Physiological impairments of individuals at low indoor air humidity

Pfluger, Rainer [1]; Feist, Wolfgang [1]; Tietjen, Andreas [2]; Neher, Andreas [3]

[1]Institute for Engineering and Materials Science, Unit Energy Efficient Buildings, University of Innsbruck, Innsbruck, Austria [2] Institute of Contact Lenses (Dr. F. Orou), Hall, Austria [3] Department of Oto-Rhino-laryngology, Division of General ENT disease, Medical University Inssbruck MUI, Innsbruck, Austria

Abstract: The indoor air humidity affects the human organism and in particular the eyes, mucous membranes and skin. Notably in the range of particular low humidity physiological disturbances occur, which could cause specific pathogenic symptoms especially in case of respective predispositions. The focus of this work is put on studies with subjects under controlled clinical trial conditions. Field trials, which are based only on a statistical analysis of subjective survey results, are less significant. Based on a literature review and the medical expertise of the co-authors on the current state of science and research from the medical specialties of ophthalmology, dermatology and otolaryngology, the physiological effects of low indoor air humidity are gathered, analysed and evaluated. A significant negative impact on the quality and stability of the tear film of the eye was shown to be a consistent result of independent studies. More differentiated results and remaining need for research exist in terms of the upper and lower respiratory tract and the mucous membranes. An important finding is, that the impairment of mucociliary clearance in low indoor air humidity increases with the age of the subjects. Regarding the effects on the skin, predispositions also play a significant role.

Key words: low indoor air humidity, ophthalmology, dermotology, otolaryngology, tear film, mucociliary clearance

Practical Implications

Researchers with experience in indoor air science and occupational health as well as medical scientists (ophthalmology, dermotology and otolaryngology) have reviewed the indoor air climate literature about physiological impairments at low indoor air humidity. The results of this review should work as a first basis for future recommendations of the approach, design and operation of ventilation systems that can deliver the most comfortable and physiologically beneficial ventilation conditions. Further interdisciplinary research will be performed in order to deepen the knowledge in this area.

Introduction

Complaints and grievances about dry air occur frequently during the heating period in cold climates in residential and office buildings, respectively. Longer periods of pronounced low level humidity in the range 10 to 20% often occur in Scandinavian countries (Reinikainen et al., 1992). Low indoor air humidity exerts a significant influence on health and performance. Hence a literature study was commissioned (Hahn, 2007) on behalf of the management trade association of the Institute for Occupational Safety - BIA (D, Sankt Augustin) specifically intended to clarify the question of the value for a lower boundary of the indoor air humidity to avoid negative impact on the health of employees. As part of this literature review, a total of 29 studies was taken into account. 17 of them, however, are field studies. The results are mainly based on statistical analysis of questionnaires about the subjective perceptions of the subjects. The conclusion of this review is: "The studies about the influence of relative humidity on human health showed sometimes very conflicting results. It can be located no medically well-founded study from which a definite lower limit of 30% or a different threshold could be derived" (Hahn, 2007). Based on that, further need for research can be derived with the aim to elaborate recommendations for lower limits of indoor air humidity. The present study therefore attempts to clarify the contradictions found, and to evaluate significant physiological contexts as far as possible on the basis of clinical tests under controlled conditions.

The influence of outdoor air change rate on indoor air humidity in the heating period is independent of the type of ventilation (e.g. natural or mechanical ventilation). The air change rate is, in addition to the degree of moisture sources in the building, the most important determinant of the indoor air humidity. Furthermore, the proper sizing of the air exchange rate, design, process engineering, control engineering as well as use-specific measures can also contribute to prevent low indoor air humidity.

Perception of air humidity and its influence on thermal comfort

Complaints about “too dry air” are frequent during the heating season. Most of the complaints refer to dry eyes, dry throat, or dry skin. However, these are already consequences of impairments. It became also clear, that secondary effects can cause a feeling of "dry air" in subjects (e.g. high room air temperatures, air pollution and increased dust levels).

In the climate chamber experiments of (Koch et al.,1960a) and (Koch et al., 1960b) ability of the subjects to directly estimate the relative humidity could not be detected. Even Andersen et al. (1974) found only an unreliable perception of a change in the relative humidity over a wide range of humidity. According to Liese (1960), there are no receptors for the water vapour partial pressure on the skin surface.

As part of the questionnaire evaluation of (Sundell et al., 1993), relationship between the actual measured indoor air humidity and the prevalence of SBS (Sick Building Syndrome) symptoms could not be detected. In contradiction to this findings (Wyon, 1992) found a reduction of SBS-Syndrome at an increase in relative humidity from 25% to 40%. On the other hand, the feeling of dryness was strongly correlated with the prevalence of reported SBS syndromes.

Astonishing instance, in a study by (Sun et al., 2009), it turned out, that particularily in areas with high relative humidity and poor indoor air quality (due to poor ventilation rate) the air was more frequently perceived as “dry”.

Numerous studies (e.g. (Fang et al., 1998a), (Fang et al., 1998b), (Reinikainen et al., 1992), (Reinikainen et al., 1997), (Fang et al., 2002) deal with the perception of air quality. The results showed, that the perceived air quality was judged as lower with increasing temperature and humidity. It turned out, that the air at high temperature and humidity is perceived as rather stuffy. In Figure 1, the acceptability of indoor air quality, calculated by the authors according to (Fang et al., 1998a) is presented. Accordingly, a consistent positive response to the indoor air quality occurs at an average indoor air pollution in the usually recommended humidity range below 60% at 20 °C. At higher temperatures (e.g. at 22 ° C and about 50% RH) the acceptance is already restricted.

