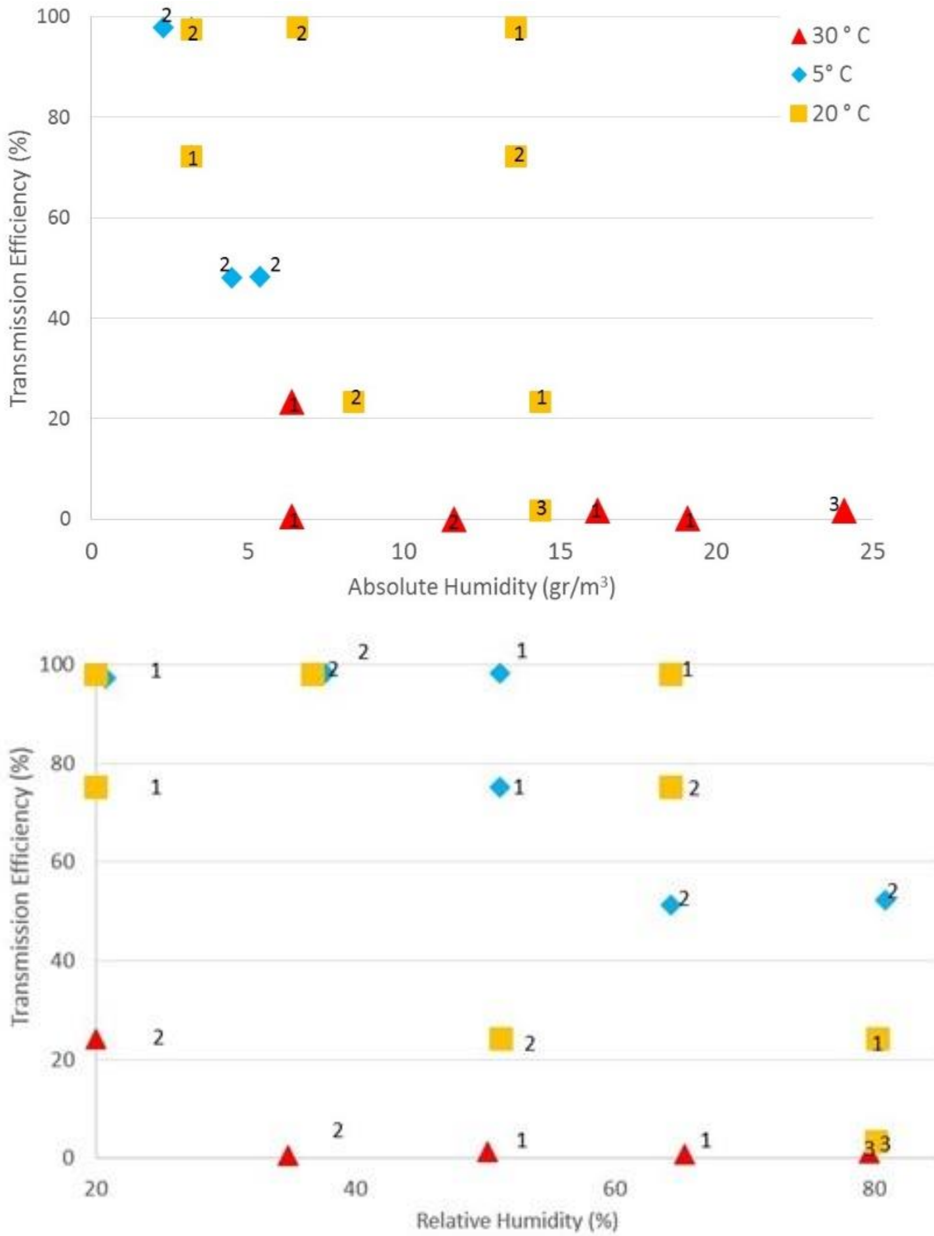

Figure 5: Virus transmission in guinea pigs changes with humidity and temperature. Data from Lowen et al (2007) [174]. The numbers near each symbol shows the number of replication in experiment.

