TIME-DEPENDENT THERMAL COMFORT VARIABLES

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# Table of Contents

Acknowledgements............................................................................................................... 3  

Literature Search.................................................................................................................. 4  

Laboratory Apparatus.......................................................................................................... 6  
  Comfort Test Station.......................................................................................................... 6  
  Sensors and Data Acquisition (DAQ) System................................................................. 10  
  Thermocouple Calibration and Uncertainty Analysis...................................................... 11  

Experimental Design......................................................................................................... 15  
  Introduction ....................................................................................................................... 15  
  Pre-Test ............................................................................................................................ 15  
  Phase I .............................................................................................................................. 16  
  Phase II ............................................................................................................................ 16  
  PostTest ........................................................................................................................... 17  

User Survey ....................................................................................................................... 18  

Conclusions......................................................................................................................... 22  

References......................................................................................................................... 23
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Objectives

The research objective is to determine a method to understand and quantize the relationship between comfort and ambient transient conditions. Fanger et. al established a basic understanding of comfort and used a predictive mean vote methodology to quantify the perception of comfort in a static condition. Once this transient relationship between perceived comfort with temperature and air movement change is understood and quantifiable, enhanced productivity with reduced energy use should be possible.

To accomplish the objectives, a laboratory test station was constructed which contained a workstation, ways to direct and modulate air flow to the test subject, and a computer used to provide a typing activity and an interactive program to query the test subject. The interactive program would interrupt the test subject at predetermined times in the test sequence to query their level of comfort.

Literature Search

Providing a thermally appropriate environment for human occupancy has long been a problem of architectural design. According to Badagliacca, the root of this problem lies in the desire of man to provide himself a “sensation of pleasantness in his interaction with any external “Entity”, that may be physical, social or of other kinds” (Badagliacca, 2002, p. 975).

Conventional methods to provide thermal comfort involve mechanical systems, which are set up to ensure a specified level of comfort through temperature, humidity and indoor air quality (IAQ) control. Zhao et al. (Zhao, Sun, & Ding, 2004, p. 1281) stated that the existing air conditioning strategy is based on keeping environmental parameters constant. According to Hanqing et al. (Hanqing et al., 2006, p. 1523) environmental parameters differ at each moment and therefore a group of lumped indoor physical parameters are not sufficient to explain thermal comfort indoors. Zhou (Zhou, Ouyang, Lin, & Zhu, 2006, p. 354) argues that the traditional air-conditioning strategy, which are preprogrammed to keep the area temperature within a constant range and to keep the airflow at low speeds, causes two problems. One is the air-conditioning syndrome, which conditions people to expect a very narrow range of thermal conditions and occurs due to lack of environmental stimulus. The other problem is high energy costs due to maintaining the temperatures at low levels. Van Hoof (van Hoof & Hensen, 2007, p. 157) and de Dear et al. (R. J. de Dear, Brager, & Cooper, 1997) stated that occupants of the air-conditioned buildings become tuned to the narrow range of comfort temperatures which makes them twice as sensitive to changes in temperature than the occupants of naturally ventilated buildings.

In addition to the occupants’ well-being, thermal comfort in office environments has significant economic consequences. Workers’ salaries in developed countries are many times that of the building operating costs (Kosonen & Tan, 2004, p. 987; Woods, 1989) and better indoor climate conditions improve worker productivity. Seppanen et al. (Seppanen, Fisk, & Faulkner, 2004) showed that better indoor climate conditions improved thermal comfort and worker productivity, which led to monetary gains.

The comfort state of people also depends on transients in which environmental and personal factors change with time. In this study, controlled experiments will be conducted in a real-like office setting using human subjects. Ambient and local environmental factors and personal parameters will be changed as a function of time. Their relationship to human body thermal state will be assessed through occupant
surveys and measured data. The measured data includes environmental conditions (temperature, humidity and air velocity) and also test subject metabolic variables (skin temperature, heart rate).

