Modelling the thermal microenvironment of footwear subjected to forced ventilation

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ABSTRACT

In this paper, we develop a mathematical model of the thermal microenvironment in footwear that considers forced ventilation of the footwear cavity. The developed model was validated using a newly developed thermal foot-manikin system and the results show that the model effectively predicts changes in foot skin temperature resulting from forced ventilation (0–90 L/min). At an air temperature of 26.4 °C and a foot thermal comfort temperature of 32.2 °C, the required minimum ventilation rate was found to be 5.4–24.6 L/min, which corresponds to a total static thermal insulation of footwear of 0.10–0.20 m²·K·W⁻¹. This indicates that ventilation can adequately control the thermal microenvironment of the footwear cavity, thereby maintaining foot thermal comfort.

Practitioner summary: An adverse footwear thermal microenvironment results in foot thermal discomfort and foot hygiene problems. We hypothesise that forced ventilation may enable thermal control of footwear microenvironments. A mathematical model was developed which can determine the forced ventilation rate required in a given type of footwear to create foot thermal comfort.

Abbreviations: I: Total footwear insulation including adjacent air-layer insulation [m²·K·W⁻¹]; I₁s: Total footwear insulation under static conditions [m²·K·W⁻¹]; I₂: Footwear intrinsic insulation [m²·K·W⁻¹]; I_c: Convective heat transfer insulation between foot skin and footwear inner surface [m²·K·W⁻¹]; I_c: Convective heat transfer insulation between foot skin and trapped air [m²·K·W⁻¹]; I_i: Radiative heat transfer insulation between footwear inner surface and trapped air [m²·K·W⁻¹]; I: Intrinsic heat resistance of footwear fabric [m²·K·W⁻¹]; I: Ventilation heat transfer insulation [m²·K·W⁻¹]; I: Total adjacent air-layer insulation, including convection and radiation [m²·K·W⁻¹]; I: Integration of footwear fabric insulation and adjacent air-layer insulation [m²·K·W⁻¹]; Q: Total heat transfer from the skin to the ambient air [W]; f: Ratio of footwear inner-surface area to shod-foot surface area; f: Ratio of footwear outer-surface area to shod-foot surface area; [9]: Correction factor applied to ventilation resistance; t: Average surface temperature of foot skin covered by footwear [°C]; Δt: Skin temperature reduction due to forced ventilation at air temperature of 26.4 °C [°C]; Δt: Skin temperature reduction due to forced ventilation at a certain air temperature [°C]; t_1: Thermal comfort temperature for feet [°C]; t: Trapped air temperature [°C]; t: Average temperature of footwear outer surface [°C]; t: Adjacent air temperature [°C]; θ: Actual mean thickness between foot skin and footwear inner surface [m]; θ: Effective mean thickness between foot skin and footwear inner surface [m]; k: Thermal conductivity of trapped air [W·m⁻¹·K⁻¹]; ε: Emission coefficients of skin surface and footwear inner surface respectively; ρ: Reflection coefficients of skin surface and footwear inner surface respectively; α: Stefan–Boltzmann constant = 5.67 × 10⁻⁸ [W/(m²·K⁴)]; ρ: Average density of trapped air and adjacent air [kg·m⁻³]; C_p: Average specific heat capacity of trapped air and adjacent air [J·kg⁻¹·K⁻¹]; V_f: Forced ventilation rate applied to footwear [L/min]; A: Surface area of foot skin covered by footwear in shod condition [m²]; I_v: Total vapour permeability index for footwear; q: Total heat loss of foot skin at the air temperature of 26.4 °C [W·m⁻²]; q: Total heat loss of foot skin at a certain air temperature [W·m⁻²]; ζ: Ratio of foot skin-temperature reduction between a certain air temperature and air temperature of 26.4 °C.

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SUPPLEMENTAL DATA

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1. Introduction

The invention of air-conditioning has led to substantial improvements in human thermal comfort in indoor environments. As a body part, the importance of foot thermal comfort for the overall body thermal comfort is known (Arens, Zhang, and Huizenga 2006a, 2006b). Unfortunately, individuals have had little limited control of their own footwear environment in most situations when shoe wearing is a must due to etiquette and/or needs, both indoors and outdoors. This is also in combination with significant exposure to footwear environment as the daily usage of footwear is long both indoors and outdoors. This means that for individuals’ overall foot comfort, their footwear must ensure foot thermal comfort, in addition to being the correct size and an appropriate shape (West et al. 2019; Witana, Feng, and Goonet 2004).