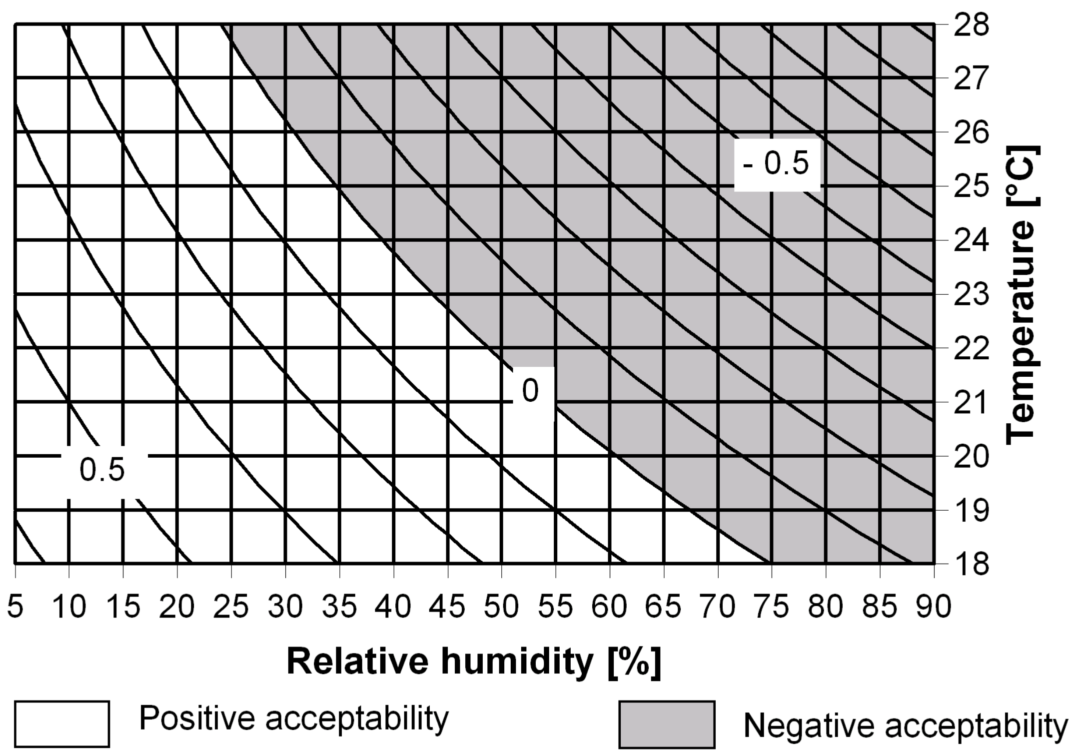

Figure 1: Acceptance of indoor air quality, calculated by the authors according to (Fang et al., 1998a), (assumptions for the calculation: polluted by carpet, mean loading)

From (Toftum et al., 1998), the effect of “respirative cooling” was quanitified, i.e. the convective cooling and evaporative cooling of the mucous membranes by the inhaled air. The air was experienced as pleasant, cool and "fresh" at low temperatures and relative humidity in spite of constant "contamination". In Figure 2 examples of the PPD values (Predicted Percentage of Dissatisfied) are shown for 1.2 met, 0.455 clo (neutrality at 22 ° C), calculated according to (Toftum et al., 1998).

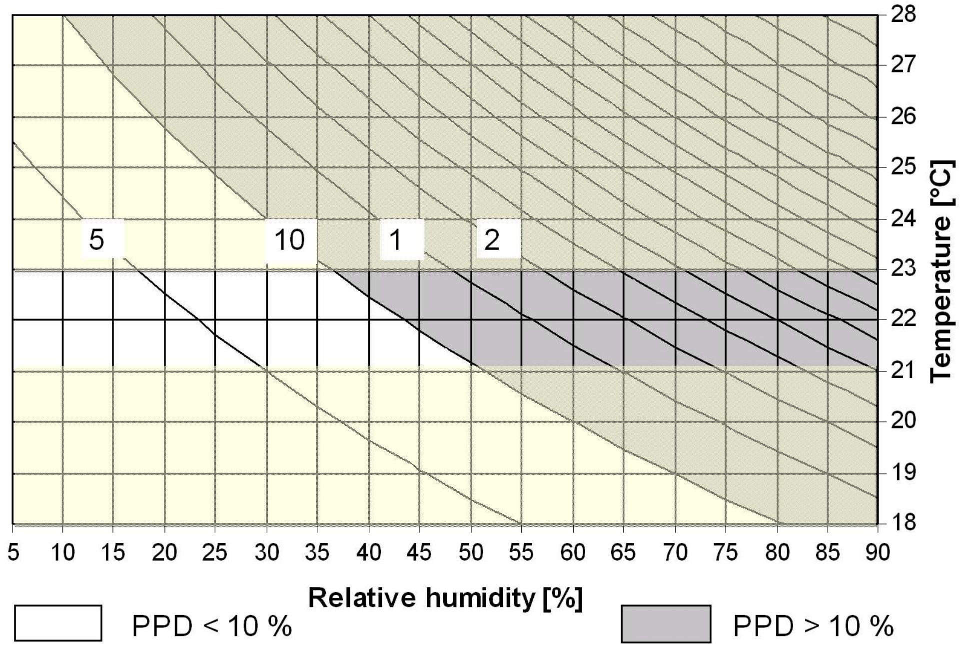

Figure 2: PPD values due lack of "respirative cooling" calculated according to (Toftum et al., 1998) for 1.2 met, 0.455 clo (neutrality at 22 °C) the rest of the temperature ranges is hidden, because the calculations apply strictly only at 22 °C at given clo-value.

The temperature ranges obove 23 °C and below 21 °C have been hidden in the graph, because the data are valid only within the temperature range of neutrality (22°C). At higher or lower temperatures the clo-value has to be adapted. If the acceptance limit is defined at 10% dissatisfied, then the relative humidity should be kept below 45 % RH at 22 °C.
The criteria defined by (Fang et al., 1998a) and (Toftum et al., 1998) tend to exhibit a similar trend, but only describe the upper limit of the accepted humidity range. Lower values are in these studies perceived rather as pleasant.
Consistently with all reviewed publications, the human being does not have a dedicated perception of "too dry air". This also explains why results from questionnaires and interviews of subjects on the perception of indoor air humidity do not have any significance. Nevertheless, even in the recent past, a costly trial study was conducted under laboratory conditions using questionnaires, which allowed the subjects to vote air quality on a 7-point scale rating between "too dry", "comfortable" and "too wet". The summary of (Grün et al., 2008) states:
"Although a very low level of humidity was compared with a medium level of humidity hardly any significant effects were observed in the context of hygric comfort. This is contrasting previous findings and needs further analysis. Potentially hygric comfort is driven by other factors, which counteract with some environmental parameters."
A literature review on the effect of indoor air humidity on thermal comfort can be found in (Schneider et al., 2003) and (Schnieders, 2009). In different standards (ISO 7730:2006, ASHRAE 55-92a and DIN 1946-2) and proposals (Leusden et al., 1951) different comfort zones are defined, neither the lower nor the upper limits being uniform. A strict lower limit is postulated in none of the proposals, also to DIN 1946, the lower limit of humidity is characterized as "uncertain", occasional undershootings of the 30% RH are admitted. The comfort temperature according to ISO 7730:2006 has only a very weak dependence on the humidity following the balance equation already given by (Fanger, 1972), the standard does not impose strict limits on the humidity.
In summary, low humidity of room air has only indirect perceivable effects (e.g. on comfort perception of indoor air pollution) and is out of the direct sensory perception. Only when physiological impairment of eye, skin and mucosa occure, there are complaints about irritation and dysfunction to the point of pain. Never the less, this is an issue – indoor air should not only be perceived comfortable, but also maintain objectively good health conditions for the users. For this reason, especially publications on particular physiological studies and analysis of clinical scores are analyzed in this study. Performance tests, known from occupational medicine can also provide information on impairments due to the indoor environment.

