INDOOR ENVIRONMENTAL QUALITY IN NON-RESIDENTIAL BUILDINGS – EXPERIMENTAL INVESTIGATION

by

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This paper presents the part of the research that has been done at the Universities both in Belgrade and Thessaloniki, Greece, taking into account indoor environmental quality in office buildings and classrooms. The measurements that are presented were done in Process Equipment Design Laboratory at Aristotle University Thessaloniki, during March 2015. Indoor environmental quality regarding air temperature, relative humidity, and CO_2 concentration in two representative offices is observed. The similar offices are located one on the north-east and the other one on the south-west side of the University building, so as to be representative of the orientation's impact. Furthermore, the impact of natural ventilation on CO_2 concentration and temperature is monitored, together with the offices' occupancy. Recommended parameters for indoor air quality are compared and discussed on the base of several standards: SRPS EN 15251:2010, ASHRAE standards 55 and 62.1, and ISO 7730. The main objectives, as set from these standards are discussed, together with the investigation results.

Key words: *ASHRAE standards 55 and 62.1, building occupancy, SRPS EN 15251:2010, indoor air quality, CO_2 concentration and temperature measurements*

Introduction

Looking at the global trends in indoor air quality (IAQ) field of research, there are several common problems that are discussed in most of the papers: the correlation of IAQ and health problems, the required number of air changes when regarding mechanical ventilation, and the possible energy savings and natural ventilation direction.

According to the Environmental Protection Agency (EPA), around 50% of elementary and secondary schools in the U. S. have problems connected to the poor IAQ [1]. Children are the most vulnerable population category, but so are adults who are spending most of their time indoors. According to the EPA, Americans spend 90% of their time indoors [2] and the significant period of that time, at work, in the offices [3]. A lot of studies were dedicated to the research of the impact of poor IAQ to human health, and Wolkoff and Kjaergaard [4] gave a detailed survey of various studies and theirs conclusions. Lazović *et al.* [5] had been investigated the CO_2 concentration impact on IAQ in correlation with the temperature and

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humidity in school buildings in Serbia. The measured results showed that the CO_2 concentration value of 1000 ppm was reached very fast in classroom during the heating seasons, already after ten minutes, and that the average daily value was around 2000 ppm [5]. The parameters mostly used for describing IEQ are temperature, relative humidity, and CO_2 concentration. The main contributor to the CO_2 generation are high occupancy and inappropriate ventilation. Mechanical ventilation can maintain adequate level of IAQ, but, together with cooling, it can account significantly to the overall energy consumption, with up to one-third of the total [6]. Natural ventilation contributes to energy savings, with about 40% lower energy costs compared to a mechanically ventilated, fully air-conditioned building [6], but there are authors who see a connection between the varying, uncontrolled air change numbers per hour and different type of diseases [7]; a property that is difficult to control in naturally ventilated buildings. Fisk *et al.* [8] investigated the relation between the low ventilation rate and short-time absence from the work that is caused by respiratory infections and they estimated that the rate of absence decreased by 2,9% for each 1 L/s per person the ventilation rate increases. Seppanen *et al.* [9] also had reported the correlation between the ventilation rates below 10 L/s per person and the impairment of IAQ and health, predominantly researched in office buildings. Having in mind the adequate decisions for sustainable buildings and system design, it is suitable to apply appropriate multi-criteria analysis that could lead to the optimal solution between lower ventilation rates and desirable indoor air quality [10].

Recommended parameters for IAQ are given in several standards worldwide: SRPS EN 15251:2010, ASHRAE standards 55 and 62.1, and ISO 7730 are discussed in this paper, together with the part of the results that have been measured in Process Equipment Design Laboratory at Aristotle University Thessaloniki, during March 2015.

Building and equipment description

The measurements that are presented in this paper were carried out in Process Equipment Design Laboratory at the School of Engineering at the Aristotle University Thessaloniki, during March 2015. The IEQ, regarding air temperature, relative humidity, and CO_2 concentration which were measured in two representative offices. The similar offices are located one on the north-east and the other one on the south-west side of the University building, so as to be representative of the orientation’s impact. The University building is oriented south-west with its main façade and has nine floors, which can be seen in fig. 1.

