

Improving Cabin Thermal Comfort by Controlling Equivalent Temperature

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ABSTRACT

An aircraft environmental control system (ECS) is commonly designed for a cabin that has been divided into several thermal control zones; each zone has an air flow network that pulls cabin air over an isolated thermocouple. This single point measurement is used by the ECS to control the air temperature and hence the thermal environment for each zone. The thermal environment of a confined space subjected to asymmetric thermal loads can be more fully characterized, and subsequently better controlled, by determining its "equivalent temperature." This paper describes methodology for measuring and controlling cabin equivalent temperature. The merits of controlling a cabin thermal zone based on its equivalent temperature are demonstrated by comparing thermal comfort, as predicted by a "virtual thermal manikin," for both air-temperature and equivalent-temperature control strategies.

INTRODUCTION

Equivalent temperature is defined as the "temperature of a homogenous space, with mean radiant temperature equal to air temperature and zero air velocity [and zero solar load], in which a person exchanges the same heat loss by convection and radiation as in the actual conditions under assessment" [1]. The equivalent temperature is impacted primarily by air temperature, air velocity, surrounding surface temperatures and solar irradiance.

Equivalent temperature can be measured directly by monitoring the total heat flow required to keep the surface of a human-sized thermal manikin at a nominal skin temperature. The temperature of a homogenous

environment which results in the same manikin heat flow as the actual environment is by definition the equivalent temperature. Determining the equivalent temperature in this manner is useful for the evaluation of the performance of an environmental control system, but is not suitable for controlling the temperature of a cabin thermal zone.

Alternatively, the equivalent temperature of a cabin thermal control zone can be estimated by measuring air temperature, air velocity, surface temperature and solar irradiance. These measurements are used to determine mean radiant and ambient air temperatures, their respective heat transfer coefficients and the absorbed solar irradiance. Equivalent temperature can be calculated from these intermediate quantities as described in the methodology section.

METHODOLOGY

The effects of an asymmetric thermal environment on thermal comfort, as well as the implications for an environmental control system strategy, were investigated using two "virtual thermal manikins" placed in a simulated aircraft cabin [Figure 1]. Both manikins are representative of 50th percentile western males. The first virtual thermal manikin (the "equivalent temperature manikin") was used to determine the equivalent temperature for the simulated cabin environment. This was accomplished by finding a homogenous environment in which the amount of heat required to keep the manikin "skin" at 34 °C is equal to the amount of heat required to keep the manikin skin at the same temperature in the simulated cabin environment. The second virtual thermal manikin (the "Berkeley Comfort manikin") was used to predict human thermal comfort in the simulated cabin environment. This manikin

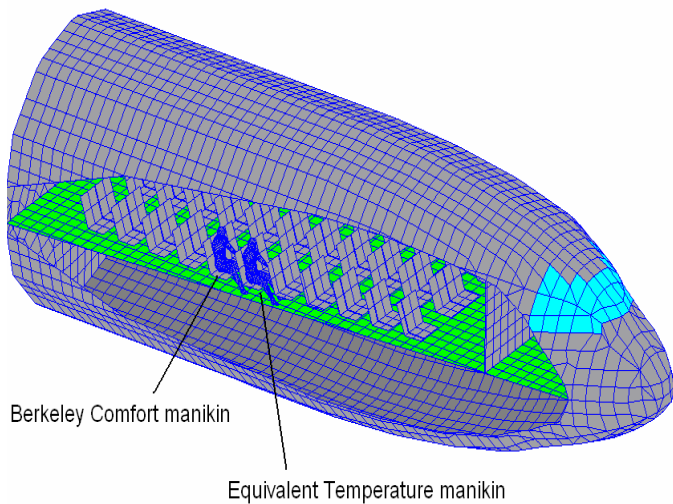


Figure 1: The aircraft cabin simulation incorporated two “virtual thermal manikins.” One manikin was used to calculate cabin equivalent temperature; the second manikin was used to predict human thermal comfort.

incorporated a physiology-based human thermal model [2,3,4] to predict body core and skin temperature. Thermal sensation and comfort were calculated from the predicted body core and skin temperatures using the Berkeley Comfort Model [5]. Sensation and comfort are reported on the 9-point Berkeley scales. Positive comfort values indicate increasing comfort and a zero sensation indicates a neutral thermal sensation. The comfort predictions were used to compare passenger comfort in cabins that were simulated with boundary conditions derived from an air temperature control strategy vs. cabins in which the boundary conditions corresponded to an equivalent-temperature control strategy.