Physiological studies and clinical scores

There is so far no generally agreed answer on the issue of thresholds - or better of threshold range - for indoor climate conditions, which cause a physiological impairment or even a pathogenic condition. The treshold range depends on side effects such as the stratification of groups of subjects, secondary effects of indoor air pollutants, drafts, etc., and length of stay in the room. Stratifying results of the literature survey specifically for each application or group of buildings (e.g. housing, office buildings, rest homes, etc.), there is the opportunity to give more detailed recommendations specifically adapted to the largely known users, usage times, and uses.
The most important clinical scores are explained within the following sections related to the medical disciplines, respectively, and evaluated on the basis of previously published studies

as comparative analysis. A medical evaluation about pathogenic condition is however in most cases not possible or is pending.
Many countries indeed have already conducted some laboratory tests with clinical trials, but unfortunately often under different boundary conditions. Hence, of particular significance for reason of comparability, are some studies that evaluated different clinical scores from different medical disciplines in a self contained study with test subjects. In particular the studies by (Fang et al., 2002) and (Sunwoo et al., 2006) feature this excellently. Both have done solid groundwork in the medical fields of ophthalmology, dermatology and otolaryngology, which are most important in this context. Figure 3 shows the respective parameter combinations, ie temperature and humidity of room air of both studies. The two studies differ in particular in the choice of levels of indoor air temperature (22 ° C (Fang et al., 2002) or 25 ° C (Sunwoo et al., 2006)).

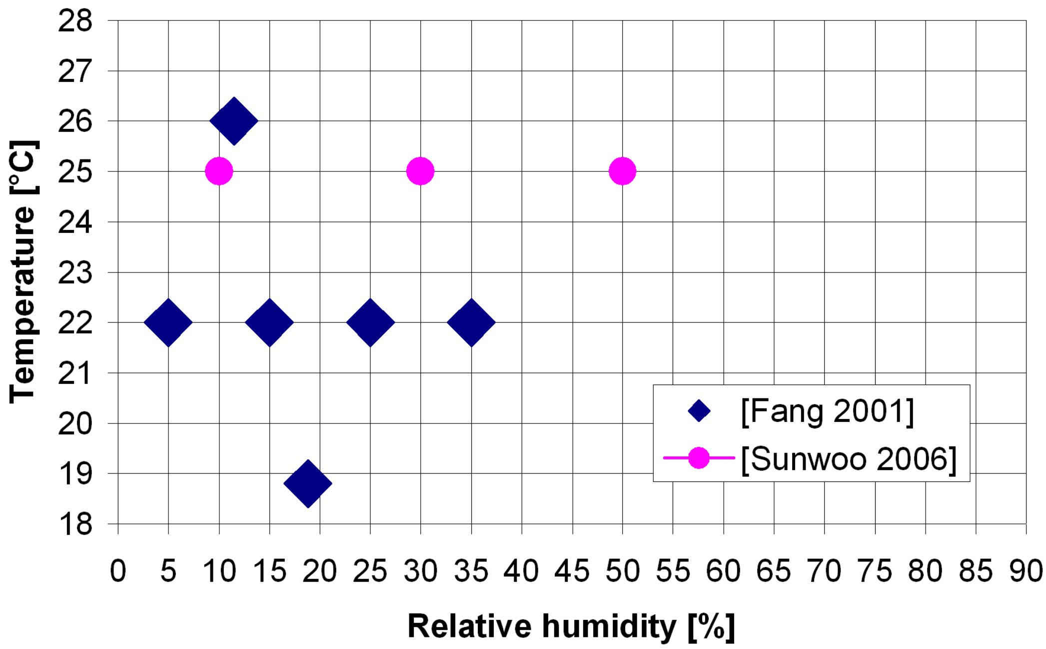

Figure 3: Parameter combinations (test conditions in the climate chamber experiments with subjects) of the parameters air temperature and relative humidity of the studies (Fang et al., 2002) and (Sunwoo et al., 2006)

Ophthalmology

One of the first complaints expressed by persons, which are exposed to prolonged dry air, is the irritation of the eyes. This experience has been shown to occure in case of a breakdown of the tear film, especially the aqueous phase, which provides primarily for the humidification of the ocular surface and the sliding of the eyelids. Moreover it has a purifying function (evacuation of pollutants). “The healthy tear film is critical to the optical quality of the eye, nutrition, and antimicrobial defense mechanism of the cornea. Quantitative or qualitative tear film disorders can result in severe impairment and illnesses” (Markovic et al., 2009).
The tear film is composed of an inner mucin phase (protein phase), an aqueous phase and an outer lipid phase. The mucinphase forms a thin, innermost layer of the eye surface to fix the entire tear film on the corneal surface. The aqueous phase binds to it and is externally covered by an outer lipid phase, which should prevent the rapid evaporation of tears.

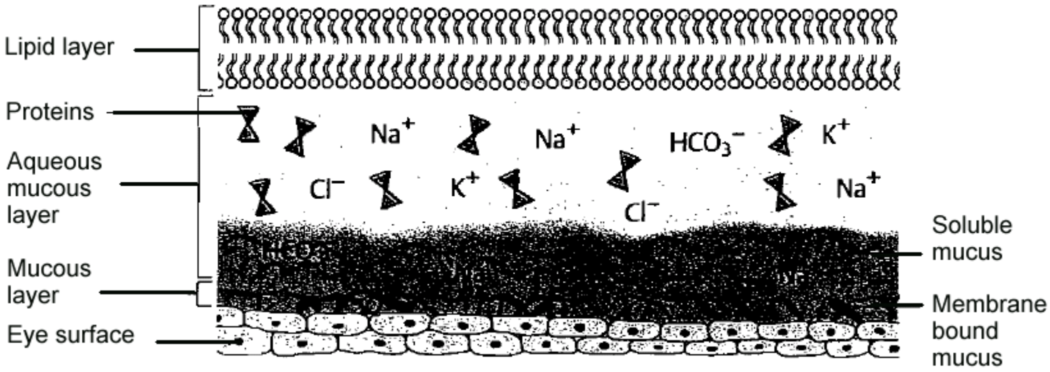

Figure 4: Structure of the tear film according to (Kroll, 3rd Ed.)

The subjective symptoms, which are recorded by numerous authors using standardized questionnaires, have for (Markovic, 2009) always a corresponding pathology. In the following, only symptoms which might be related to physical boundary conditions are cited:

"*Drought* is caused by changes in osmolarity (Foulkes et al., 2007) of the tear fluid, which mostly occure by a minimization of the aqueous phase.

