Renewable and Sustainable Energy Reviews xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

A review of human thermal comfort experiments in controlled and semi-controlled environments

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ARTICLE INFO

Keywords:
Thermal comfort
Experiment
Methodology
Climate chamber
Questionnaire
Survey

ABSTRACT

There are three main methods to improve thermal comfort in existing buildings: modeling, experiments and measurements. Regarding experiments, no standardized procedure exists. This article provides an answer to the question: "What is the most common practice for human thermal comfort experiments in (semi-)controlled environments?". A total of 166 articles presenting results on 206 experiments were collected and analyzed to extrapolate the most common practice. The results are arranged in five main themes: subjects (e.g. number and age), climate chamber (e.g. surface area), thermal environment, experimental procedure (e.g. phases and duration), and questionnaire.

A typical experiment was found to employ 25 subjects and to take place in a permanent climate chamber with a floor area of 24 m^2 During the experiment, 3 air temperature variations are used. The test itself takes 115 min, but is preceded by a preconditioning and conditioning phase. The subject is given a questionnaire at regular intervals of 15 min, with questions highly dependent on topic, but including thermal sensation and comfort vote rated on a bipolar 7-level scale.

Number of subjects, gender distribution, type and floor area of the climate chamber and utilization rate of the scale for rating thermal comfort and sensation are all linked to topic, as well as number of different air temperatures, whether conditioning is employed and questions in the questionnaire.

Several links between experiment characteristics reciprocally are also identified.

1. Introduction

Since the beginning of the 20th century, it has become possible to change the indoor thermal environment to fit our comfort needs [1, p. 7]. The advent of powerful computers allows detailed simulation of these thermal environments. However, since comfort is not a physical quantity but rather a state of mind, it is impossible to simulate directly. Comfort models must be employed to link (simulated) physical characteristics to these psychological parameters.

The development and refinement of comfort models is a relatively new scientific research field. In 1936, Gagge [1] published the first scientific article exploring thermal comfort. MacPherson [2] proposed six main parameters which influence thermal comfort in 1962 : air temperature, mean radiant temperature, relative humidity, air velocity, clothing and metabolism. The research field really took a start with the publications of Fanger in 1967 and 1970 [3,4]. He created a controllable thermal environment, exposed people to this environment and asked them to rate their comfort on a 7-point scale. From these experiments, a model was developed to predict the thermal environment rating of a group of people based on measurement of the six MacPherson parameters. This model became known as the Predicted Mean Vote (PMV) – model.

Since then, a lot of multidisciplinary research on thermal comfort is performed following the same overall experimental method. A review of developed models and discoveries on the human thermoregulatory system can be found in [5] and [6]. In recent years, several other literature reviews on thermal comfort have been published. An overview of gender differences in comfort was presented by Karjalainen in 2012 [7]. Taleghani et al. published a review of steady-state studies, field studies and comfort standards in 2013 [8]. Both field studies and laboratory experiments are used to explore thermal comfort, and while the former type of studies was the subject of two recent review articles

Abbreviations: IAQ, Indoor air quality; IEQ, Indoor environmental quality; Min, Minimum; Max, Maximum; NRS, Numeric rating scale; PMV, Predicted mean vote; Q1, First quartile; Q3, Third quartile; SET*, Standard Effective Temperature; TSV, Thermal sensation vote; TCV, Thermal comfort vote; VAS, Visual analogue scale

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https://doi.org/10.1016/j.rser.2017.10.053
Received 19 December 2016; Received in revised form 29 June 2017; Accepted 27 October 2017

[9,10], no overview of thermal comfort experiments in laboratory conditions has been published in recent years. This article tries to fill the gap. In [11], Rupp and Vasquez distinguished two types of laboratory experiments based on the thermal environment in which those were performed: controlled versus and semi-controlled. In controlled experiments, all six influencing parameters (air temperature, radiant temperature, relative humidity, air velocity, metabolism and clothing) proposed by Fanger [3] have to be controlled. In semi-controlled experiments, at least one of the parameters is determined by the subject itself, or not controlled at all.