The Process Equipment Design Laboratory is placed at the eight floor, and its plan section is depicted in fig. 1, and it is representative of one typical floor at the whole building. The positions of data loggers which are placed in two offices in order to measure desired IAQ indicators are marked with red spots (numbers 1 and 2) and shown in fig. 2. The sensors were placed 0.6 m above the floor, in the level for seated occupants, as it is recommended by ASHRAE standard 55. The office on the south-west side is marked with number 1, and the other one on the north-east is numerated as 2. The office 1 has one occupant, and in office 2, the number of occupants varies from one to four, depending of the day and duty.

HOBO UX100-03 data loggers were used in both offices for temperature and relative humidity measurement and logging. In the office 2, the CO_2 concentration is measured, using Telaire 7001 manual CO_2 sensor. CO_2 concentration is measured taking into account a number of occupants and natural ventilation. The different natural ventilation rates are enacted, by opening the window and the door of the office.

The HOBO data logger records temperature with ±0,21% accuracy and humidity within ±3,5% accuracy. The temperature range is from –20 °C to 70 °C and humidity sensor

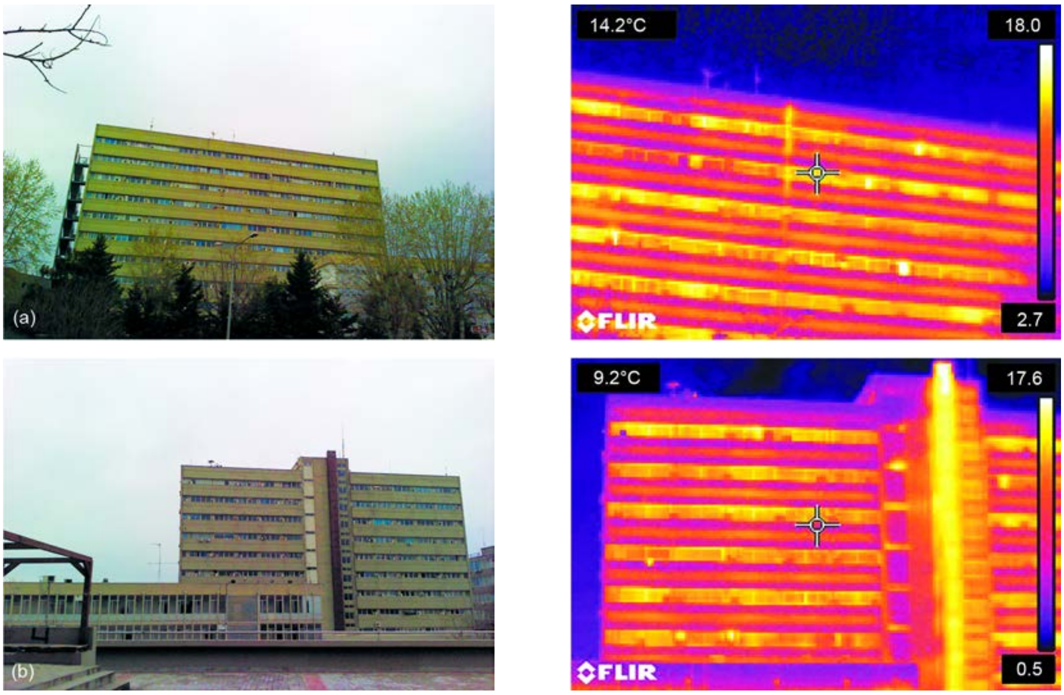

Figure 1. (a) South-west façade, (b) north-east façade *(for color image see journal web-site)*

range is from 15% to 95%. The Telaire 7001 manual CO_2 sensor has a measurement range from 0 to 10000 ppm, with ±5% accuracy.

The instruments were calibrated and positioned away from the internal heat sources, as well as from the reach of the direct sunrays in order to gather as more as precise results.

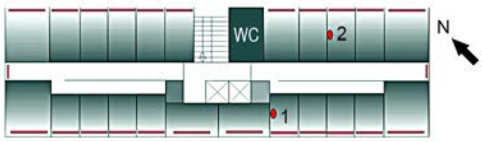

Figure 2. Process Equipment Design Laboratory at Aristotle University Thessaloniki – floor plan [11] and data logger displacement

Standards for IAQ

SRPS EN 15251:2010

Basic criteria for indoor air quality and ventilation rates in non-residential buildings are given in SRPS EN 15251:2010 through the method based on person and building component, the method based on ventilation rate per person or per m^2 floor area, and recommended values of CO_2 for energy calculation [12]. This standard is identical to EN15251:2007, and valid in Europe, and also in Republic of Serbia, according to Institute for Standardization of Serbia. Recommended ventilation rates can be calculated, according to this standard, using eq. (1):

$$q_{\rm tot} = nq_{\rm p} + Aq_{\rm B} \tag{1}$$

where $q_{\rm tot}$ [Ls^{-1}] is the total ventilation rate of the room, n – the design value for the number of the persons in the room, $q_{\rm p}$ [Ls^{-1} per person] – the ventilation rate for occupancy per person, A [m^2] – the room floor area, and $q_{\rm B}$ [Ls^{-1}m^{-2}] – the ventilation rate for emission from building.