Scraping: The sign of the eye surface roughness can be observed in long-standing and pronounced dysfunction of wetting of the eye.

Burning indicates an inflammation of the eye surface caused by a physical stimulus of friction, which can not be compensated any longer.

Foreign particle sensation may occur with pronounced roughness of the surface, often linked to incipient degradation of epithelium. In case of insufficient humidification, and thus increasing friction of the surface of the eye, the musculature of the eyelids has to work against a greater resistance.

Pressure / pain is a symptome caused by both epithelial degradation and as well by non-specific stimulation.

Bonded, non-bacterial infected eyes are the result of a phase disturbance in the eye, which leads to precipitation of the protein layer and thus produces a tenacious secretions."

In addition to the influence of the air humidity immunologic, toxic, hormonal and psychological factors may play a role. "The dry eye (sicca syndrome) is one of the most common diagnoses made in ophthalmology, but because of the variety of straining factors it has an especially difficult access to therapists". The evaporation rate is clearly dependent on the humidity and thus offers an explanation for the increase in the sicca-symptomatology in a dry environment. In the experimental laboratory study (McCulley et al., 2006) the evaporation rate was measured by evaporimeter within the humidity ranges from 25 % to 35 % and between 35 % and 45 %. There was a specific evaporation rate of 0.029 ± 0.009 to 0.043 ± 0.016 µl/cm^2/min within the high humidity range, and a rate of 0.044 ± 0.013 to 0.058 ± 0.018 µl/cm^2/min for the lower range of humidity.
(McCulley et al., 2006) concluded, that "(…) a decrease of 10% RH resulted in an average difference of between 28.33% to 59.42% increase in evaporation. The increase in evaporation at lower humidity has significant clinical implications for patients with aqueous deficient dry eyes, and possibly those undergoing laser-assisted in situ keratomileusis (LASIK)".
In assessing the physiological impairment caused by low indoor air humidity, cross influences are to be minimized as much as possible or to be included in the statistics by stratification of the group of subjects. Cross influences are a major reason for missing significance in correlations of numerous field studies. Better results can be found by clinical tests under defined boundary conditions and preliminary examinations of the subjects. On the other hand, an increased influence of indoor air humidity may occure through a combination of factors:

E.g. for office jobs concentrated on screen work, the draft as well as the lower blink frequency plays an important role. The latter leads to a disturbance in the structure of the tear film and thus a temporary drying of the ocular surface (Backmann et al., 1999). For this reason, both clinical tests and tests for the performance of (simulated) screen work has been conducted and evaluated under different boundary conditions of indoor air humidity (Fang et al., 2002). The results are discussed further below in more detail.

Against this background the question is raised giving meaningful clinical scores, which can quantify an impairment of the eye due to low indoor air humidity. For this purpose a series of clinical tests and procedures in ophthalmology are known (see also (Kroll, 3rd ed.)). For all invasive procedures, however, there is a risk of falsifying the results of the test if it causes an irritation of the eye or if it has an impact on the blink frequency. For example, the "break up time" (i.e. break up time of the tear film) is a measure of the tear film stability. A better measure however is the measurement of eye blinking frequency, because it can be performed without any influencing of the eye.

(Liviana et al., 1988) found no effect on visual acuity and astigmatism at 10 %, respectively 30 % RH over a period of ten hours. However, the subjects felt increasingly harassed under both circumstances after four hours. Also (Sato et al., 2003) presented increased complaints of dry eyes in the staff of the facility with only 2.5% RH.

By increasing the relative humidity from an average of 26% to an average of 33% it is possible to reduce the incidence of complaints about dry eyes according to a study by (Reinikainen et al., 1992).

According to (Liviana et al., 1988) the discomfort of the eye increases with time if the dew point temperature is below 2 °C. This represents an absolute humidity of 4.4 g/kg or a RH of 27% at 22 ° C respectively.

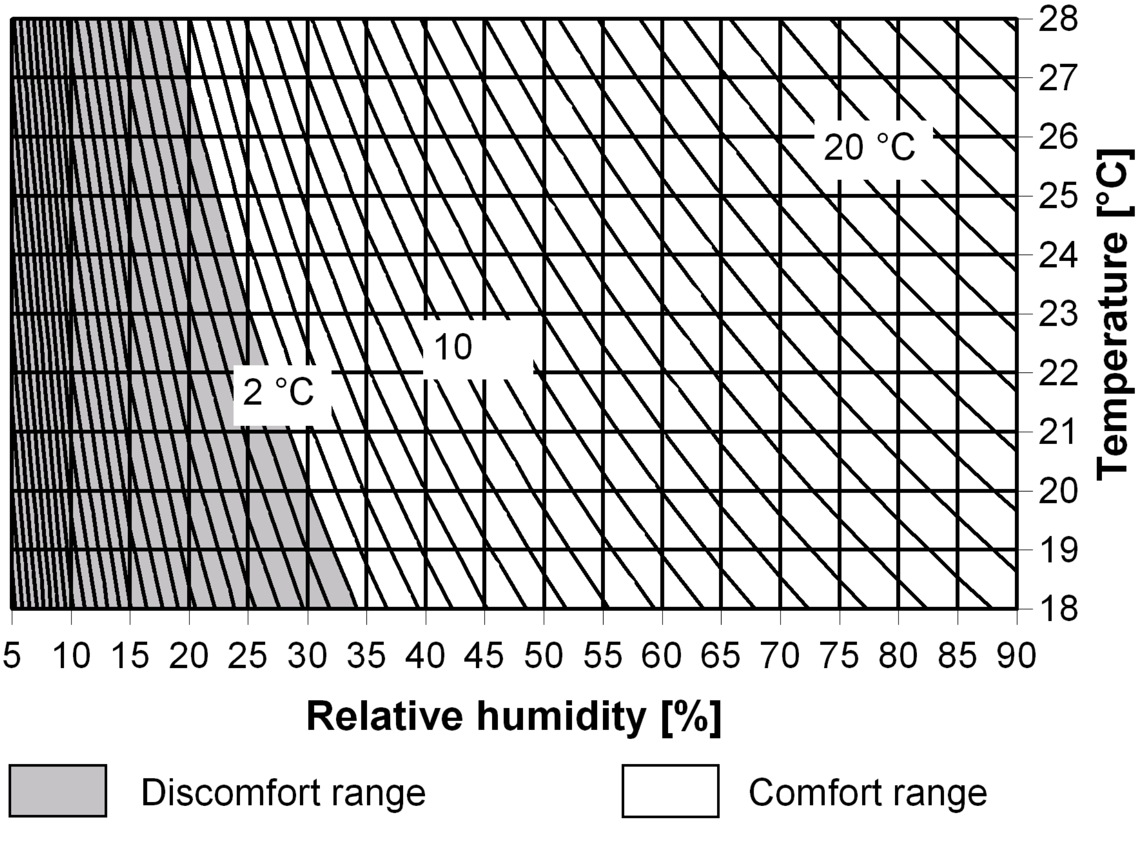

Figure 5: Illustration of the dew point temperature and the range with dew point temperature < 2 °C. Falling below this threshold, the discomfort of the eyes increases over time according to (Liviana 1988].