Well-insulated footwear prevents heat loss from the footwear cavity, which means that the skin temperature of a shod foot is higher than that of a bare foot (Quesada et al. 2015; Smith et al. 2013). If an individual’s foot skin temperature exceeds a certain level under neutral or warm conditions, the individual experiences local thermal discomfort. A study found that subjects’ comfortable barefoot skin-temperature range was 28.3–31.1°C when the surrounding air temperature was 20°C (Song, 2008). In another study, subjects’ comfortable barefoot skin temperatures ranged from 29.3 to 32.2°C when the surrounding air temperature ranged from 21 to 29°C (Yao et al. 2007). In shod condition, the foot skin temperature varied from 25 to 40°C, with a comfortable temperature zone of 28–29°C to 33–34°C (Irzmańska 2014).

In order to achieve foot thermal comfort, efforts have been made on the improvement of the materials used for footwear. It has been determined that the upper fabrics, toecap types, and insoles of footwear affect the amount of heat retained inside footwear (Bogerd, Brühwiler, and Rossi 2012; Irzmańska and Brochocka 2014; Irzmańska 2014). It follows that optimising the level of insulation provided by various parts of footwear would enhance its thermal performance, thereby increasing foot thermal comfort. In some environments, this may require the use of additional, non-insulating materials. For example, the use of phase-change materials (PCMs) in footwear has been explored, as PCMs act as thermoregulators to stabilise foot skin temperatures in a hot or cool environment (Borreguero et al. 2013; Endrusick et al. 2000). In another approach, biologically active materials were incorporated into footwear to automatically adjust the air permeability of the upper materials of the footwear in response to changes in the footwear microenvironment (Puma & MIT 2021). However, there are limitations to these approaches for improving footwear materials. For example, PCMs may restrict the dissipation of sweat from feet to the surrounding environment, resulting in condensation inside footwear, whereas footwear incorporating biologically active materials may be too expensive for consumers.

As an alternative approach, we hypothesise that forced ventilation may enable thermal control of footwear microenvironments, analogous to the ability of natural and mechanical ventilation to effectively decrease temperatures inside buildings. Forced ventilation has previously been incorporated into personal cooling systems in clothing (Chinevere et al. 2008; Zhao et al. 2013), but these systems have not been widely adopted. Clothing ventilation has been shown to efficiently remove heat and moisture from clothing micro-environments, and the greater the ventilation in a body region, the less the moisture accumulation in this region (Ueda et al. 2006). Its cooling performance would be enhanced when clothing incorporated PCMs (Kang et al. 2018). However, no studies have examined the use of forced ventilation in footwear; this may be because the stricter space, weight, and fabric-thickness limitations of footwear mean that it is more difficult to incorporate forced ventilation into footwear than into clothing.

In this paper, we explore the feasibility of using forced ventilation for footwear microenvironmental control by developing a new simple mathematical model of the thermal microenvironment of footwear that considers forced ventilation of the footwear cavity. This model is developed to focus on effective total footwear thermal insulation, and is also combined with a thermoregulation model to afford an integrated model that can determine changes in foot skin temperature in response to changes in the rate of ventilation. This integrated model can therefore determine the forced ventilation rate required in a given type of footwear; this may be because the stricter space, weight, and fabric-thickness limitations of footwear mean that it is more difficult to incorporate forced ventilation into footwear than into clothing.

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2. Methods

Modelling of thermal microenvironment of footwear cavity

Figure 1 shows a model of the insulation elements that compose the total dry-heat insulation between the foot skin and the ambient environment with forced ventilation. This model is based on the
four-layer clothing model (Lotens 1993), but we consider only three layers, i.e. the trapped air layer, the footwear fabric layer, and the adjacent air layer, and exclude the sock layer. The mean radiant temperature of the surrounding environment is assumed to equal the ambient air temperature. This model requires many geometrical parameters of the foot, footwear, and footwear cavity to be defined (Table 1).

Based on Figure 1, the total insulation \( l_t \) can be expressed as:

\[
l_t = \left( l_{ct} + l_a \cdot f_o^{-1} \right)^{-1} + \alpha \cdot l_v^{-1}
\]

where \( l_{ct} \) represents the static insulation characteristic of clothing, \( l_a \) represents the adjacent air-layer insulation, \( f_o \) means the ratio of footwear outer-surface area to shod-foot surface area, \( \alpha \) means the ventilation correction factor, and \( l_v \) represents the ventilation insulation. The effect of ventilation is added to the conventional clothing-insulation formula (ISO 2004a), which is:

\[
l_t = l_{ct} + l_a \cdot f_o^{-1}
\]

If there is a negligible amount of heat transferred via ventilation, Equations (1) and (2) are identical.

