

Coupling a Passive Sensor Manikin with a Human Thermal Comfort Model to Predict Human Perception in Transient and Asymmetric Environments

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ABSTRACT

Passive sensor (HVAC) manikins have been developed to obtain high-resolution measurements of environmental conditions across a representative human body form. These manikins incorporate numerous sensors that measure air velocity, air temperature, radiant heat flux, and relative humidity. The effect of a vehicle's climate control system on occupant comfort can be characterized from the data collected by an HVAC manikin. Equivalent homogeneous temperature (EHT) is often used as a first step in a cabin comfort analysis, particularly since it reduces a large data set to a single intuitive number. However, the applicability of the EHT for thermal comfort assessment is limited since it does not account for human homeostasis, i.e., that the human body actively counter-balances heat flow with the environment to maintain a constant core temperature. For this reason, a thermo-physiological human model is required to accurately simulate the body's dynamic response to a changing environment. Consequently, thermo-physiological based comfort models are preferred for analyzing transient and asymmetric environments since they relate sensation and comfort to body temperatures rather than to environmental conditions.

This paper demonstrates that coupling a thermal comfort model with a passive sensor manikin can accurately predict the overall comfort reported by a group of individuals. A test protocol was developed to expose a group of human subjects to mildly asymmetric radiant conditions and a slow change in ambient temperature. An HVAC manikin was positioned among the test participants. The HVAC manikin measurements were input to a human model so that thermal sensation and comfort could be predicted and compared to the values recorded by the human subjects. Model predictions were shown to accurately reproduce the group trends and the "time to comfort" at which a transition occurred from a state of discomfort to comfort.

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INTRODUCTION

Physical manikins can be used to predict the thermal comfort of passengers within an automotive test scenario [1]. Although an adaptive manikin (i.e., a sweating thermal manikin coupled with a thermophysiology model) is capable of reproducing human thermal responses to a test environment, a passive sensor (HVAC) manikin can provide more insight. An HVAC manikin incorporates numerous sensors that measure air velocity, air temperature, radiant heat flux, and relative humidity, and is designed to obtain high-resolution measurements of environmental conditions across a representative human body form.

The effect of a vehicle's climate control system on occupant comfort can be characterized from the data collected by an HVAC manikin. Equivalent homogeneous temperature (EHT) [2] is often used as a first step in a cabin comfort analysis, especially since it reduces a large data set to a single intuitive number. However, the applicability of the EHT for thermal comfort assessment is limited since it does

not account for human homeostasis, i.e., that the human body actively counter-balances heat flow with the environment in order to maintain a constant core temperature. For this reason, a thermo-physiological human model is required to accurately simulate the body's dynamic response to a changing environment [3] [4]. Thermo-physiological based comfort models are preferred for analyzing transient and asymmetric environments since they relate sensation and comfort to body temperatures rather than to environmental conditions [5] [6] [7].

METHODOLOGY

A test protocol was devised to expose a group of human subjects to mildly asymmetric radiant conditions while incorporating a slow change in ambient temperature. An HVAC manikin was positioned among the test participants. The HVAC manikin measurements were input to a human model so that thermal sensation and comfort could be predicted and compared to that recorded by the human subjects.

Test Protocol

Two groups of seven test subjects were exposed for 70 minutes to an environment within a climate chamber at Volvo Car Corporation (Gothenburg, Sweden). Group 1 consisted of 5 females and 2 males and Group 2 consisted of 5 males and 2 females. Anthropometric measurements were not taken as part of this study. The chamber, designed for vehicle studies, was controlled via an air temperature set-point that could be adjusted by the test operator located in a control room. The mild transient condition prescribed by the test protocol was partly due to limitations in the test chamber's capabilities. Specifically, the chamber was not capable of responding quickly to a rapid temperature rise over the time period of interest, which precluded more extreme exposures from being considered for testing. The test protocol therefore incorporated a cool soak of the chamber so that the test would begin at a homogeneous temperature of 14 °C. At 20 minutes after test start, the set-point was incrementally increased, and, roughly 15 minutes before the conclusion of the test, was held constant. The test chamber was constructed such that the walls and ceiling temperatures track with the air temperature but experience a slight lag when responding to a change in set-point temperature. The relatively large thermal mass of the floor, which was known to respond very slowly to changes in air set-point temperature, would produce the desired temperature asymmetry.