Discussion

As shown in the experiment, cold temperature and low humidity increases influenza transmission. The authors suggested that mid-range of humidity at room temperature results in decreased influenza transmission. One advantage of this study is that a large range of various environmental conditions was tested. However, the limited number of guinea pigs did not create a large sample size, and, as a result, only four possible transmissions occurred. A unique advantage of this experiment is that the researchers considered transmission of influenza, not only the viability of viruses. However, the study also contained weaknesses. For example, the researchers focused on airborne viruses, but many other methods for virus transmission are available in nature. In addition to the air, influenza virus may be transmitted among humans by direct contact with infected individuals or contaminated objects. Also, this experiment was not conducted on people, so the results must be generalized to human influenza transmission and there is not a lot of data on each combination

Authors concluded that midrange humidity (50% RH) at room temperature reduces influenza transmission. The epidemic influenza must be minimized in hospitals or nursing facilities, and humidifying to midrange humidity could be one of the easiest ways to prevent the spread of influenza. Indoor air temperatures at 20°C and humidity around 50% RH may reduce the airborne spread of influenza. This is especially important in winter, since RH decreases, with the use heating systems. Lack of virus transmission at 80% RH was surprising based on other studies.

2.4 Theunissen et al. (1993)

Theunissen, H. J., Lemmens-den Toom, N. A., Burggraaf, A., Stolz, E., and Michel, M. F. (1993). Influence of temperature and relative humidity on the survival of Chlamydia pneumoniae in aerosols. Applied and Environmental Microbiology, 59(8), 2589-2593.

Objective

Study the influence of temperature and relative humidity on the survival of aerosolized *Chlamydia pneumonia*

Test conditions

Researchers aerosolized *C. pneumonia* into an environmental chamber. Air samples were taken 30 seconds after aerosolization and then every minute until 5.5 minutes. Temperatures used for this experiments were 8.5°C, 15°C, 25°C and 35°C, and three RH levels, 5%, 50%, 95%, were tested at each temperature. Survival of *C. pneumonia* was studied at these temperatures and relative humidities.

Results

For *C. pneumonia*, in the first 30 seconds after aerosolization there was a rapid, order-of-magnitude decrease in percent of viable. As time increased, the percent viable continued to decrease, but at a more gradual rate. The optimal range of temperature and humidity for bacteria survival was shown to be 15-25°C and 95%, respectively, since those cases had the highest survival fractions. Results showed that *C. pneumoniae* can persist in aerosols. Bacteria viability at 95% RH was higher than at 50% RH. The result at 8.5°C was similar to 15°C, 95% RH. Decline in the first 30 seconds of aerosolization was the sharpest at all humidities. In 8.5°C that both 50 and 95 % RH the results had very similar trends.

Maximum survival occurred at temperatures of 15°C and 25°C but no great differences were observed between survivability at 15°C and 25°C. The minimum survival rate for 50% RH occurred at 35°C (Figure 6).