Thermal comfort research evolved in two distinct paths over the last 40 years. The first path focused on climate chamber research to understand the relationship between the human body and the environment. This research methodology evolved into comfort models such as Predicted Mean Vote (PMV) and thermal comfort standards. The second path focused on holistic human environment relationship, which led to the field research and the development of adaptive thermal comfort models (R. de Dear, 2004, pp. 32-33).

The research method of this study is aligned with the first path, which is a deterministic model. Practical answers are sought to the following problem based on the background information given above: “What is the alternative environmental conditioning system design and operation method in relation to architectural space that would increase thermal comfort by responding to thermal comfort requirements under transient conditions?” One specific objective of the study is maximizing the effectiveness of airflow in providing thermal comfort while cutting-back the energy costs. Zhou (Zhou et al., 2006, p. 354) states that higher temperatures can be offset by the cooling effect of airflow which will also help reduce energy consumption.

This Final Report covers: a) literature survey; b) the laboratory apparatus for transient and asymmetrical thermal comfort conditions; c) the experimental design with the test sequences; d) design of the user survey; and e) conclusions.
Laboratory Apparatus

Comfort Test Station

Predicting human thermal sensation based on heat transfer principles in moderate, homogenous, and steady-state environments is relatively straightforward and well-understood (Fiala, Lomas, & Stohrer, 2003, p. 179). Physiological responses to transient conditions introduce complexity and differ significantly from the steady state conditions. The predictive models of transient responses require verification through controlled experiments.

The design of the laboratory setup focused on delivering airflow to exposed skin on the hands, feet and face of the human body to test transient effects as well as the effects of asymmetrical conditions on human comfort. Zhang et al. (H Zhang, Huizenga, Arens, & Wang, 2004), Melikov (Melikov, 2004), and Pellerin (Pellerin, Deschuyteneer, & Candas, 2004) documented the relation between the local thermal comfort and the whole body thermal comfort for different environmental conditions. Pellerin (Pellerin et al., 2004) and Huizenga et al. (Huizenga, Zhang, Arens, & Wang, 2004) and Zhang et al. (Hui Zhang et al., 2008) stressed the importance of hands, feet and the face in providing comfort for the whole body. The test setup design allows the investigation of local cooling affects on the hands, feet and face. Unlike the previous studies on the local comfort, the test setup allows the delivery of air to local body parts while the activity to generate elevated metabolic rates is occurring.

The Comfort Station is composed of three major assemblies: the two side walls and the base unit. The side walls are hollow and are connected to the base unit via 4” metal air ducts (Figure 1 through Figure 3). An external fan delivers air to the side walls through the base unit. The side walls will be pressurized during the tests and the air will be delivered to the desired location on the human body through the adjustable nozzles. Two nozzles on each side of the body are placed at three different locations based on the sitting posture of the user (Figure 3). The layout of the environmental chamber in which the experiments will take place is shown in Figure 4. An area measuring 1.5’ by 2’ was built into the rear floor of the Comfort Station to accommodate a small bicycle ergometer (Figure 5). The bicycle will allow the user to exercise without leaving the Comfort Station. Exercising during the test is needed to increase the metabolic rate which is an important variable in thermal comfort.

The Comfort Station was designed as a standalone unit which does not require connection to an external source for air delivery. It takes room air and directs it to the desired locations on the human body. This feature of the Comfort Station allows operation under various conditions by varying the room conditions.

The design and drawings of the Comfort Station were completed in summer 2008. Construction was finished in November, 2008. Figure 6 shows the various stages of assembly starting with a wall through the full assembly.
Figure 1. Plan of the Comfort Station.

Figure 2. Cross section of the Comfort Station.
Figure 3. 3-D reconstruction of the Comfort Station.

Figure 4. Environmental chamber.

