# Determination of Footwear Area Factors

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## Introduction

The thermal resistance measured on a thermal manikin is the total resistance which includes the intrinsic resistance and air layer resistance. The intrinsic resistance is often required for analysis of heat transfer through clothing and mathematical simulation of thermoregulation in clothed humans, but is not directly determined through manikin measurement. The intrinsic resistance can be calculated from the total resistance and the air layer resistance if the area factor (Fcl) is known. The Fcl is the ratio of clothing surface area to manikin surface area. It can be measured by the photographic method as is recommended by ISO 9920, or by a 3D scanning method (2,3). From a heat transfer point of view, the Fcl is inversely proportional to the ratio of the heat flux on the manikin surface to the heat flux on the clothing surface. Therefore, it may be possible to estimate the Fcl from the heat flux ratio.

While a clothing database provides information on Fcl for various clothing ensembles (4), no Fcl information for footwear is available. The purpose of this study was to determine the Fcl of five footwear systems by the photographic method and to determine whether the Fcl can be measured from the ratio of heat flux.

## Methods

### Heat flux method

In steady state, the heat leaving the manikin foot surface is equal to the heat leaving the footwear surface, and this can be described by the equation:

$$A_1 \cdot H_1 = A_2 \cdot H_2$$

where $A_1$ is the manikin surface area in $m^2$, $H_1$ is the heat flux in $W/m^2$ on the manikin surface, $A_2$ is the footwear surface area and $H_2$ is the heat flux on the footwear surface. This equation can be further rewritten as:

$$Fcl = \frac{A_2}{A_1} = \frac{H_1}{H_2}$$

$H_1$ is measured during the process of the manikin test. Thus, the Fcl can be determined if $H_2$ is also measured.

Five footwear systems were tested on a thermal foot manikin (Northwest Measurement Technology, Seattle). The heat fluxes on the footwear surface at seven sites were measured at the same time for Fcl calculation, as shown in Figure 1. The seven locations were: left and right side of the foot, 5 cm above ankle; left and right side of foot at top of arch; heel; above toes; and below toes. The heat flow data were collected using 1" diameter heat flow sensor disks with integral thermistors manufactured by Concept Engineering (Old Saybrook, CT). Agilent Visual Engineering Environment (VEE) software (Santa Clara, CA) running on a Windows based PC provided an interactive graphical programming environment for measurement and analysis. Measurement hardware included Agilent 34970A Data Acquisition Control Unit and Agilent 34901A Multiplexer. The heat fluxes were sampled and recorded every 10 seconds. The manikin test procedure was the same as our regular method for measuring the thermal resistance of footwear (1). The foot manikin surface temperature was maintained at 35°C while climatic chamber conditions were set at 15°C, relative humidity of 40% and wind speed of 0.3 m/s. After the thermal foot manikin was dressed and turned on, it took 1-2 hours to reach steady state. The manikin measurement data and heat flux data over 30 min steady state period was used to calculate thermal resistance and the Fcl.

**Figure 1**. Heat flux sensors and footwear

**Photographic method**

Details of the photographic method for clothing ensembles are described in the paper by McCullough et al (3). As the focus of the present study is footwear, the method was slightly modified. A digital camera was positioned on a tripod at the same horizontal level as the foot manikin, and the photographs of the foot manikin and footwear were taken from three azimuth angles of 0°, 45°, and 90°. As shown in the Figure 2, the foot manikin/footwear was rotated from the front view, to the 45° view, to the profile view when the pictures were taken. After the photographs were printed on the same type of paper, the projected areas of the clothed and nude manikin were cut out and then the cut pictures were weighed on an analytical balance (Sartorius, model ME215). The weight ratio of clothed manikin to nude manikin is considered the Fcl.

**Figure 2.** Foot manikin/footwear from front view (left), 45° view (middle) and profile view (right)

**Footwear**

Five footwear systems used in the study are listed in the Table 1:

**Table 1.** Footwear Description

| Boot Name | Description |
|---|---|
| Hot Weather Combat Boot | 30 cm high, uninsulated leather boot |
| Wellco Modular Boot System | Multi-climate footwear system |
| Belleville Modular Boot System | Multi-climate footwear system |
| Intermediate Cold Wet Boot | 30 cm high, insulated leather boot |
| Cold-Wet VB Boot | 25 cm high, rubber vapor-barrier boot |

**Results and Discussion**

The area factors determined by the heat flux method and photographic method, as well as thermal resistances are listed in Table 2. The Fcl-hf are the Fcl determined by the heat flux method, the Fcl-3 are the Fcl determined by the weight of all three pictures, Fcl-2 are the Fcl determined by the weight of two pictures (angle 45° and 90°), and the Fcl-1 are the Fcl determined by the weight of the front picture (angle 0°). R is the thermal resistance in clo.

**Table 2.** Area factors and thermal resistances

| Boot Name | Fcl-hf | Fcl-1 | Fcl-2 | Fcl-3 | R (clo) |
|---|---|---|---|---|---|
| Hot Weather Combat Boot | 1.69 | 1.62 | 1.42 | 1.49 | 0.88 |
| Wellco Modular Boot System | 1.77 | 1.86 | 1.47 | 1.61 | 1.01 |
| Belleville Modular Boot System | 1.56 | 1.85 | 1.73 | 1.77 | 1.11 |
| Intermediate Cold Wet Boot | 2.16 | 1.87 | 1.61 | 1.71 | 1.35 |
| Cold-Wet VB Boot | 2.43 | 1.94 | 1.70 | 1.78 | 1.38 |

In general, area factors increase as the thermal resistances increase. This is consistent with area factors of clothing ensembles (3). However, the Fcl determined by various methods differ from each other. The photographic method is a proven method and recommended in ISO 9920. Thus, the Fcl-3 is considered accurate and ranges from 1.49 to 1.78. The photographic method requires 6 pictures from two horizontal positions for clothing evaluation. However, only three pictures were taken in this study, as the size of footwear was much smaller in comparison with clothing ensemble. The Fcl-2 was close to the Fcl-3, but the Fcl-1 was higher than both the Fcl-3 and Fcl-2. The differences among Fcl-1, Fcl-2 and Fcl-3 indicated that one photograph

appears not enough for determining footwear Fcl, although a previous study demonstrated that one photograph from the front is adaptive for determining the Fcl of clothing ensembles (3).

Fcl-hf results were significantly higher than Fcl determined by the photographic method. The HF method was simple and theoretically correct. HF measurement could be integrated into the existing data acquisition system of the foot manikin. However, the challenge was how to measure heat fluxes accurately. Differences between heat fluxes at different locations could be as much as two fold higher. The heat flux results were easily influenced by the environmental conditions. The heat flux sensor itself has thermal resistance and might affect the accuracy of measured heat fluxes.

## Conclusion

The area factors of five footwear systems were determined by the traditional photographic method and newly developed heat flux method. The heat flux method was simple and theoretically correct, but requires further work to make it practical.

## Disclaimer

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