Since no standardized procedure is available for this type of experiments, comparison between different experiments (or starting a new experiment) may prove challenging. The main research objective for this review is to provide an answer to the question: “How is a typical thermal comfort experiment in a (semi-)controlled environment performed?” This “typical” practice includes the number and nature of the participants, size and type of controlled environment, thermal environment created, procedure to be followed and instruments to be used. The common practice can form a basis for future experiments. Because the number of topics in which comfort experiments are performed is so diverse, a second question is posed: “Are the experiments performed differently for different topics?”. Finally, correlations are researched to answer the question: “Are there decisions in the design of the experiment that influence other decisions?”. The answers to these research questions will help researchers start new thermal comfort experiments in laboratory conditions, thereby expanding the research base for the topic.

In the first section of this paper, the method for collecting all articles that served as a basis for the analysis, is presented. Subsequently, all collected articles are presented per topic. The third section comprises the statistical methods for analyzing the data collected from the articles. The results of this analysis are presented and discussed thereafter. The final sections contain the conclusions from this analysis.

2. Methods

2.1. Literature selection criteria

The review of human thermal comfort performed by Rupp, Vásquez and Lamberts [11] was taken as a starting point for collecting the papers. Multiple levels of references and citations were used, leading to 6147 references in total. Two sets of exclusion criteria were then applied to reduce the original dataset. The first set contains only article-related exclusion criteria. In the second set, experiment-related criteria were used to filter the collected articles for topic relevance.

The first set contains the following five exclusion criteria:

I. Duplicates: Duplicates were excluded from the final sample
II. Missing of incomplete reference data: articles with missing or incomplete reference data could not be retrieved and were excluded from the final sample
III. Review articles: literature reviews do not provide sufficient detail for the analysis and were therefore excluded from the final sample. However, the original references of all literature reviews were added to the sample.
IV. Conference articles: conference articles were excluded because the peer review process for these articles is not guaranteed
V. Non-scientific articles: Newspaper articles, standards and non-written references (such as audio and video recordings) were excluded from the final sample
VI. Publication year: papers published before 2000 were excluded from the final sample

In the second set, the following criteria were used:

I. Environments: only experiments performed in (semi-)controlled environments were included. This resulted in the exclusion of case and field studies
II. Participants: only experiments employing human subjects were included. Experiments using only thermal manikins were excluded
III. Survey: only experiments where subjects were required to complete surveys during the test, were included
IV. Topic: only experiments on thermal comfort, thermal well-being and thermal sensation were included in the final set
V. Language: only articles published in English were included in the final sample

Section 3.1 elaborately describes the collection process of articles.

2.2. Data extraction plan

The data needed to be extracted from all papers in a structured manner. The analysis was split in two phases: in the first phase, data regarding the research methodology was collected; the second phase dealt with the experiment results. Data extracted from the articles was collected in an MS-Excel spreadsheet.

For the first phase of the data collection, focusing on research methodology, data on the following themes was collected:

I. General article: article author, title, journal and year of publication, number of pages and database, and country where the experiments were performed
II. General experiment: topic, research question or hypothesis and type of experiment. For semi-controlled experiments, the uncontrolled parameters were recorded.
III. Participant: number of subjects, age, weight and height, and gender. Gender was recorded. A question on whether subjects were compensated was included. This was complemented with practical information regarding subject compensation, clothing, position, activity and metabolism values of the subjects in the test chamber.
IV. Climate chamber: type and dimensions of the climate chamber
V. Thermal environment: air and radiant temperature, relative humidity and air velocity values as well as steps were recorded.
VI. Experimental procedure: whether (pre)conditioning was applied, (pre)conditioning length and test length
VII. Questionnaire: survey questions, delivery method, delivery schedule, whole-body TSV and TCV rating scales

In the second phase of the data collection, focusing on research results, the following data extraction plan was used:

I. Scale usage: minimal and maximal individual TSV and TCV ratings, and minimal and maximal average TSV and TCV values
II. Differences in responses: identification of gender differences in TSV and TCV response and time-dependent differences
III. Further research: further research suggested in the articles.
IV. PMV comparison: whether responses were compared with PMV-calculations, and if applicable the results and explanation of the differences

2.3. Analysis methods

The data collected from the articles was analyzed using a number of statistical methods using the statistical software package SPSS version 23 [12]. The significance level for all tests was set at $\alpha = 0.05$ [13, p. 16–23].

Descriptive statistics for metric variables (such as number of subjects) are provided. The average and standard deviation [14], as well as the first and third quartile[1] are reported [15].

[1] The first and third quartile are the middle numbers between the median and the