Figure 5. Small bicycle ergometer.
Figure 6. Construction of the Comfort Station.  a) Wall, b) Base Unit, c) Right wall and base unit with fan, d) Assembled Comfort Station.
Sensors and Data Acquisition (DAQ) System

Instruments and sensors which will be used for this project comply with ISO 7726-1998, ISO 7730-2005 and ASHRAE Standard 55-2004 (ISO7726, 1998; ISO7730, 2005; Standard55, 2004). A National Instruments PCI-6031E type DAQ terminal and card is used to collect and store data. This specific card has 64 single ended or 32 differential analog inputs with 16 bits resolution, 2 analog outputs with 16 bits resolution and 8 programmable digital input/output channels. A custom LabView program was designed to collect data and control the fan sequence for air pulsing effect that will be used in the experiments (Figure 7).

T-type thermocouple (TC) wires from Omega Inc. (Figure 8a) were used to make the temperature sensors which will be used to measure skin temperature as well as the air temperature and the wall temperatures inside the environmental chamber. The T-type TCs, with special limits of error (SLE), have an accuracy of 1°F or 0.4% of the measurement, whichever is larger. Each TC is connected to the DAQ system by INOR MiniPaq Low Profile Transmitters which amplifies and converts TC voltage into 4-20 mA current signal (Figure 8b). Airflow measurements inside the environmental chamber will be made using a TSI 8475 omni-directional probe which has an accuracy of 3% of the reading. Relative humidity (RH) inside the chamber will be calculated from dew point temperature. Dew point temperature will be measured using the General Eastern Dew-10 chilled mirror sensor which has an accuracy of 1°F. The mental stress

Figure 7. DAQ software interface.
of the test subjects will be assessed by measuring skin conductance. The metabolic rate of the subjects will be assessed through heart rate (ISO8996, 2004). Both skin conductance and heart rate will be measured using Coulbourn Isolated Skin Conductance Coupler and Direct Coupled Bioamplifier.

![Figure 8. a) T-type thermocouple, b) INOR transducers](image)

Thermocouple Calibration and Uncertainty Analysis

TCs were fabricated using T-type TC wire with special limits of error (SLE) from Omega Inc. The calibration procedure has three steps. Step 1 is to check the quality of the fabricated TCs by comparing the output results of all TCs with each other. Step 2 requires processing the data to determine and offset errors. Random errors are filtered by oversampling and averaging. Calibration was done using calibrated thermometers and the procedure from Nicholas et. al (Nicholas & White, 1994, p. 50). Step 3 requires a correction to eliminate the systematic error for the temperature regions of interest. Uncertainty in a measurement can be characterized by the standard deviation of the repeated measurements for the same temperature. This is also called the standard uncertainty (Nicholas & White, 1994, p. 51).

Auxiliary measurement is an integral part of the systematic error analysis. Three certified thermometers from Brooklyn Inc. were used as the auxiliary measurement devices. Calibration is done by exposing the temperature-measuring device to known fixed-point temperature environments such as melting or boiling point of some substances. Doebelin (Doebelin, 2004, p. 683) stated that calibration of a sensor is done by placing the auxiliary measuring device and the uncalibrated sensor, in intimate thermal contact, into a temperature controlled bath. Correction factors can be established by varying the temperature of the bath over a desired range while recording the measurements.

The calibration of the thermometers was checked using the two fixed point calibration method. An ice-bath and the boiling point of distilled water was used to ensure that thermometers are usable as auxiliary measuring device (Figure 9). The ice-bath then stabilized for 2.5 hours and the boiling water for 30
minutes. Measurements were taken every 15 minutes during the process. All three thermometers measured 32°F for the ice-bath and 212°F for the boiling point of distilled water.

![Ice-point Calibration Setup](image1)
![Boiling-point Calibration Setup](image2)

Figure 9. Ice-bath and boiling water calibration setups.