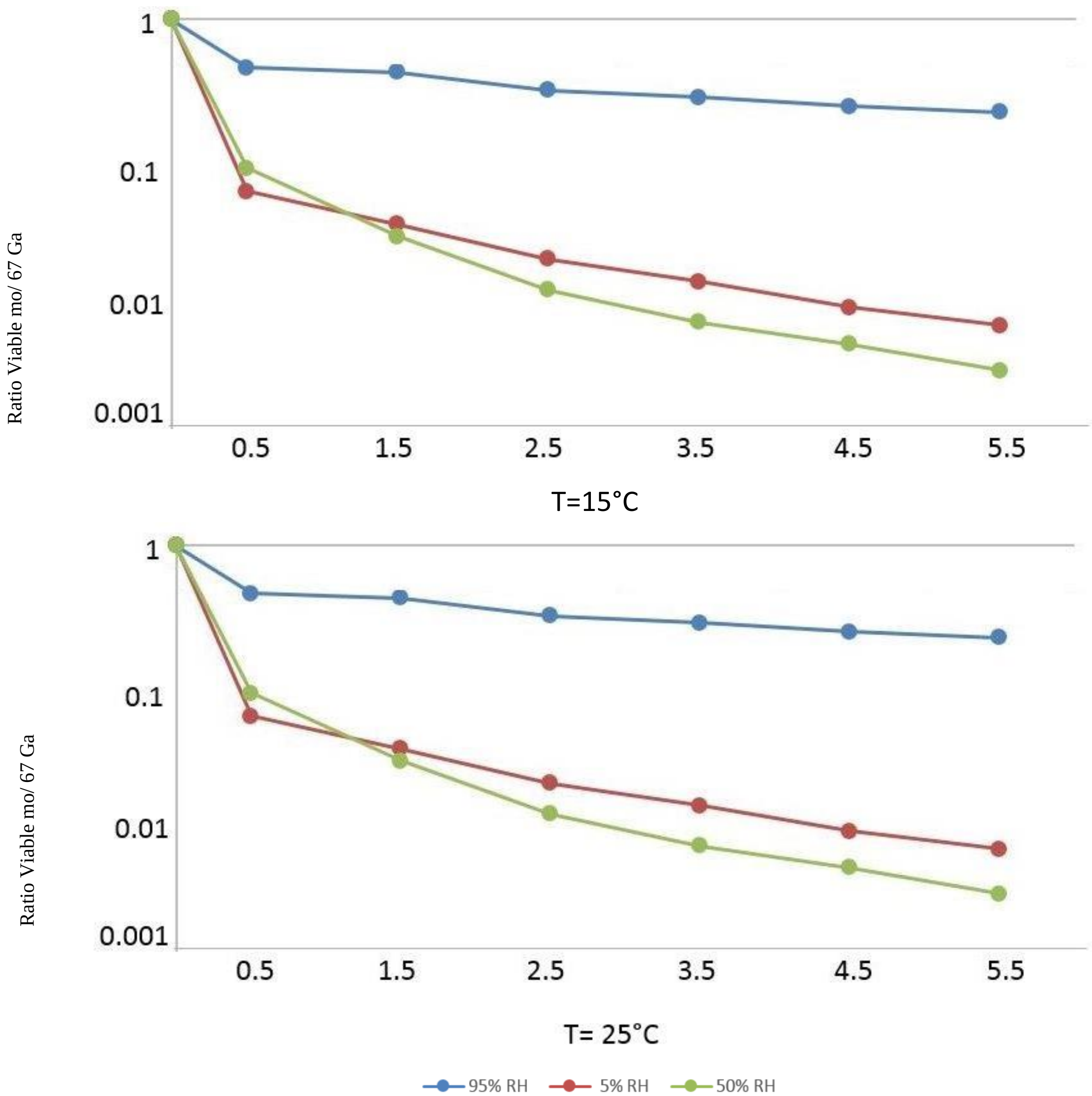

Figure 6: Survival of C pneumoniae at different temperatures and RH. The decline of infectious organisms number in aerosols are shown by the ratio of survival in microorganisms/67Ga. Data from Theunissen et al. (1993) [114]

Discussion

Factors such as RH, temperature, oxygen, UV radiation, and constituents of the aerosol and air were shown to affect the survival of microorganisms in aerosols. The time after aerosolization and the type of the microorganism are essential for determining the effects of each factor. Bacteria are classified based on their membranes, gram positive and gram negative. Gram negative bacteria, typically have higher lipid content, and because of different envelopes, gram negative bacteria survive better in dry cold air. However, gram positive bacteria live longer in humid cold air. Viruses with lipid membrane can survive better in low RH. Gram negative bacteria and lipid-containing viruses show changes in their external phospholipid bilayer membranes in response to fluctuating humidity and temperature. Virus surfaces without lipid membrane react faster to low RH, thereby decreasing viability [175]. In this case, although *C. pneumonia* is classified as a gram negative bacteria, it can survive best in aerosols in humid air between 15°C and 25°C. This behavior is opposite of other gram negative bacteria, leading to the conclusion that its outer protein membrane is more coherent compared to other bacteria. Other structural components can also increase the rate of survival and it is not a general role for classification microorganism based on the gram positive and gram negative.

Dry air also plays a dramatic role in inactivation of *C. pneumonia* by removing structural water molecules decreased RH increases evaporation. The optimum temperature range for survival of *C. pneumonia* is 15-25°C and high RH. Time is important in this trend. This bacteria shows significant decrease in inactivation due to evaporation in low RH, where the membrane will react to this change and lipids' liquid crystalline state will change to gel state and leads to inactivation. A lipid membrane phase transition changes the gel state to irregular fluid (liquid crystal). However, the transfer is dependent on the temperature. Below this temperature it is in gel state and above this temperature it converts to liquid crystal [176]. Time is important since in the first 30 seconds it shows a sharp and then gradual decrease in survival in 5 minutes.

This study included three ranges of RH and four separate temperatures which showed a wide range of environmental conditions. Time is an important factor. The authors showed the result for a time period of (0-5.5 minute). At 25°C and 15°C, survival declined to a steady state value, but for temperatures of 8.5°C and 35°C a steady state was not achieved, and more changes occurred over time. A very sharp change was observed in the first 30 seconds and then there was a gradual decline, but every case did not reach steady state after 5.5 minutes. The researchers sampled frequently, which is very helpful but percent of viability was stable and not a function of time in some environmental conditions.