DETERMINING THE TEMPERATURE SET POINT - The equivalent temperature that produces maximum thermal comfort was found by placing the Berkeley Comfort manikin in a homogenous environment that was varied over a range of temperatures. The manikin was simulated wearing a long sleeve shirt and pants resulting in a whole body clothing insulation value of 0.6 clo (0.09 (m² K) / W). The metabolic rate was set to 1 met (58 W/m²) which would be typical of a passenger at rest. A value of 25.5 °C was found to produce the maximum thermal comfort [Figure 2]. This is in agreement with the equivalent temperature of 25.3 °C reported to maximize estimated comfort for (non-virtual) thermal manikin settings of 70 W/m² and 0.5 clo [1]. A set point of 25.5 °C was used for both the air-temperature and equivalent-temperature control strategies.

CONTROL STRATEGY EVALUATION – The aircraft cabin was modeled so that the internal air temperature, floor temperature and cabin wall temperatures could be independently set to arbitrary values. The effect of solar loading through the cabin windows was also simulated. Air velocity and the changes in air temperature were

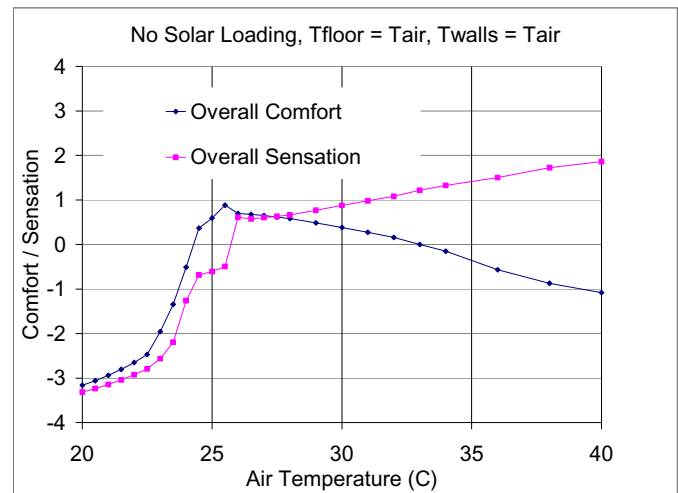


Figure 2: In a homogeneous environment with no solar loading and all surfaces equal to the air temperature, comfort as predicted by the Berkeley Comfort manikin, is a maximum at an air temperature of 25.5 °C.

assumed to be sufficiently small such that the convective heat transfer coefficients would not change from case to case and therefore could set to a constant value. Five different cases were examined [Table 1]. For each case, thermal sensation and comfort predictions were obtained from the Berkeley Comfort manikin. The cabin equivalent temperature was found by recording the whole body heat flux as indicated by the equivalent temperature manikin and finding the homogenous environment that would result in the same heat flux.

The air temperature control strategy was simulated by setting the cabin air temperature to 25.5 °C. The equivalent temperature control strategy was simulated by manipulating the cabin air temperature to obtain the optimal equivalent temperature of 25.5 °C. Surface temperatures (other than those that were being manipulated to create an asymmetric environment) were

Table 1: Four asymmetric cases were compared to the homogeneous baseline.

Case	Solar Loading	Floor Temperature	Wall Temperature
Baseline	No	= T _{air}	= T _{air}
Baseline with Solar	Yes	= T _{air}	= T _{air}
Cold Floor	No	= 20 °C	= T _{air}
Cold Floor with Solar	Yes	= 20 °C	= T _{air}
Hot Floor, Cold Walls	Yes	= 28 °C	= 17 °C