Ensuring that thermometers and TCs are exposed to same temperature during the calibration process is the most critical issue. A refrigerator was modified and used as the temperature chamber (Figure 10a). A 40W lamp supplied heat to increase the temperature inside the chamber. A personal computer CPU fan mixed the air and created a homogenous temperature environment. A webcam and a LED light source was used to record the thermometer reading without having to open the refrigerator door during the calibration. Webcam snapshots of the thermometers provided readings of the thermometers. The values were then manually entered in a spreadsheet. All TCs were placed on a copper-block between the mica and plastic washers (Figure 10b). Silicone thermal paste was applied between the copper block and the mica washer to ensure good thermal contact between the TCs and the copper block. The thermometers were also thermally coupled with the thermal block using the thermal paste.
TC temperatures were recorded every 0.5 seconds during the calibration. Filtering reduced the random errors exhibited in this data (Figure 11). Running averages of 10 seconds, 30 seconds and 60 seconds were calculated. Figure 10 shows that 10-second filter reduced the majority of the random errors and 30-sec filter eliminated the large fluctuations in the 10-second data. The 30-second filtering represents a good representation of the data with the noise filtered.

A visual inspection of Figure 12 showed that each TC has an offset from the true temperature, which is an indicator of systematic error. A regression equation of the TC-1 data provided Equation 1.

\[ y = 0.3144x + 84.082 \quad (R^2 = 0.9966) \]  

Eqn. 1
The thermometer data and the TC data were then compared for the whole range of measurements. The mean error between the thermometers and the TC-1 is 0.923°F. The standard deviation for the mean error is 0.035°F. From these results, there is a 95% confidence that TC-1 has an offset between 0.991°F and 0.854°F with a mean error of 0.923°F. This procedure was repeated for all 28 TCs. The offset errors will be used to correct the readings of each thermocouple.

Figure 12. TC measurements compared to the thermometer data.
Experimental Design

Introduction

Time-dependent thermal comfort experimental procedures arrange a sequence of timed events and measure the response of a test subject to these sequenced events. Using the same process a statistical correlation of responses to these events can be performed over different modes of environmental and personal variables which are applied periodically. The methodology of the study is based on investigating correlations between the measured environmental data and user responses to the environmental conditions.

There are two types of surveys, namely the Background and the Online Survey. In this study, both are the modified versions of ASHRAE comfort field survey (Cena & De Dear, 1998). The Background survey will be conducted before the experiments start and the Online Survey will be conducted during the experiment. Since a standard for test protocols for time dependent thermal comfort variables has not yet been established, the sensitivity of the protocol to the protocol parameters will first be tested. Regression analysis will be employed between the environmental variables and the subjective votes to create relationships between these variables.

The literature search revealed the existing studies of the laboratory experiments of thermal comfort with human subjects (Fanger, 1970; Gagge, Stolwijk, & Hardy, 1967; Gagge, Stolwijk, & Saltin, 1969; McNall, Jaax, Rohles, Nevins, & Springer, 1967; McNall, Ryan, Rohles, Nevins, & Springer, 1968; Hui Zhang, 2003). The test protocol of the phases is based on the studies by Astrand et al. (Astrand, Rodahl, Dahl, & Stromme, 2003), Kistemaker (Kistemaker, Den Hartog, & Daanen, 2006), Zhang (Hui Zhang, 2003), and van den Heuvel (van den Heuvel, Ferguson, Gilbert, & Dawson, 2004). Currently, the design of the experiment sequence is complete and the experimental process is composed of four steps, namely, Pre-Test, Phase I, Phase II, and Post-Test.

Pre-Test

The Pre-Test phase consists of getting participants ready for the experiment and collecting background data. Previous studies suggested 10 minutes to durations exceeding 60 minutes in the environmental chamber to acclimatize with the environment (Greenspan, Roy, Caldwell, & Farooq, 2003; Huda & Homma, 2005; Jones & Ogawa, 1992; Strigo, Carli, & Bushnell, 2000; Yao et al., 2007). Participants in this study will spend minimum a 30 minutes in the test room during this phase for their body to acclimatize with the environment.