Based on the research of (Liviana et al., 1988), the ASHRAE Standard 62-1989 (ASHRAE, 1989) recommended an optimal indoor air humidity range of 30-60% RH. The ASHRAE Standard 55-1992 (ASHRAE, 1992) introduced a lower limit of absolute indoor air humidity of 4.5 g/kg, (i.e. dew point temperature 2.43 °C or 28% RH at 22 °C), which is slightly higher than the absolute humidity threshold according to (Liviana et al., 1988).
Regardless of the exact value of the threshold, the assessment based on the absolute humidity is only appropriate if a constant temperature of the tear film is assumed. In fact the surface temperature of the eye depends on the heat transfer from the surface to ambient and the ambient air- and radiation temperature. Therefore there is still need for further research in this field.
Since the evaporation is proportional to the difference between the vapour pressure of the air and the saturation vapour pressure at temperature of the tear film, it is sufficient, therefore, to define a minimum level of absolute humidity (or of the the dew point temperature of the air respectively), if a constant surface temperature of the eye is assumed.
The choice of the relative humidity (e.g. 30 %) as a physiological threshold however is misleading: E.g. the evaporation of the tears at 18 °C room temperature and 35 % RH is as high as at 23 °C and 26 % RH, the physiological effect is equivalent as in both cases the absolute humidity is 4.5 g/kg.

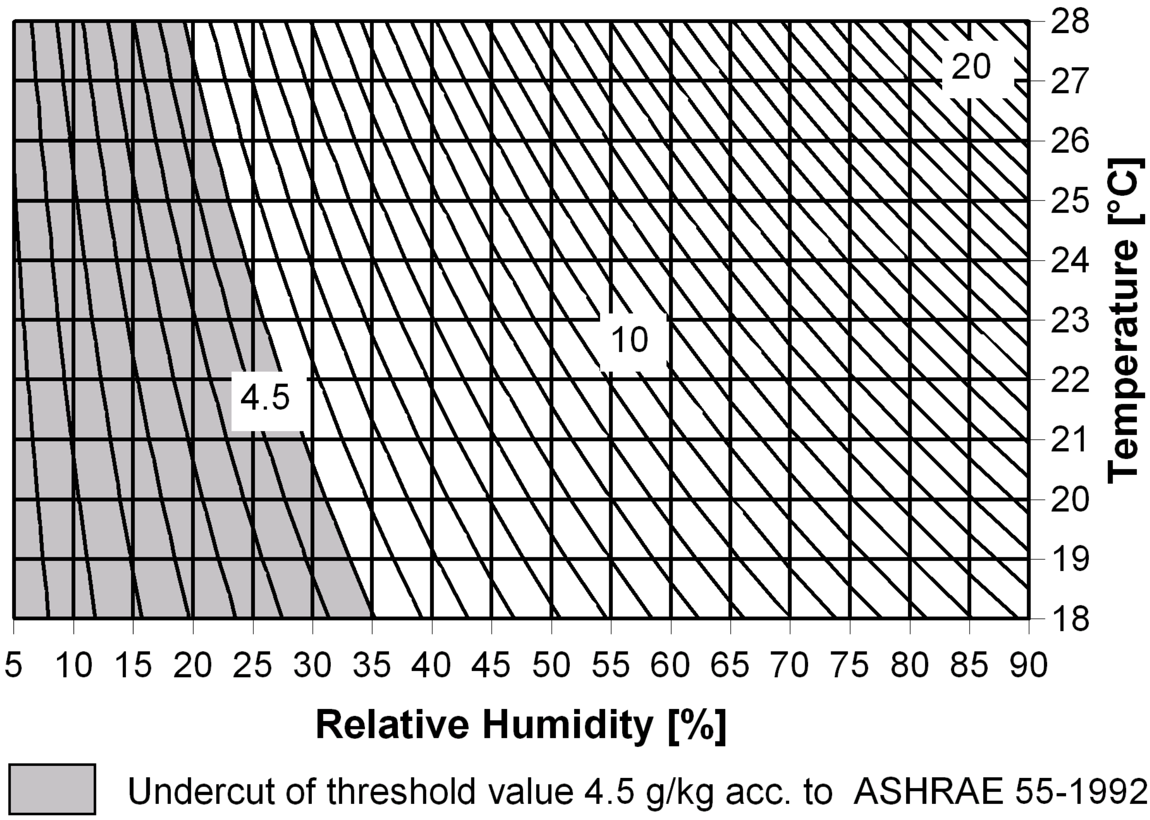

Figure 6: Lower limit of the absolute humidity of the air according to (ASHRAE 55-1992)

Based on this state-of-the-art of science, the ASHRAE 1160-TRP as part of the Technical Committee 2.1 commissioned the TUD (Technical University of Denmark) to analyse more closely the recommendations for a lower limit for the room air humidity from a physiological point of view. Climate chamber experiments and field studies were performed by TUD, in order to be able to provide more informed recommendations and guidelines for the air conditioning. The results are fully documented in the final report (Fang et al., 2002) (test

points and air conditions see Figure 3), in this chapter the main results are summarized from an ophthalmologic point of view:
After the selection of the subjects (total 60 participants aged 19-31 years, mean 23 years) the group was stratified between contact lens-wearing and non contact lens-wearing subjects. Another distinctive category was whether symptoms of allergic rhinitis in pollen season occurred or not (predisposition regarding allergic reactions). In the context of climate chamber experiments, questionnaires about the subjective sensations were evaluated and medical tests and performance measurements (simulated office work) were performed and evaluated as well.
From an ophthalmologic point of view, the thesis of an influence of low indoor air humidity on the tear film stability and ocular mucosa was in focus of investigations. This hypothesis was confirmed in several ways. In contrast to similar studies, the climate chamber experiments of (Fang et al., 2002) are characterized by the fact that the air was burdened with both high or low pollution levels, in order to include the effects of pollution.
The statistical analysis of survey responses to the sensation of dry eyes and eye irritation showed an increase with decreasing humidity, beginning at 35% RH, in accordance with (Wyon, 1992). Sypmtome of eye irritation grew even progressive, the limit was around 20% RH.
With regard to the ophthalmologic physical measurements, the so-called "mucous ferning test" (quantitative evaluation of the crystallization structure of the tear film after applying a sample on a slide under a microscope) of the tear fluid of the subjects was performed after exposure to different air conditions in clean and polluted air. After exposure to clean air at 22 °C between 25% and 15% relative indoor air humidity, the mucus quality showed an abrupt deterioration. Another significance was found in contaminated air, the degradation increased linearly from 18 ° C over 22 ° C to 26 ° C at 2.6 g/kg absolute humidity.
This finding approves the assumption that the quality of the tear film is influenced not only by the evaporation rate corresponding to the vapor pressure difference, but also by the temperature of the air.
In addition, the blink rate of the subjects was analyzed. A significance was found with exposure to clean air at 22 °C, the blink rate increased significantly between 35% and 5% relative humidity.