The ventilation rates for given occupants and building's emissions are given in the standard as a function of the building category. For category II, temperature range for heating is between 20 °C and 25 °C, and recommended airflow per person is 7 L/s per person, and 0,7 L/s/m^2 for low polluting building. Expected percentage of dissatisfied is 20. Corresponding CO_2 above outdoors for energy calculation is 500 ppm for category II as it is given in standard [12].

ISO 7730

International standard 7730 determines the predicted mean vote (PMV) and predicted percentage of dissatisfied (PPD) as a function of the activity and clothing. The PPD and PMV express warm and cool discomfort for the whole body. The limits for the light, mainly sedentary activity during the winter period are given in standard. The operative temperature shall be between 20 °C and 24 °C. The vertical air temperature difference between head and ankle level shall be less than 3 °C. The relative humidity shall be between 30% and 70% [13].

ASHRAE Standard 55

This standard defines the thermal environmental conditions for human occupancy. It describes the metabolic rate, clothing insulation, air temperature, radiant temperature, air speed, humidity, and position of the measuring equipment. Operative temperature or PPD, PMV shall be measured or calculated at a height of 0,6 m level above the floor for seated occupants and at the 1,1 m level for standing occupants [14].

ASHRAE Standard 62.1

Standard 62.1 gives ventilation criteria for acceptable IAQ when the mechanical ventilation system is designed. According to this standard, minimum ventilation outdoor air rate in breathing zone for office space per person is 2,5 L/s per person, while the outdoor air rate per area is 0,3 L/s/m^2 [15]. Maximal allowed CO_2 concentration for offices, according to ASHRAE 62.1:2013 is 700 ppm higher than outdoor air level. Typical CO_2 concentration level in outdoor air is between 300 ppm and 500 ppm [15], so maximal recommended CO_2 concentration for offices is between1000 ppm and 1200 ppm, but it should be emphasized that the CO_2 concentration level is not the only and also not necessarily the most representative criterion for IAQ. Besides this, volatile organic compounds have a dominant influence on IAQ. It is important to underlinethat the allowed concentration should always be determined as the difference between indoor and outdoor concentration.

Measurement results and discussion

During the two weeks (10 working days), from March 9 2015 till March 20 2015, the CO_2 concentration measurements were carried out every 15 minutes during the working hours in office 2. The results of measurement are shown in fig. 3. The CO_2 concentration values are correlated to the number of the people in the office and the opening of doors and windows. Various patterns of opening the window and the door were performed in office 2 in order to simulate the influence of natural ventilation. The time series of the minimum and maximum values is depicted in tab. 1.

The highest CO_2 concentration was recorded during the day, when the window was not opened and there were three occupants in the office. In that period, alack of working concentration and productivity was mentioned by the occupants, together with complaints about suffering headaches and sensing a bad odor. The indoor air temperature varied from 20,28 °C