Lowen et al. [171] studied the effect of RH on the transmission of influenza virus, and Theunissen et al. [114] focused on viability of *C. pneumonia* bacteria. These two experiments showed that the life cycle of many microorganisms which negatively affect human health are dependent on temperature and humidity. For influenza the midrange of humidity had the lowest transmission rate. In conclusion, indoor humidity levels are a key factor for pathogen viability and survival.

2.5 Nordström et al. (1994)

Nordström, K., Norbäck, D., and Akselsson, R. (1994). Effect of air humidification on the sick building syndrome and perceived indoor air quality in hospitals: a four month longitudinal study. Occupational and Environmental Medicine, 51(10), 683-688.

Objective

Study effects of humidity on sick building syndrome (SBS) and indoor quality in winter

Test conditions

This research studied 104 people who worked in two geriatric hospitals in Sweden. Four units in the hospital had never had air humidification prior to the experiment. In two of these units, air humidifiers were installed increasing the indoor RH to 40%-45%. Two other hospital units served as control groups, with no air humidification, and subsequent lower humidity (25-35% RH). The temperature in all units was 21-22°C and the study duration was for four months during the heating season. Before and after the experiment, symptoms and perceived indoor air were assessed. Researchers studied medical, dermal, and general symptoms using a standardized self-questionnaire. The researchers obtained measurements, such as humidity, temperature, static electricity (using a field meter and metal bracelet and a pen plotter for recording the charge), aerosols, microorganism, ventilation and volatile organic compounds (VOCs).

Results

Measurements showed that some parameters were affected and other parameters were not affected by humidification. No great differences in ages, duration of employment, proportion of smokers, and job categories were observed between humidified and non-humidified groups. The control group contained more people with asthma or hayfever. No changes in temperature, VOCs, or degree of ventilation were found as a result of humidification. In addition, not many differences in overall scores of SBS symptoms, asthma, and psychological scores were noted between the humidified and non-humidified groups. Relative humidity reached 40%-45% in humidified units. Before air humidification, employee complaints were due to dry air, static electricity, and stuffy air. After humidification, however complaints of static electricity and dry air decreased to 26% and 24%, respectively in the humidified groups compared to 55% and 37%, respectively, in the control group. Therefore humidification decreased the perception of dry air but it did not change sensation of unpleasant odor or stuffy air. Humidification did not have statistically significant effects on eyes, nose or skin dryness. Moreover, studies of supply water humidification showed no bacteria or viable molds from the water supply system. Also, in humidified units, prevalence of air symptoms such as throat dryness, mental fatigue, and cough were statistically lower than the control group (Table 6).

Table 6: Changes of symptoms in humidified group and control group. Data from Nordström et al. (1994) [42]

Symptoms	Humidified Units Incidence of (%)		Control units Incidence of (%)		P -Values
	Decreased symptom	Increased symptom	Decreased symptom	Increased symptom	
General fatigue	20	13	35	8	NS
Feeling heavy headed	34	7	12	16	0.05
Headache	24	14	26	17	NS
Nausea or dizziness	18	4	8	19	NS
Difficulties in concentrating	14	14	15	12	NS
Itching eyes	29	7	12	11	NS
Irritated nose	20	10	12	16	NS
Hoarse, dry throat	61	4	16	32	<0.001
Cough	28	4	17	25	0.005
Dry facial skin	21	10	19	15	NS
Itch of scalp or ear	7	14	12	12	NS
Dry skin on the hands	11	18	16	36	NS

Discussion

In this study, several factors changed as an effect of humidification and others did not changed significantly. This study, which considered a region that typically has dry winters stated that a range of 40%-60% RH is acceptable for buildings occupants. Other studies stated that mid-range humidity is a desirable range of humidity for health and comfort. The authors asserted that high RH may cause mold, airborne bacteria, or microorganism growth and therefore, humidity must be controlled.