Visual performance tests in (Fang et al., 2002)

The increase in blink rate is a compensatory measure of the eye at high evaporation rates. The increase of blinking frequency is shown to represent a deterioration in the performance of demanding visual tasks (simulated office work), as established by performance test with the test persons: When typing text, a progressive decrease in typing speed was found at indoor air humidity decreasing from 35% to 5% RH. When proofreading a 7% progressive reduction in performance was noted from 35% to 5% RH. When running simple additions, the test resulted in a 9% decrease in performance when indoor air humidity was reduced from 35% to 5%. Even with a correction of the learning curve applied, the performance reduction is still around 5%.
For contact lens wearers, not any dependancies of the performance on air humidity was identified.
Dependence on indoor air humidity of reading speed and comprehension of the text could not be detected. This is explicable, because these performance indicators are less dependent on visual performance.

Dermatology

The retention of moisture in the skin is achieved by the outermost cell layers of the stratum corneum, where the water content is about 10-40%. In contrast, the innermost cell layer of the stratum corneum has a water content of up to 70%. While the innermost cell layer is in contact with the cells of the stratum granulosum, its outer layer is adjacent to ambient air. The continuous transport of water from the aqueous milieu of the cells to the environment is known as transepidermal water loss (TEWL or short TWL). This concentration difference leads to a continuous supply of stored water to the environment. The state of the stratum corneum substantially determines the degree of TEWL.

While the degree of TEWL can be determined using an evaporimeter, the water content of the skin can be measured using a corneometer.

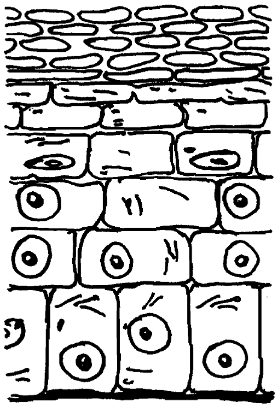

Figure 7: Cross section through the epidermis, the uppermost of the skin layers

When considering the physiological effects of low indoor air humidity on skin physiology; i.e. TEWL homeostasis, genetic factors that determine disposition (e.g. mutations in the filaggrin gene) have to be considered.

(Schmuth et al., 2007) states, "A genetically pre-disposed, weakened skin barrier could facilitate the penetration of allergens and an increased the risk of atopic inflammation of the skin.

How it works in detail and which other factors of the human immune system and the environment come into play, is currently the subject of further research efforts". In general, complains of dry, brittle and cracked skin are more common in permanently low humidity environments. Chronic skin disorders such as atopic dermatitis and psoriasis may be aggravated by an excessively dry skin.

According to (Sunwoo et al., 2006), the relative humidity of the air does neither affect the activity of the sebaceous glands of the skin, nor the mean skin temperature.

The physiology of the skin (according to (Sunwoo et al., 2006) shows no differences in drought in terms of age: regardless of the age of the subjects, the skin (measurement of the water content of the skin) becomes dry at indoor air humidity below 30% RH. The results of the measurements of the water content by evaporimeter agree with the results of (Fang et al., 2002), the effect of dry skin increases significantly ($p < 0.0003$) at a relative humidity of indoor air between 35% and 15%. Furthermore, a significant increase in TEWL (measurement of the passive diffusion rate of water vapor through the skin using evaporimeter) with temperature at constant absolute humidity of 2.6 g kg was found.

Temperature [°C]	Transepidermal water loss [g/m²/h]
18	2.95
22	3.15
26	3.90

Table 1: Transepidermal water loss as a function of temperature at constant absolute indoor air humidity of 2.6 g / kg according to (Fang et al., 2002)

With decreasing indoor air humidity two opposing effects occur in the skin. On one hand, the water vapor partial pressure (and hence the potential of diffusion) decreases, on the other hand the diffusion resistance of the strateum corneum increases. Hence, according to (Grice et al., 1972), a maximum of TEWL arises in the range of about 30% RH. This also explains why (Fang et al., 2002) did not find any significant changes while varying the relative humidity at constant temperature, because the TEWL has its maximum precisely in this area. On the other hand an increase of transepidermal water loss could be detected with increasing temperature at constant absolute humidity because of the increasing partial pressure of the skin at only slightly decreasing relative humidity.

In addition to the above mentioned parameters, the skin surface roughness represents measurable score concerning the moisture content of the skin. Its dependency on the humidity of the room has been investigated by (Egawa et al., 2002). There was a significant change in skin surface roughness on facial skin (cheek) and ventral forearm after 6-hour exposure with an air temperature of 24.5 °C and 10% RH.

The investigations of (Fang et al., 2002) however, which evaluated the reddened skin applying an adhesive with soap solution on the forearm of the subjects, showed no significant dependence on indoor air humidity after 24 hours.

Otolaryngology

As mentioned above, the indoor air humidity does on one hand not directly affect the respiratory tract in terms of perceived comfort, on the other hand it does so indirectly via the perception of indoor air quality and odor in case of indoor air pollution. In this paper, however, mainly physiological impairments will be addressed, especially of the mucous membranes and their self-cleaning effect. The access to the upper respiratory tract is much easier, considerably more investigations have been published about results in this area compared to the the lower respiratory tract. Of physiological interest, however, is the impact on the entire respiratory tract. Its main sections (nose, trachea, bronchial tree) and their functions are briefly presented below to improve understanding about potential adverse effects due to low indoor air humidity.

The nose

The respiratory tract, consisting of nose, trachea and bronchial system is in direct contact with the inhaled air. Its conditions directly influence the heat transfer and humidification performance. The entire respiratory tract is covered with an aqueous layer.

„The integrity of this aqueous layer is essential for the function of the epithelial cells since dessication leads to ciliary and cellular injury, and even destruction" (Proetz, 1953). Regardless of the ambient conditions, the air has to be conditioned in the respiratory tract to 37 °C and 100 % RH. The respiratory area of the nose plays a significant role for preconditioning the air. 90% of the heat and moisture transfer is performed in the areas from nostril via turbinate to the nasopharynx (nasopharyngeal).