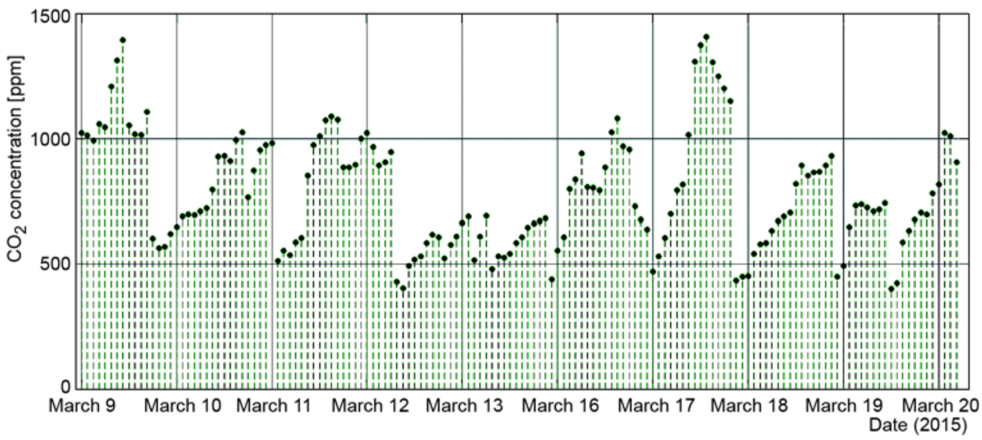

Figure 3. The CO_2 concentrations during two weeks in office 2

Table 1. Maximal and minimal CO_2 concentrations during two weeks in office 2

Date (2015)	CO_2 max [ppm]	CO_2 min [ppm]	Time	Window	Door	Occupants
March 9	1394		13:47	open	open	2
		991	12:15	closed	open	3
March 10	1025		13:44	open	Closed	2
		564	10:09	open	Open	1
March 11	1089		12:38	closed	closed	2
		513	9:50	closed	closed	0
March 12	692		14:15	closed	open	1
		403	10:15	open	open	0
March 13	681		13	closed	closed	1
		480	9:50	closed	closed	1
March 16	1080		13:41	half closed	closed	3
		440	10	closed	closed	0
March 17	1406		13:17	closed	half closed	3
		470	10	open	closed	0
March 18		433	10	closed	open	1
	930		14:30	closed	half closed	3
March 19		450	10	open	open	0
	743		13:44	closed	open	2
March 20		402	9:45	closed	closed	0
	1023		13:35	closed	closed	3

to 25,09 °C, depending on the window opening and the number of the people in the office. During most periods of time the CO_2 concentration was slightly higher than the recommended one. It can therefore easily be concluded, that the variation of CO_2 concentration varies strongly during the working hours, and is very difficult to predict in a naturally ventilated office buildings: it depends on the number of occupants and on the arbitrary way in which natural ventilation is occurring. The similar investigation had been done by Brouce-Konuah [16], but in much more detaile, as a part of his Ph. D. thesis. Brouce-Konuah had been observed two field study buildings, predominantly with offices. The main focuse was on windows' opening impact on temperature in offices and CO_2 concentration in five representative offices. The measurements were done on three levels: floor level, table high, and top level (around 1.7 m above the floor). For further details please see [16].

Furthermore, the relative humidity and the temperature were measured in this office, in a period from March 2 2015 until March 20 2015 with data logging every 15 minutes. The heating system in the University building is central, two-pipe system with radiators and with thermostatic valves. The results of the measurements are presented in fig. 4, together with the boundaries of recommended criteria. The green line (1) represents the lowest thresholdfor relative humidity, which is considered to be comfortable for occupants as, according to ISO 7730, recommended values are between 30% and 70% [13]. Respectively, the orange lines (2) represent the range of recommended temperatures according to ISO 7730, with recommended values being in range 20-24 °C [13]. It should be noted that SRPS EN 15251:2010 allows a slightly wider range: 20-25 °C. Seppanen had investigated the impact of the high temperature on working performance and concluded that the working performance increases for temperatures up to 21-22 °C and decreases when they rise to 23-24 °C [7]. There is quite a number of studies which deal with indoor air temperature's influence on thermal comfort, air quality, sick building syndrome, and performance in work [17-19], and also with the influence of changing set-up temperature by occupants on total energy consumption [20]. The reader is encouraged to consider the relevant literature for a more detailed study of the phenomenon.

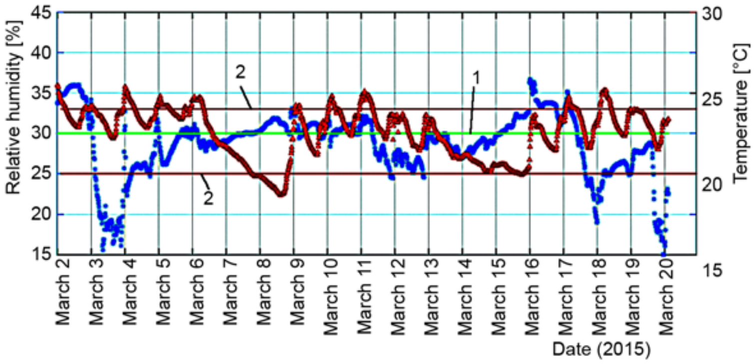

Figure 4. Temperature and relative humidity measured in office 2

From fig. 4 it can be seen that the temperatures are in the desired range for more than 75% of the time. Only in 6.5% of the time, the temperature was lower than 20 °C, but still higher than 18 °C. Around 18.5% of the time, the temperature was higher than 24 °C, but it never reached 26 °C. These results are expected, having in mind the heating system with the thermostatic valves.