This experiment utilized a questionnaire and all subjects were humans with different perceptions of dryness or stuffiness. The Reinikainen et al. [158] case study, which was also in Scandinavian climate, studied the effect of humidification on health. Researchers observed a decrease in allergic reaction, skin dryness, eye dryness, and allergic symptoms as a result of humidification. Although the range of humidity in the study was 30%-35%, less humidified than the Nordström et al. [42] study, test subjects felt that indoor air was stuffier than indoor air in Nordström et al. [42] These two studies emphasize inconsistent impacts of humidification. One possible explanation for the inconsistency is that, the Reinikainen et al. [158] study contained fewer test subjects and the research time period was shorter (2 weeks versus 4 months). It is important because a human body characteristic might be to adapt to the new condition in longer time periods.

One strength of this study is that the researchers compared data from humidified units to data from a control group. In addition, the study had a good sample size (104 people) and an extended time period for the experiment (4 months). Moreover, researchers measured factors such as health and comfort. However, one of the weaknesses of this experiment was that subjects changed during the study period. Some of the subjects participated in December 1991 and some subjects began the study after humidification in April, potentially causing bias to responses and analysis.

Overall, the study by Nordström et al. (1994) showed that humidification affects the feeling of dryness and static electricity but does not affect eye, skin, or nose dryness. The conclusion can be made that humidification can change the indoor humidity but its effect is not extreme. Also, both of these studies were conducted on a Scandinavian population that encounters very dry air indoor and outdoor conditions during the heating season. Although humidification demonstrated some effects on the perception of dryness and indoor air quality, the effects were not that strong.

2.6 Kaminsky et al. (1995)

Kaminsky, D. A., Irvin, C. G., Gurka, D. A., Feldsien, D. C., Wagner, E. M., Liu, M. C., and Wenzel, S. E. (1995). Peripheral airways responsiveness to cool, dry air in normal and asthmatic individuals. American Journal of Respiratory and Critical Care Medicine, 152(6), 1784-1790.

Objective

Study the effects of cool, dry air in normal and asthmatic individuals.

Test Conditions

This study used 16 subjects, of which eight subjects were asthmatic with Exercised - Induced Bronchospasm (EIB) and eight subjects did not have asthma. Asthmatic subjects did not take any asthma medication 12 hours before visit. The experiments were conducted over the course of 4 days, and the maximum time between study days was 24 hours. For showing that subjects have asthmatic signs they conducted three different procedure. First, Spirometry, (uses a pneumothachograph- based system to measure forced expiratory volume (FEV), and a bronchial challenge test, which is a medical test used to assist in the diagnosis of asthma requiring the patient to breathes into nebulized methacholine or histamine were conducted on the first day of the study. On the second day, subjects performed an exercise challenge on a treadmill, and subjects experienced a cold, dry hyperpnea challenge on the third day. Each subject wore a nose clip and breathed cold, dry, air. Researchers used a wedged bronchoscope technique to examine the isolated lung, measuring peripheral resistance in warm humid air at 37°C with 100-1000 ml/min. The segmental challenge occurred in cool, dry air of 500-1000 ml/min in 22°C for 3 minutes, followed by a recovery period of 45 minutes.

Results

The asthmatic subjects showed a great maximal increase in peripheral resistance (R_p) following cool, dry air. Also their baseline peripheral airways resistance correlated with airways hyperresponsiveness to exercise. The pressure generated in the lung periphery also demonstrated much more heterogeneous response to increasing flows in asthmatic subjects as compared to normal subjects. As flow decreased (pipe diameter), pressure drop increased to maintain the flow rate. The same happens in the lungs when the size of bronchial tubes changes. Asthmatic subjects responded to cold dry air differently in recovery and the base line period, but the healthy people showed almost no changes. Although normal subjects had no significant increase in their R_p, changes in R_p were observed at 3 min and 10 min. after the challenge (Figure 7).