As mentioned above, \( l_{ct} \) represents the static insulation characteristic of clothing. It is known that the level of such insulation decreases during human activity or due to adjacent air movement, i.e. when there is dynamic clothing insulation. Studies have established that walking and wind speeds modify the insulation characteristics of clothing to a limited extent (ISO 2004a; Havenith and Nilsson 2004; Lee et al. 2016; Lu et al. 2015).

The concept of total insulation or total thermal resistance is a convenient one, as it means that if the temperature of the foot skin \( t_s \) and the surrounding air \( t_a \) are known, the total heat transfer \( Q \) can be easily calculated by \( Q = A_i \cdot l_t \cdot (t_s - t_a) \), where \( A_i \) is the total skin surface area. Similarly, a total vapour permeability index \( i_m \) can be defined for use in moisture calculations.

In Equation (1), the ventilation correction factor \( \alpha \) is used to account for the heat removed by ventilation, \( \frac{(t_{tr} - t_a)}{l_v} \), and is defined as

\[
\alpha = (t_{tr} - t_a) \cdot (t_s - t_a)^{-1}
\]

where \( t_o, t_{tr}, \) and \( t_a \) are the temperatures of the skin surface, trapped air, and adjacent air, respectively.

A formula for \( \alpha \) can be derived from a function of insulation elements (thermal resistances) using the two independent energy-balance equations that represent the model in Figure 1 and apply at a steady state. These are expressed as follows:

\[
(t_s - t_{tr}) \cdot l_{cs}^{-1} + (t_t - t_i) \cdot l_i^{-1}
\]

\[
= (t_{tr} - t_a) \cdot l_v^{-1} + (t_t - t_o) \cdot \left( l_{tr} \cdot f_1^{-1} + l_a \cdot f_o^{-1} \right)^{-1}
\]

\[
(t_s - t_{tr}) \cdot l_{cs}^{-1} = (t_{tr} - t_a) \cdot \left( l_{ct} \cdot f_1^{-1} \right)^{-1} + (t_t - t_o) \cdot l_v^{-1}
\]

Equations (4) and (5) means that \( \alpha \) is given by:

\[
\alpha = \frac{(l_{tr}^{-1} + l_o^{-1}) \cdot l_{cs}^{-1} + l_i \cdot l_{ct} \cdot (l_{cs}^{-1} + l_k^{-1})}{(l_{tr}^{-1} + l_o^{-1}) \cdot l_{cs}^{-1} + l_i \cdot l_{ct} \cdot (l_{cs}^{-1} + l_k^{-1}) + l_i \cdot l_{ct} \cdot (l_{cs}^{-1} + l_k^{-1})}
\]

where \( l_o \) is a combination of footwear fabric insulation and adjacent air-layer insulation, and is given by

\[
l_o = l_i \cdot f_1^{-1} + l_a \cdot f_o^{-1}
\]

Equation (1) can then be rewritten as:

\[
l_t = \left[ \left( l_{ct}^{-1} + l_i^{-1} \right)^{-1} + l_o \right]^{-1} + \alpha \cdot l_v^{-1}
\]

Thus, the total footwear insulation \( l_t \) can be calculated after the insulation elements \( l_{ct}, l_{cs}, l_{ct}, l_t, l_o, \) and \( l_i \) and the geometry parameters \( f_i \) are determined. We also assume that the convective heat-transfer coefficients for heat transfer between the trapped air and the two surfaces are identical, i.e. \( l_{cs} = l_{ct} \). Thus, based on the derivation in Supplementary Appendix I,
The reason why effective mean thickness is introduced is that, the cavities of some footwear contain dead space (e.g. in the toe-cap region) that does not contribute to the dynamic heat transfer caused by forced ventilation. If the volume of the dead space was included for the calculation of mean thickness between foot skin and footwear inner surface, the calculated value would be larger than the actual value. Therefore, the volume of the dead space should be excluded. To account for such dead space, the effective gap-space volume was determined by incorporating the effective space factor β into the calculation of the actual gap-space volume. Therefore, the effective mean gap thickness ᶪ was calculated by multiplying the actual mean gap thickness δ by β.