The situation with relative humidity is a quite different one: during more than 61% of the time, the relative humidity was lower than recommended 30%, and only in 39% of the time, was humidity within the recommended limits. Around 49% of the time, the relative humidity was between 25% and 30%. This is clearly a result of the combination of overheating and of less ventilation than required. The lowest recorded value was *RH* = 15% and it was recorded at 8:15 a. m., in the period when the office was empty, when no vapour was produce due to the lack of occupants. During the working hours, from 10 a. m. till 2 p. m. the significant number of recorded values, about 92%, was lower than minimal recommended value. It was only during 8% of the working hours that the recorded relative humidity was higher than 30%, and therefore in the desired range.

According to the previous results, it could be concluded that the IAQ, during most of the working hours was not satisfactory. Some authors who investigated the impact of low humidity on human health concluded that it can result in dryness of the eyes and skin and dryness of the nasal mucous membrane [21]. It was also stated that low humidity can influence the increasing of bacterial, viral and other respiratory infections [21].

In office 1, the measurement of temperature and humidity are also taken. The results are shown in fig. 5. The green line (1) represents the lowest threshold for relative humidity that is considered to be comfortable for occupants, with recommended values from 30% to 70%, according to ISO 7730, whilst the orange lines (2) represent the range of recommended temperatures according to the same standard, with recommended values being between 20 °C and 24 °C [13]. In office 1, the temperatures are in between the desired range in more than 92% of the time. Minimal recorded value is 20.27 °C, and maximal value is 26 °C. Due to that, in only 8% of the time the temperature was higher than 24 °C and lower than 26 °C. The average temperature during the working hours was 23 °C.

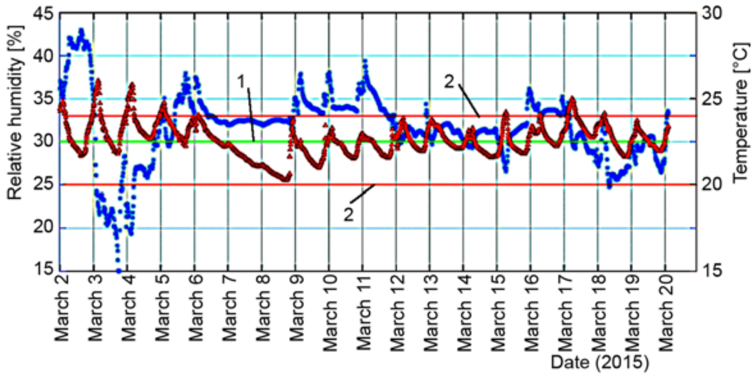

Figure 5. Temperature and relative humidity measured in office 1

Looking at the relative humidity, the situation in office 1 is much better than in office 2; the relative humidity was in the desired range for 75% of the time. During the working hours, the average value of relative humidity was *RH* = 32%, and in the 76% of the time it was equal or higher than *RH* = 30%. Minimal recorded value was *RH* = 15%, and maximal *RH* = 43%.

Conclusions

This study is a part of a bigger, ongoing research on indoor environmental quality and the energy performance of buildings aiming at determining the correlation between IAQ and optimal working performances in office buildings and classrooms. The work presented in this paper is interesting, in that it depicts the difficulties in assessing IEQ in naturally ventilated office buildings, but also in deducing some first conclusions. In this line of approach, the key problems in offices with natural ventilation in the winter period are low relative humidity and high CO_2 concentration levels, due to the rather limited ventilation. This was shown, as the relative humidity in office 2, that is north-east oriented, is significantly below the desired range during the 92% of working hours. The situation in south-west orientated office 1 is better, but still not satisfactory during the 25% of the working hours. These differences can be connected to the slightly higher temperature in office 2, which had been recorded in 18.5% of the time, than in office 1, where the temperature higher than 24 °C had been recorded during only 8% of the time. Considering the temperature, the situation is much better compared to the one of relative humidity, monitoring desirable values, mainly due to the thermostatic valves that had been installed.

The control of IAQ indicators and appropriate ventilation is crucial for occupants' health and productivity and naturally also for conserving energy and reducing operational expenses having in mind the expenses of treatment and workers' absences. The decision about the appropriate ventilation rates should always take into account the anticipated benefits for occupants' health, rather than choosing the minimal rates for energy savings.