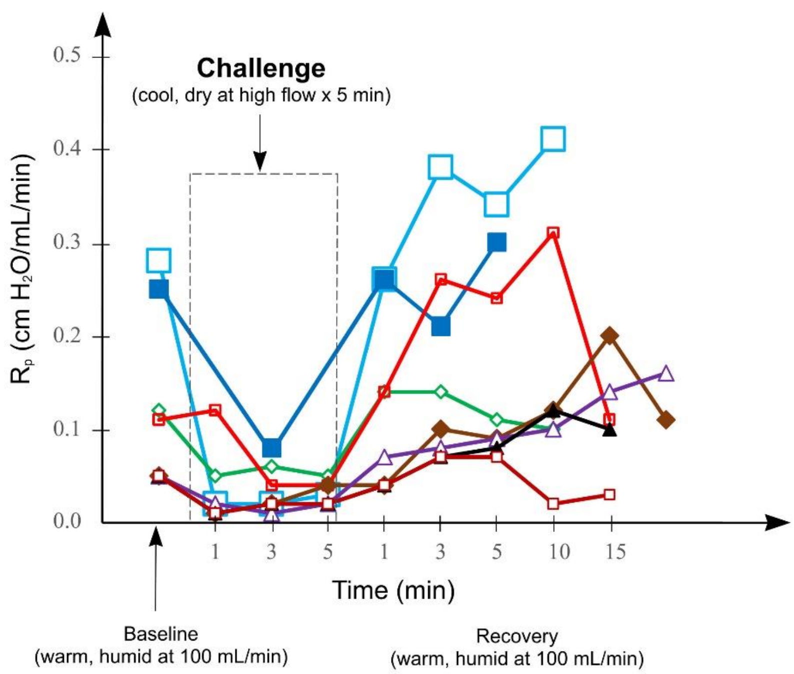

Figure 7: Difference in peripheral resistance (R_p) before and after cool, dry air challenge in asthmatic subjects. Data from Kaminsky et al.([173]

Discussion

This study showed that R_p in asthmatic subjects is much more at baseline than in normal subjects, since mildly asthmatic subjects have more severe airflow limitations compared to normal subjects. Asthmatic subjects had stronger reaction to dry air and were more susceptible. The strength of the study is that extensive testimony of asthmatic subjects was included, although the weaknesses of the study were that the authors investigated the procedures from the mechanism of asthma perspective and they did not consider RH conditions, it cannot be achieved from the study which range of humidity is considered to be dry or humid.

In conclusion, implications of this study for building occupants are important, especially for asthmatic subjects, since when R_p increase at baseline requires asthmatic subjects to be more careful about airflow in comparison to healthy people. In addition, an increase in R_p may causes chronic inflammation for asthmatic subjects. Therefore controlling airway can help improve the medical situation.

2.7 Arlian et al. (2001)

Arlian, L. G., Neal, J. S., Morgan, M. S., Vyszenski-Moher, D. L., Rapp, C. M., and Alexander, A. K. (2001). Reducing relative humidity is a practical way to control dust mites and their allergens in homes in temperate Climates. Journal of Allergy and Clinical Immunology, 107(1), 99-104.

Objective

Study controlling relative humidity as a method to control dust mites and their allergens in homes

Test conditions

This experiment took place in southwest Ohio, in a temperate climate from May 1998 to October 1999. Researchers studied dust mites and allergens in three sets of homes. The first group of 19 homes used a dehumidifier and air conditioning to keep the humidity level below 50%. The second group of 26 homes used only air conditioning. Throughout the study, windows were closed in the homes in these two groups. In the third group 26 homes used only windows for natural ventilation without any use of air conditioning or dehumidifiers. Dust samples were taken from couch, living room floor, and bedroom floor every 4-6 weeks. At the beginning of the study, no differences in the number of dust mites were noted in each home. The study was conducted over a 17 months periods. Outdoor RH average during the summer (June to September) of the first year and second year were 73.3% and 63.5%, respectively. Outdoor temperature ranged from 20°C to 25.9°C during summer and indoor temperature ranged from 22.2 °C to 25.3°C. Other conditions such as house cleaning were not altered.

Results

Buildings were monitored for temperature and RH. Houses that used windows for ventilation had higher summer RH than houses that used air conditioning with or without dehumidifier. The houses with air conditioning or air conditioning and a dehumidifiers, were grouped into two groups: one, one group had an average RH < 51%, and the second group had a RH >51%. The third group used only natural ventilation. All houses had an average indoor RH below 48% in the winter, but differences in the number of mites and allergens were apparent in the summer. At the beginning of the study, live mite count was 401.2 ±124 mites per gram of dust in homes with a low RH average. However, the number of allergens decreased significantly at the end of March 1999 it reached to 8.2 ± 2.6 at the end of study in October 1999 when maintaining < 51% RH. But in two other houses, the number of mites increased reaching a seasonal peak (997.8±173.7 mites per gram) during the first summer season. In houses with low RH, the number of dust mites was 10 times lower compared to the humid houses. The number of

Dermatophagoides farinae was much more than *Dermatophagoides pteronyssinus* in houses in this study, proving that this species is more tolerant to dryness.