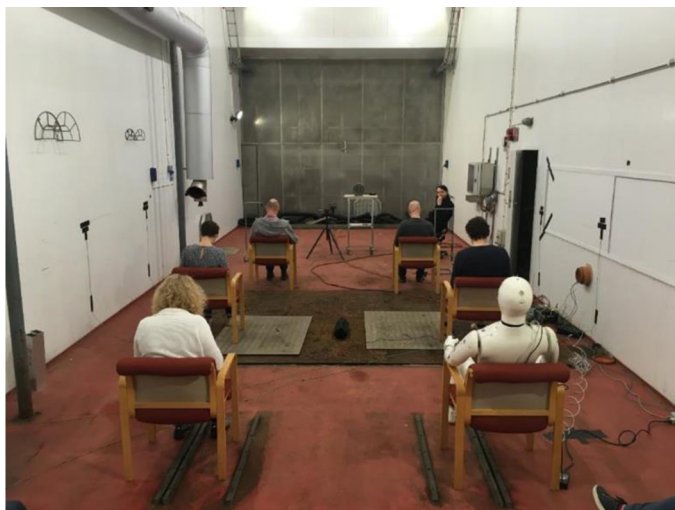


Figure 1. HVAC manikin positioned among the test participants

While both group tests were designed to expose the human subjects to a similar slow transient change in temperature, they were not expected to produce identical results. Both tests were performed on the same day, the first (i.e., Group 1) in the morning, and the second (i.e., Group 2) in the afternoon. For the Group 1 test, the chamber had been preconditioned with an overnight soak, which allowed the floor to reach a steady state temperature. However, for the Group 2 test, the chamber was conditioned only for approximately 3 hours. It was

anticipated that this difference in chamber preconditioning would result in the Group 2 participants experiencing a slightly warmer exposure than the Group 1 participants.

The chamber setpoint temperature changes were not logged given the manual operation of the control system. However, the effective chamber conditions that would have been experienced by a test subject were obtained by reducing the HVAC Manikin measurements into a single whole body EHT value. The measured EHT for the Group 1 and Group 2 tests are shown in [Figure 2](#).

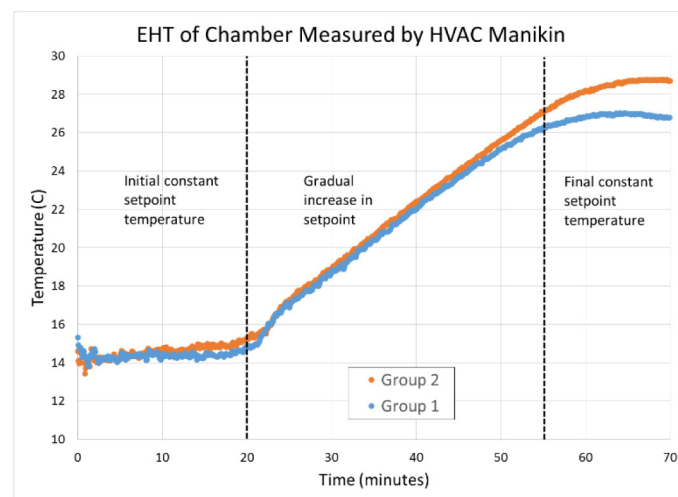


Figure 2. Equivalent Temperatures derived from the manikin measurements

The EHT for both tests begins at the initial chamber temperature and then exhibits a steep rise when the set-point is increased at the 20-minute mark, eventually leveling off during the last 15 minutes of the test. Due to the warmer initial temperature within the floor slab during the Group 2 test, the EHT rises at a slightly higher rate than the Group 1 test and subsequently reaches a maximum EHT that is 2 °C higher than the Group 1 test.

Passive Sensor Manikin

The manikin used in this project (HVAC Manikin, Thermetrics) [8] was constructed from a carbon-fiber epoxy shell outfitted with sensors positioned throughout its body form, as illustrated in [Figure 3](#). The instrumentation consisted of 60 pairs of air temperature sensors: precision glass thermistors with a range of -20 °C to 70 °C and air velocity sensors (omnidirectional hot-bead anemometers) with a range 0.1 to 5.0 m/s. An additional 31 radiant heat flux sensors (thin foil sensors with a range of approximately 0 to 3000 W/m²) were used to measure local mean radiant temperature. Five humidity sensors (non-condensing capacitive-type sensors with a range of 0% to 100%) were used to account for any potential stratification in relative humidity. The manikin's posture was adjusted using specially manufactured friction joints located at the neck, shoulders, elbows, wrists, hips, knees, and ankles, which was useful for replicating the posture of the test participants.