At its entrance, the nose formes the narrowest part of the respiratory tract with the highest flow rate. In its inner part, the air is diverted several times by guide elements, the so-called choanae, and swirled so that an intense mucosal contact is achieved. In the nose, the air is warmed and humidified during inspiration, during expiration it is cooled and dehumidified, working as a regenerative heat exchanger. “A portion of the water evaporated to condition inspiratory air is recovered during expiration: 30-40% in humans and even more in some animals. Secretions from nasal seromucinous glands and goblet cells are largely water; they are supplemented in the nose by lachrymal and paranasal sinus secretions and in the mouth and phyrynx by salivation: all contribute to the aqueous layer (Cole, 1988).

“The ‘mucociliary transport’ is the cleaning mechanism of the respiratory tract. This cleaning system is also named mucociliare clearance (MCC) because of the co-operation of phlegm (mucus) and ciliated cells (cilia). It is part of the nonspecific resistance to infection. If there is a disturbance of this mechanism, the mucus transport breaks down, the mucus becomes inspissated and forms an ideal medium for bacterial colonization. Due to the lack of or limited cleaning, bacteria and viruses can easily dock on to cells of the respiratory tract. The consequences are recurrent infections" (Neher, 2009).

These cilia can easily be lost when injurious influences occur, they have to be regenerated later. Today, the measurement of cilia beat frequency is a reproducible method for the detection of external influences on the cilia activity. "To measure the cilia beat frequency, a digital high speed imaging technique is used, that works through a combination of a new microscope, a special software and a high-speed video camera. A special computer software is applied to faciliate the evaluation" (Neher, 2009).

The trachea and the bronchial

The trachea and the bronchial tree are the next major section of the airways. Their epithelium is filled with cilia as well.

The wall of the trachea is reinforced by cartilage rings and is thus essentially rigid, while the wall of the smaller bronchi and bronchioles has a circular muscle contraction and can be expanded. Contaminants and potential pathogens can be transported from respiratory tract to larynx. They are removed by coughing in case of irritation of the mucous membranes from this part of the airways, or by the movement of cilia.

Studies on the drying of the mucous membranes

Based on the climate chamber studies of Andersen (Institute of Hygiene, University of Aarhus, Denmark, (Andersen et al., 1972) and (Andersen et al., 1974) it is assumed that the indoor air humidity exerts no influence on the mucosal transport. This thesis has been published in numerous papers. As it turned out, different results can be explained mainly by the influence of age: The studies on the nasal mucus flow from (Andersen et al., 1972) and (Andersen et al., 1974) could demonstrate no significant effect of relative humidity on the flow of mucus in the nose, the study was limited, however, exclusively to young volunteers. The subjects were healthy Danish university students 21 to 26 years of age. All were men without any symptoms or signs of diseases. All were “nose breathers”, and none had evidence of nasal allergy. The nose of the young subjects was able to compensate for relative humidities of 9% over a period of 78 hours by the body's own moisturizing.

Workers at a manufacturing facility were exposed to even more extreme conditions (2.4% RH) without any differences in the frequency of complaints compared to non-exposed colleagues, according to (Sato et al., 2003). It is however acknowledged, that this investigation was carried out for cleanroom conditions with highly filtered air.

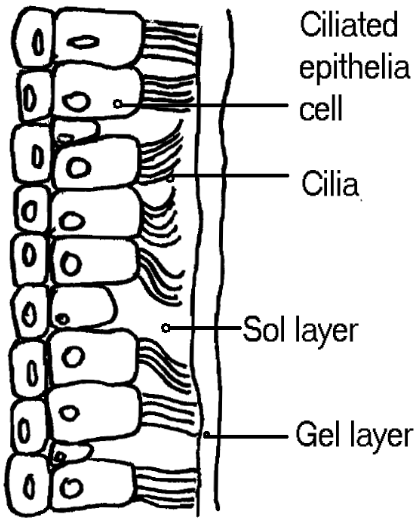

Figure 8: Principle of the mucociliary transport system (source: Prof. Dr. Guggenbichler)

Divergent observations have been documented by (Strauss et al., 1978) in asthmatics. Humidification contributed to a relief of symptoms because the disease limits the body's own moisturizing.

(Guggenbichler et al., 2007) carried out experimental and clinical studies of the secretory transport. A correlation between a reduced humidity in the bedroom for at least 8 h and the transport speed of the gel layer of the mucosa was determined.

The high individual spread was noticeable, depending on the hydration status and the individual characteristics of subjects. (Guggenbichler et al., 2007) concluded from his investigations that for an efficient mechanical clearance of the airways (mucociliar clearance) a humidity of at least 30%, better 45% is required. This was important particularly for especially exposed persons such as people in hospitals and nursing homes. Sufficiently high humidity also leads to a lower susceptibility to infections of the airways.

The question now is, how these partly contradictory results can be explained. In this context, the study by (Sunwoo et al., 2006) is of special interest, because the subjects were stratified in two groups according to age.

The so-called saccharin test was applied in order to evaluate the saccharin clearance time (SCT). The test measures the transport time of a saccharin particle from its introduction in the nasal septum or in the bottom area of the nose of the subjects to its recognition as a sweet taste in the throat. This SCT showed no significant dependence on the indoor air humidity in case of the young test subjects in accordance with the findings of (Fang et al., 2002), but showed different results in case of the subjects of the higher age group (mean 71.1 ± 4.1 years) (Sunwoo et al., 2006). The SCT at 10% RH was significantly longer in case of the elderly than among younger (mean 21.7 ± 4.1 years).

Young people are indeed able to feel lighter the dryness in the eyes, throat and nose than older ones, but only the older people showed a prolonged SCT.

Viscosity of the mucous

(Guggenbichler et al., 2007) investigated the viscosity of the secretions (sol and sol-gel layer) and drew the following conclusion from the measurements: "Even small deviations from the norm can lead to severe health problems (effect of summation). This summation is observed especially in patients in hospitals, but also for persons in nursing homes or in homes for the handicapped, and so generally in humans being unable to regulate their fluid balance themselves.

The reduced number of mucus goblet cells, combined with inadequate fluid intake (often in case of the elderly) may lead to extremely high viscosities of the mucus layer and a heavily impared self-cleaning function of the airways. A decrease in humidity to values below 25% RH has a particularly unfavorable impact on this group of people" (Guggenbichler et al., 2007).