Then, as

\[ \delta_c = \frac{\delta}{k} \quad (9) \]

where δ is the effective mean thickness between foot skin and the footwear inner surface, and k is the thermal conductivity of the trapped air.

The radiative insulation \( I_c \) between the two surfaces is given by

\[ I_c = \frac{4 \varepsilon_1 \varepsilon_2}{1 - \rho_1 \rho_2} \sigma \left( \frac{273.15 + t_s + t_i}{2} \right)^3 \quad (12) \]

where \( \varepsilon_1 \) and \( \varepsilon_2 \) are emission coefficients, and \( \rho_1 \) and \( \rho_2 \) are reflection coefficients, for the skin surface and footwear inner surface, respectively. \( \varepsilon_1 = 0.97 \) for the human skin surface (Charlton et al. 2020), and thus \( \rho_1 \) is calculated to be 0.03 for an opaque skin surface. For many fabric materials, \( \varepsilon_2 = 0.8 \) and \( \rho_2 = 0.1 \) (Lotens and Havenith 1991), which leads to a typical \( \varepsilon_1 \varepsilon_2 / (1 - \rho_1 \rho_2) \) value of 0.78. Finally, \( \sigma \) is the Stefan–Boltzmann constant (\( \sigma = 5.67 \times 10^{-8} \text{ W/(m}^2 \cdot \text{K}^4) \)).

The insulation element \( I_{fa} \) is given by

\[ I_{fa} = l_{fa} = (l_{fa}^{-1} + t_{fa}^{-1})^{-1} \quad (13) \]

which was determined under static conditions and assumed to be constant under dynamic conditions.

The ventilation resistance \( I_v \) is calculated as

\[ I_v = 60000 \cdot \frac{A_i}{\rho_a C_{p,a} V_a} \quad (14) \]

where \( A_i \) is the skin surface area of the foot; \( \rho_a \) and \( C_{p,a} \) are the average density and average specific-heat...
capacity of the trapped air and adjacent air, respectively; and $V_a$ is the mechanical ventilation rate (L/min).

Thus, to determine the relationship between the total dry-heat insulation (the total footwear insulation including adjacent air-layer insulation) $I_t$ and the imposed ventilation rate $V_a$ we need to determine the foot and footwear geometric properties ($l_t$, $\delta_t$, and $A_t$), surface temperatures ($t_s$ and $t_i$), air thermal properties ($k$, $\rho_v$ and $C_p.a$) that correspond to the air temperatures ($t_r$ and $t_a$), and one insulation element ($l_{st}$).

The determination of foot and footwear geometric properties is introduced in Table 1. $t_s$ and $t_a$ were set as 34 and 22°C respectively, which served as input data for the footwear cavity model. The total footwear insulation under static conditions $I_{ts, st}$ was obtained using a thermal foot manikin under static conditions. The last two unknown parameters in the footwear cavity model, $t_r$ and $t_i$, were determined via the enumeration method shown in Supplementary Fig. S1. The value of $t_r$ was set from 22 to 34 at 0.01°C intervals until $\Delta t_r$ infinitely approached 0. The values of $t_r$ and the corresponding values of $t_i$ were then determined.

In order to determine whether the set values of $t_s$ and $t_a$ would affect the model output, we tested the situations when $t_s$ was set as 25–40°C at intervals of 1°C, and $t_a$ was set as 20–35°C at intervals of 1°C. The typical shod-foot skin temperature is known (Irzmańska 2014). A typical air temperature in air-conditioned spaces is 20–25°C (Choi and Loftness 2012), whereas typical ambient air temperatures can be as high as 35°C (Yeo 2004). The surrounding air temperature $t_a$ is always less than the foot skin temperature $t_s$. We tested 190 sets of reasonable $[t_s, t_a]$ combinations and compared the results.

**Thermoregulation model**

In order to predict the foot skin temperature when wearing a certain type of footwear in a certain indoor environment, Lotens et al. developed a 2-node thermoregulatory model where a nutritional blood flow was assumed to be constant (Lotens, Heus, and Van de Linde 1989). The model has been validated to be effective when the model limitations are considered (Kuklane, Holmér, and Havenith 2000). In our study, the classical Stolwijk 25-node thermoregulation model (Stolwijk 1971) was used to predict the changes in the skin temperature of various parts of the body. The purpose was to see whether the adoption of forced ventilation on footwear cavities would affect the skin temperature of other body parts. The details of this model are not described here, but a general description is as follows. The model comprises two components: the controlled system and the controlling system. The controlled system describes the thermal characteristics of various parts of the body, whereas the controlling system describes the active thermoregulatory responses of the body, i.e. sweating, shivering, vasoconstriction, and vasodilation. The controlled system consists of six body parts (the head, trunk, arms, hands, legs, and feet) that each comprises four concentric layers (skin, fat, muscle, and core layers). The central blood compartment constitutes the last node of the model, which exchanges heat with the other 24 nodes via convective heat transfer.