- Upon arrival, participants will be given the consent form together with verbal briefing of the procedure. Time will be provided for any questions that the participant may have.
- If the participant agrees to partake, he/she will be seated at the desk to familiarize with the computerized survey environment.
- The participant then fills out the background survey.
- Finally, thermocouples will be placed for skin temperature measurements.
Phase I

Phase I will last one hour (Hour I) in which thermal sensation of the occupants will be measured for transient ambient temperature with sedentary activity level and transient activity level with neutral ambient temperature (Figure 13). The initial conditions will be set to 24°C for ambient temperature and to 50% for relative humidity. This test procedure was adapted from the experiments of Gagge et al. (Gagge et al., 1967) and Strigo et al. (Strigo et al., 2000, p. 700) and is given below.

- Upon start, an online survey will be given to record the initial thermal sensation of subjects to neutral ambient conditions.
- In the first 40 minutes, room temperature will be adjusted and thermal sensations will be recorded every 5 minutes.
- Between 40 and 60 minutes, room conditions will be kept neutral while the subject exercises. Thermal sensations will be recorded every 5 minutes.

![Figure 13. Time-dependent representation of Test Phase I.](image)

Phase II

Phase II will be comprised of Hour II and Hour III. The tests performed in Hour II (shown in Figure 14) use exercise to increase the internal body temperature and “discomfort”. The test periods to quantify the test subjects’ response to pulsed air and local air, which can be aimed at exposed skin in the hands and head. Hour III, shown in Figure 15, uses the same tests with room air substituted for local air. Local air is room air temperature blown at specific areas of exposed skin. Room Air is at the same room temperature but is not blown at exposed skin. These two hours will be used to measure the test subjects’ thermal sensation and their physiological response to transient environmental conditions at high metabolic rates. This test procedure was adapted from Gagge et al. (Gagge et al., 1969).

- First, an online survey will be given to record the initial thermal sensation of subjects.
- Participants will exercise on bicycle ergometer for 10 minutes at 116 W/m² (2 Mets) – which is equivalent to medium activity such as shop assistant and domestic work according to ISO 7730.
The exercise period will be followed by a 10 minute resting period during which subjects respond to the Online Survey about their thermal sensation every 5 minutes.

- Combinations of air pulsing frequency and air movement location will be applied based on 10 minute exercising and resting sequence (Figures 14 and 15).

![Figure 14. Time-dependent representation of Test Phase II.](image)

![Figure 15. Time-dependent representation of Test Phase III.](image)

**PostTest**

Participants will be given an optional evaluation form of the test procedure.
User Survey

Two types of user surveys, namely Background and Online Surveys have been developed for this study. The Background Survey is a modified version of a background survey of a previous ASHRAE report (Cena & De Dear, 1998) (Figures 16 through 19). This survey aims at collecting data on the background characteristics of the user, personal environmental control over their usual workplace, health characteristics, and sensitivity to different environmental stimulus. Figure 16 shows the background characteristics that will be collected from the test subjects. These contain demographic attributes including age, gender, year in college and physical attributes such as weight and height. Figure 17 shows the personal control information collected. This will be used to determine the test subject’s degree of environmental control over their current workspaces as well as the different control strategies that they can apply. Figure 18 shows the health characteristics which the subject experiences at their workplace. This information will provide data on some of the sick building syndromes that subjects experience in their usual work areas. Finally, figure 19 shows the environmental sensitivity which the user feels he/she has. This data will help categorize the subjects’ sensitivity to environmental stimulus such as light, airflow, noise and temperature. In the data analysis, the data collected in the Background Survey will be used in the analysis of the test subject’s responses to the Online Survey on perceived thermal comfort sensations.