Mouth breathing

The nose is generally regarded as a preferential respiratory airway, but not all people apply nose breathing during most of the time. According to (Cole, 1953) most humans readily resort to mouth breathing and about 15% do so habitually. Cole showed, that heat and water are less effectively recovered from expiratory air by the mouth than by the nose. “In addition, chronic mouth breathers suffer from the discomfort of oropharyngeal dryness and some develop gingivitis” (Cole, 1988).
Normally, the so-called “isothermic saturation boundary” (ISB) is sited just below the carina in adults. The ISB is the point at which gas in the tracheobronchial tree reaches 37 °C at 100% relative humidity (fully saturated). This is normally located just below the carina in adults. In case of mouth breathing, the air conditioning is less effective and the ISB is shifted downward. The consequence of this shift is, that bronchi with normally perfect humidity are now taking part in heat and moisture exchange. The heat and moisture exchanging function of the upper respiratory tract has been well demonstrated. Ingelstedt (1956) directly measured temperature and relative humidity (RH) via a criothyroid puncture. He found a temperature of 32 °C in the subglottic space and 98% RH during nose breathing and 30.5 °C during mouth breathing with 90% RH. “With nasal breathing the inspired water content is about 83 % of that expired” (Hedley et al., 1994).

Colds, aerosol and airborne particulate matter

"Germs (bacteria and viruses) are still 20% active at 65% relative humidity after an hour of exposure time. Below this relative humidity the activity decreases. A transfer of germs only arises in the diffusion through micro-aerosols. E.g. larger drops, which are flung into the air after coughing or by ‘runny nose’, land within a distance of one meter on the ground. In dry air, the surface begins to evaporate quickly to very small droplets. These aerosols can carry bacteria and viruses and are deeply inhaled into the lungs " (Lazzarin 2004].
After laboratory investigations of [Hemmes 1960] the viability of influenza viruses in the air is high in the humidity range of about 15 to 40% RH, however minor for indoor air humidity ranging from approximately 50 to 90%, (see also [Green 1974], [Green 1985] and [Arundel, 1986]).
Another reason for the higher incidence of colds in low indoor air humidity is probably due to the beneficiary developing dust. Dust particles and microorganisms contained therein will remain airborn for a longer period according to [Sale 1972] and [Lubart 1979]. At higher relative humidity bacteria and other particles are surrounded with water. This increases the particle diameter, which leads on the one hand to an increase in settling velocity ([Sale 1972] and [Arundel, 1986]) and, secondly, the penetration of bigger particles in the respiratory tract is hindered [Green 1985].

Synopsis and further research

In contrast to the vague and sometimes even contradictory statements from interviews and surveys from field studies, the results of evaluations derived from measurable clinical scores of subject experiments under controlled conditions show more concrete evidence and findings. The following key messages can be summarized as:

Perception of indoor air humidity: Human beeings do not have a dedicated ability to directly perceive humidity. The acceptability of indoor air quality decreases with increasing temperature and humidity due to decreased convective cooling and evaporative cooling of the mucous membranes by inhaled air. Complaints of "too dry air" only occur when physiological impairments or sequelae already occurred – which takes a certain amount of time and is depending on individual conditions.

Ophthalmology: The evaporation rate of the aqueous phase of the tear film through the lipid phase is determined through the partial pressure between the tear film and air. Hence, the decisive factor is the absolute humidity of the air as well as the temperature of the tear film. Further research is needed to find a correlation between ambient conditions and evaporation rate. A decrease in visual performance takes place with falling absoute humidity of indoor air. In addition, however, a deterioration in the quality of the tear film was observed at constant absolute humidity with increasing temperature. This might be a result of a higher evaporation rate at higher temperatures as a consequence of higher eye surface temperature.

Dermatology: The effect of partial pressure difference increasing with decreasing indoor air humidity is compensated partially by increasing diffusion resistance of the skin. In the range of about 30% RH the transepidermal water loss (TWL) reaches a maximum level. At extremely low humidity, a significant change in skin surface roughness occurs. If a majority of the body surface is covered by clothing, the humidity of the air adjacent to the skin under clothing depends on room temperature and the thermal resistance (clo-value) of the clothing. With increasing temperature, perspiration of the skin gains effect in addition to mere diffusion while TWL falls, because TWL only counts the water transport by diffusion. There is still a lack of knowledge about the optimum indoor air conditions from a dermatological point of view.

Otolaryngology: The air is warmed and humidified during inspiration in the nose and the upper airway. During expiration the air is cooled and dehumidified, making the nose a regenerative heat and moisture exchanger. The human being in pure nasal breathing is able to heat and moisturize a wide range of air conditions from ambient air to alveolar condition (37 °C, 100% RH). The thesis of Anderson, that the indoor air humidity does not affect the mucus membrane transport and thus the self-cleaning effect of the respiratory tract, is cited in numerous papers. Recent evidence from clinical studies, however, suggest at least a connection to age. Accordingly, the reduction in transport speed of the mucus was found to be significant at low indoor air humidity for the group of elderly subjects. Further research is needed to confirm these findings of Sunwoo at typical indoor air conditions of 22 °C.
Besides the aging of the ciliated layer, oropharyngeal dryness might be caused by mouth breathing at low relative humidity. Chronic mouth breathing is a frequent phenomenon, about 15% do so habitually. Heat and water are less effectively recovered from expiratory air by the mouth than by the nose [Cole 1953]. Moreover, transport phenomena of bacteria and viruses

by aerosol and airborne particulate matter are also related to low indoor air humidity. "These aerosols can carry bacteria and viruses and are deeply inhaled into the lungs" [Lazzarin 2004].

Conclusion

Clinical studies with quantitative analysis of scores under defined boundary conditions can explain at least some of the apparent contradictions found by a statistical analysis of field studies using questionnaires. Valuable insights into the physiological effects of indoor air humidity are gained. In conclusion, low humidity has a significant negative effect on the eyes, skin and mucous membranes. A lasting exposure at extremely low absolute humidity harmfully affects general health. This applies especially to older persons or groups with corresponding predisposition.

As conclusion of this review, the need for a lower limit for longterm indoor air humidity range can be deduced, but further research is needed to gain deeper knowledge about the effects of low indoor air humidity. This knowledge will help to save a lot of technical expenditure as well as energy for indoor air conditioning.

How to avoid low humidity indoor air conditions

A discussion of this topic in detail goes beyond the scope of this paper, but a detailed study will be published soon, to give references for designers and engineers.

Ventilation for the living area should be adjusted to the moisture sources in space and occasionally reduced, especially in case of very low outside air humidity. In cold climates during heating season, the absolute external humidity is about 1 to 5 g/kg whereas the indoor absolute humidity is around 7 to 9 g/kg. Each cubic meter of air change indoor- by outdoor air takes some 2 to 8 g of water vapour out of the building. Reducing the ventilation rate and accounting for the air quality at the same time is one of the most appropriate ways of raising the indoor humidity level.

In extreme cases humidifying action is recommended, taking into account the hygiene requirements. Moisture recovery may also contribute to a slight increase in the indoor air humidity.

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