We modelled an adult with a bodyweight of 65.6 kg and a height of 1.71 m. The total skin surface area was estimated to be 1.77 m² (ASHRAE 2017), and the surface area of the feet was 0.126 m² obtained from the statistical data of the eight participants described later. The metabolic rate was set as 70 W/m², which represents the metabolic rate of an individual sitting in a calm environment and performing light office-type work, such as typing or Web browsing (ISO 2004b). The ensemble thermal insulation was set as 0.83 clo, which represents the ensemble thermal insulation of an individual wearing trousers and a short-sleeved cotton shirt (ISO 2007). The footwear insulation was determined from the footwear cavity model under various forced ventilation rates.

As the output of the footwear cavity model is $I_t$, the $i_m$ for footwear must be determined to enable the calculation of the total water-vapour resistance of footwear in the thermoregulation model. For many types of one- or two-layered permeable clothing, the $i_m = 0.38$ (ISO 2007), whereas for footwear (including sports shoes, leather shoes, and safety shoes) the $i_m$ is 0.20–0.44, and decreases with increasing total insulation (Nomoto et al. 2020). We inputted $i_m$ values from 0.20 to 0.44 at 0.01 intervals into the thermoregulation model, which generated outputs that were not significantly different. We therefore used an $i_m$ of 0.38 in the model.

**Experimental validation of the footwear cavity model**

Measurements of $I_t$ were conducted inside an environmental chamber fitted with an isolated ventilation system. The air condition inside the chamber at a height of 1.0 m (where the footwear tests were performed) was maintained at a temperature of 22.2 ± 0.5°C,
relative humidity of 50.0 ± 2.9%, and an air velocity of 0.02 ± 0.01 m/s. The mean radiant temperature was maintained at 22.3 ± 0.7 °C, which was regarded as equal to the air temperature.

A left-foot-shaped EU 42-sized thermal foot-manikin system (Figure 2(A–D)) was fabricated from stainless steel by three-dimensional (3D) printing. A stable temperature was established on the manikin surface by a constant flow of warm water into and out of the manikin cavity with constant heat flux. The values of $I_t$ were therefore obtained based on the difference between the temperature of the foot-manikin surface and the temperature of the adjacent air, with these temperatures measured by type-K thermocouples. The details of this setup are given in Supplementary Appendix II. Each test was performed in triplicate and the coefficient of variation (CV) for $I_t$ was calculated to determine the repeatability of the measuring system.

Two sizes (EU 42 and 43) of five types of footwear were tested (Table 2), which meant that 10 different shoe types were tested. As these were tested with and without holes for forced ventilation, a total of 20 footwear type–size–hole settings were tested. The $I_t$ was measured for each of these 20 settings using the thermal foot-manikin system at seven forced ventilation rates: 0, 15, 30, 45, 60, 75, and 90 L/min.

A high-resolution 3D scanner (Artec Eva, Artec3D, Luxembourg) was used to record the 3D geometric information of the foot manikin and footwear, and the volume and surface-area data of each scanned target.

Figure 2. (A–D) Schematic diagram of the thermal foot-manikin system and forced ventilation system. Two ventilation designs were tested. In the first design, only three ventilation supply outlets (a1, a2, and a3) were included, which allowed ventilation to be supplied at a constant flow rate into the footwear cavity. In the second design, in addition to the three supply outlets, three holes (b1, b2, and b3) were added to facilitate ventilation. (E) Ten positions on the foot-manikin surface where a type-K thermocouple was attached to measure temperature (1 – big toe; 2 – middle instep; 3 – medial instep; 4 – lateral instep; 5 – medial ankle; 6 – rear; 7 – first metatarsal; 8 – heel; 9 – medial calf; and 10 – lateral calf).
were obtained using Artec Studio 15 software (Artec3D, Luxembourg). Table 1 lists the scanned data that can be used to calculate the geometry parameters, and the measured geometry parameters are shown in Table 3.