![Background Info Form](image)

Figure 16. Background characteristics section of the Background Survey
Figure 17. Personal control section of the *Background Survey*

![Personal control section of the Background Survey](image1)

Figure 18. Health characteristics section of the *Background Survey*

![Health characteristics section of the Background Survey](image2)
The Online Survey will be used to collect subjects’ perception of thermal comfort and thermal sensation during the experiments. The ASHRAE 7-point scale is used for thermal comfort and sensation votes. The above version is the result of several iterations. User behavior studies were also done to avoid biasing the responses. Previous versions and user behavior studies are presented in the Appendix. The literature survey showed variations in the thermal comfort surveys. Thermal comfort scales used in some of the recent studies are summarized below.

Kaczmarczyk et al. (Kaczmarczyk, Melikov, & Fanger, 2004):
- **Thermal Sensation**: (-3) (0) (+3)
- **Air Movement Acceptability**: (-1) (0) (+1)

Huda et al. (Huda & Homma, 2005):
- **Thermal Sensation**: (-2) (0) (+2)
- **Thermal Comfort**: (-2) (0) (+2)

Melikov (Melikov & Knudsen, 2007):
- **Thermal Sensation**: (-3) (0) (+3)
- **Thermal Acceptability**: (-1) (-0) (+0) (+1)

Yao et al. (Yao, Lian, Liu, & Shen, 2007):
- **Thermal Sensation**: (-3) (0) (+3)

Zhang et al. (Y. F. Zhang, Wyon, Fang, & Melikov, 2007):
- **Thermal Satisfaction**: (-3) (0) (+3)
- **Thermal Sensation**: (-3) (0) (+3)

Zhang and Zhao (Y. Zhang & Zhao, 2008):
- **Thermal Sensation**: (-3) (0) (+3)
- **Thermal Acceptability**: (-1) (-0) (+0) (+1)
- **Thermal Comfort**: (-2) (-0) (+0) (+2)

Zhang et al. (Hui Zhang et al., 2008):
The Online Survey has analog scales for thermal comfort and thermal sensation. Discrete scales are used for thermal environment acceptability, temperature and air movement preference (Figure 19). A break was placed between the two halves of the thermal comfort scale to encourage the subjects make a decision for their thermal comfort level. The Online Survey is designed to pop-up on the computer screen of the test subject at specified times during the experiments. The timing of the surveys can be either preset or random which is controlled through an initial screen (Figure 20).
Conclusions

Time-dependent thermal comfort variable research has four major parts. The first part is the literature survey and test design. This part of the study started in 2006 and still in progress. The second part is the design of the DAQ software and the sensor electronics, which started in early 2007. The third part is the construction of the physical setup. Finally the fourth part is the design and coding of the user surveys which lasted 1.5 years.

Providing a thermally comfortable space for human occupancy is one of architecture’s major goals. Since the development of the psychrometrics at the beginning of the 20th century, thermal comfort inside buildings has been represented with a limited number lumped parameters. Environmental conditions in occupied spaces were considered to be steady-state and uniform. However, literature shows that during the course of a typical day environmental conditions as well as the human body’s thermal state are far from being neutral and uniform. In addition, individual differences and preferences further complicate the problem rendering the assumptions of steady-state and uniform environmental conditions obscure. An improved understanding of human environment relationship needs to be developed in order to provide comfort for the building occupants.

This research study aims at developing an improved understanding of human environmental relationships under transient conditions. A goal of this study is to also provide data which can be used to specify and design transient environmental conditions which provide superior thermal comfort for the building occupants. The BSA grant has been used for the design of the physical test layout, sensors and instrumentation. In this report, the systems components and design of the test setting are shown. This system is capable of delivering air to different parts of the body for local cooling and non-uniform environment experiments. The experimental data acquisition system and sensors that will be used are documented. The calibration of the thermocouple, which will be used for skin and environment temperature measurements, are included in this report. The survey forms and online user surveys are documented. Finally, the test sequence which will be used to develop understanding about transient human environment relationships is presented. The information given in this report is available for other researchers to use for their thermal comfort research.


References