A final comment is on the link between the heating and the indoor air quality: the response speed of a heating system working with radiator panels working with water at around 85 ^{o}C and controlled by thermostatic valves is quite different than the effect of natural ventilation, especially if it is cross sided, by opening the door and the windows. The strategy of ventilation has therefore to be carefully considered by the users, in order to maximize its effectiveness on indoor air quality without reducing thermal comfort and, of course, without unnecessarily increasing energy consumption.

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References

[1] Aglan, H. A., Predictive Model for CO_2 Generation and Decay in Building Envelopes, *Journal of Applied Physics*, *93* (2003), 2, pp. 1287-1290
[2] ***, United States Environmental Protection Agency, Healthy Buildings, Healthy People: A Vision for the 21st Century, Report No. EPA 402-K-01-003, US, 2001
[3] Stavova, P., *et al*., A New Approach for Ventilation Measurement in Homes Based on CO_2 Produced by People, *Proceedings*, 17th Air-Conditioning and Ventilation Conference 2006, Prague, Czech Republic, 2006, pp. 291-296
[4] Wolkoff, P., Kjaergaard, S. K., The Dichotomy of Relative Humidity on Indoor Air Quality, *Environment International*, *33* (2007), 6, pp. 850-857
[5] Lazović, I. M., *et al.*, Impact of CO_2 Concentration on Indoor Air Quality and Correlation with Relative Humidity and Indoor Air Temperature in School Buildings, *Thermal Science*, *20* (2015), Suppl. 1, pp. S297-S307
[6] Allocca, C., *et al.*, Design Analysis of Single-Sided Natural Ventilation, *Energy and Buildings*, *35* (2003), 8, pp. 785-795
[7] Seppanen, O., Scientific Basis for Design of Ventilation for Health, Productivity and Good Energy Efficiency, *Proceedings*, 11th Indoor Air Congress, Copenhagen, Denmark, 2008, ID 744
[8] Fisk, W. J., *et al.*, Benefits and Costs of Improved IEQ in U.S. Offices, *Indoor Air*, *21* (2011), 5, pp. 357-367
[9] Seppanen, O., *et al.*, Association of Ventilation Rates and CO_2 Concentrations with Health and other Responses in Commercial and Institutional Buildings, *Indoor Air*, *9* (1999), 4, pp. 226-252

[10] Avgelis, A., Papadopoulos, A. M., Application of Multicriteria Analysis in Designing HVAC Systems, *Energy and Buildings*, *41* (2009), 7, pp. 774-780
[11] Avgelis, A., Building Energy Management with Emphasis on Air Quality and Indoor Climate, Ph. D. thesis, Aristotle University of Thessaloniki, Thessaloniki, Greece, 2008
[12] ***, DS/EN 15251: Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings Addressing Indoor Air Quality, Thermal Environment, Lighting and Acoustics
[13] ***, ISO 7730:2005 International Standard – Ergonomics of The Thermal Environment – Analytical Determination and Interpretation of Thermal Comfort Using Calculation of the PMV and PPD Indices and Local Thermal Comfort Criteria
[14] ***, ASHRAE Standard 55 – Thermal Environment Conditions for Occupancy
[15] ***, ASHRAE Standard 62.1-2010 Ventilation for Acceptable Indoor Air Quality
[16] Bruce-Konuah, A., Occupant Window Opening Behaviour the Relative Importance of Temperature and Carbon Dioxide in University Office Buildings, Ph. D. thesis, The University of Sheffield, Sheffield, UK, 2014
[17] Seppanen, O., *et al.*, Control of Temperature for Health and Productivity in Offices, *ASHRAE Transactions*, *111* (2005), 2, pp. 680-686
[18] Lan, L., *et al.*, Quantitative Measurement of Productivity Loss due to Thermal Discomfort, *Energy and Buildings*, *43* (2011), 5, pp. 1057-1062
[19] Seppanen, O., *et al.*, *Room Temperature and Productivity in Office Work*, eScholarship Repository Lawrence Berkeley National Laboratory, University of California, Berkeley, Cal. USA, 2006
[20] Todorović, M., Bajc, T., The Influence of the Regimes of Use of Building on Total Building Energy Consumption, *Proceedings*, 3rd Regional Conference on Industrial Energy and Environmental Protection in Southeastern Europe, Kopaonik, Serbia, 2011
[21] Sunwoo, Y., *et al.*, Physiological and Subjective Responses to low Relative Humidity, *Journal of Physiological Anthropology*, *25* (2006), 1, pp. 7-14

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