Discussion

This study investigated the effects of low humidity on dust mite survival. The authors suggested lowering humidity as a way to decrease the dust mite population in houses because dust mites depend on water from the air for survival. Results showed that 50% RH is a detrimental level for dust mites because the mites dehydrate at that low RH and reproduction is limited. Therefore when the RH level is reduced to below 50% in homes for long time there will be no significant number of mites and dust mite allergens which are harmful for allergic patients.

This method can utilize dehumidifiers in subtropical climates to improve the health of patients with dust mite sensitivity. This method can also be combined with regular vacuum cleaning in order to manage dust mite level in buildings. This study demonstrated some specific strengths. First of all, the experiment was conducted over the course of two years and over two humid summers, allowing researchers to regularly record the dead and live mite density every 4-6 weeks. Second, researchers used a scientific criteria for intentional selection of houses for the study, such as age, style, and construction of houses as well as types of heating.

However, this study also has limitations. For example, researchers did not consider dust mite levels inside mattresses and bedding, which is an important health issue since people can be exposed to dust mite allergens while they sleep. The most prominent places for dust mite breeding are mattresses, carpets and fabric furniture. Therefore reducing home RH below 50%, and replacing carpets with wood floors, can significantly reduce residential dust mite allergens. In addition to use of chemicals to control dust mites, carpet should be replaced with wood floor if lowering RH is not desirable.

Chapter 3 - Conclusions and Future Work

The purpose of this review was to identify the influence of low humidity on health, comfort and IEQ using studies conducted over the past thirty years. Over 500 papers were identified to find relevant papers that included a control group and used RH below 40%. The reviewed research clearly demonstrated that low humidity has a variety of effects on health and comfort and no precise and defined border line exists for distinguishing acceptable low humidity. Acceptable low humidity levels depend on many factors such as building location, purpose, age of occupants, and climate. Due to the variety of effects, the building's purpose and occupants must be known in order to determine appropriate lower bounds on humidity, if any.

From a biological perspective, the behavior of microorganisms at low humidities is not identical. As discussed in Theunissen et al. [114], gram positive and gram negative bacteria do not behave identically in low or high humidities. Lowen et al. [171] defined an optimum range for humidity as approximately 50%. Virus transmission rates were high at humidities higher than 65% and below 35% RH, potentially impacting health. Evidence from Sunwoo et al. [22] showed that one of the health problems and discomfort caused by low humidity can be high SCT, for young people and elderly people, but time and RH did not significantly impact the perception of nasal dryness for both groups of subjects. Moreover, someone who suffers from respiratory disease such as allergies or asthma, as shown in Kaminsky et al. [173] and Reinikainen et al. [158], may experience breathing difficulties at low humidity. Therefore, serious consideration should be given to indoor air conditions, and the effects of low humidity.

The research cited above determined that although low humidity negatively affects health and comfort, low humidity also offers some benefits. An example is control of house dust mites by keeping indoor air dry. Finding natural, non-toxic ways to control household insect pests and allergens has always been a concern. Arlian et al. [170] showed that dry environments can prevent dust mites from regeneration. It may be advantageous to keep humidity below 50% in order to reduce dust mite populations.

In conclusion, low humidity has advantages and disadvantages depending on the application. However, additional research and testing is required to gain increased understanding of the influence of low humidity on health. This study analyzed various aspects of humidity, but new studies could be beneficial. Time is an important consideration when designing the studies since human beings can adapt to new conditions. Various ranges of time periods were observed in the mentioned case studies. For example, Arlian et al. [172] conducted an experiment for 18 months and the study duration for Nordström et al. [42] was 4 months. Reinikainen et al. [158] conducted an experiment for 6 weeks and Lowen et al. [171] conducted a transmission experiment for one week. The study by Kaminsky et al. [173] lasted for 4 days. The study by Sunwoo et al. [22] lasted for 230 minutes and the study by Theunissen et al. [114] lasted 5 minutes.

Each case study and corresponding results introduced in this report provides a guide to future research. Although a variety of cases showed the effects of humidity on mammals such as guinea pigs and healthy young people, very few studies have focused on elderly subjects. Therefore, directions for future research include changing the study location to places such as schools, as well as introducing new subjects or using subjects that already have respiratory problems in the real world (not in laboratories) and studying them at various levels of humidity. In addition, it is not yet clear how mechanisms acts for helping elderly in sensation of dryness. Therefore much research remains to be done on different subjects, such as adolescents, teenagers, or the elderly.

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