The forced ventilation was generated by three diaphragm air-compressor vacuum pumps (5–30 L/min, 22D1180-201-1002, GAST, USA). To ensure that the forced ventilation was distributed evenly into the front, middle, and rear parts of the footwear, the three pumps were connected to three separate outlets (a1, a2, and a3, \( D = 8 \text{ mm} \)) on the footwear surface (as shown in Figure 2(C and D)). The flow rate at each of these outlets was consistent. In addition, in some settings, three ventilation holes (b1, b2, and b3, \( D = 3 \text{ mm} \)) were present on the footwear surface between any two outlets, which allowed fresh air to enter the footwear to improve ventilation efficiency when the air-permeability of its upper materials was insufficient. Thus, tests were performed with and without ventilation holes to explore whether these holes were necessary for adequate footwear ventilation.

A comparison of the model predictions and experimental data enabled the root-mean-square error (RMSE) to be calculated for the six forced ventilation rates, i.e. 15, 30, 45, 60, 75, and 90 L/min. For each of the 20 type-size-hole settings (hereafter, 20 cases), there were 100 sets of model outputs; as \( \beta \) was set to a value from 0.01 to 1 at 0.01 intervals, which corresponded to 100 RMSE values. The required \( \beta \) value for each case was determined when the lowest RMSE value was found.

### Table 1. Specifications of the five types of footwear.

| Types | Footwear A | Footwear B | Footwear C | Footwear D | Footwear E |
|-------|------------|------------|------------|------------|------------|
| Images | ![Image A] | ![Image B] | ![Image C] | ![Image D] | ![Image E] |
| Upper material | Chamois leather | PU leather | PU leather | Genuine leather | Polyester |
| Fabric construction | Non-woven | Non-woven | Non-woven | Non-woven | Knitted |
| Size (EU) | 42 & 43 | 42 & 43 | 42 & 43 | 42 & 43 | 42 & 43 |

### Table 2. Geometrical parameter data and static insulation data of the five types of footwear.

| Footwear Type | Size | \( I_{lt} \) (m\(^2\) · K · W\(^{-1}\)) | \( A_l \) (m\(^2\)) | \( f_l \) | \( \delta \) (m) | holes* | \( \beta \) | \( \delta_0 \) (m) |
|---------------|------|---------------------------------|----------------|--------|------------|--------|----------|----------------|
| **A**         | EU 42 | 0.176                           | 0.0651         | 1.33   | 0.0024     | ✗      | 0.91     | 0.0021         |
|               | EU 43 | 0.148                           | 0.0654         | 1.44   | 0.0025     | ✗      | 1.00     | 0.0018         |
| **B**         | EU 42 | 0.139                           | 0.0521         | 1.30   | 0.0015     | ✗      | 0.97     | 0.0015         |
|               | EU 43 | 0.115                           | 0.0525         | 1.33   | 0.0022     | ✗      | 0.52     | 0.0012         |
| **C**         | EU 42 | 0.198                           | 0.0571         | 1.30   | 0.0021     | ✗      | 0.92     | 0.0020         |
|               | EU 43 | 0.177                           | 0.0578         | 1.36   | 0.0024     | ✗      | 0.76     | 0.0016         |
| **D**         | EU 42 | 0.111                           | 0.0475         | 1.21   | 0.0029     | ✗      | 1.00     | 0.0018         |
|               | EU 43 | 0.108                           | 0.0496         | 1.30   | 0.0031     | ✗      | 1.00     | 0.0019         |
| **E**         | EU 42 | 0.097                           | 0.0524         | 1.33   | 0.0010     | ✗      | 1.00     | 0.0015         |
|               | EU 43 | 0.064                           | 0.0539         | 1.37   | 0.0017     | ✗      | 1.00     | 0.0010         |

See Symbols Table for the physical meaning of each symbol.
* ✗ = without holes; ✗ = with holes (as shown in Figure 2(D)).

### Human subject validation of the integrated footwear cavity model and the thermoregulation model

We compared the calculated and measured skin temperatures of six body regions (head, trunk, arms, hands, legs, and feet) of eight healthy participants, whose details are shown in Table 4. The experiment was conducted in the above-mentioned environmental chamber, where the air temperature (26.4 ± 0.5 °C), relative humidity (62.5 ± 2.0%), air velocity (0.03 ± 0.01 m/s), and mean radiant temperature (26.2 ± 0.4 °C) were controlled and monitored at a height of 1.2 m (participants' eye level). Only one set of indoor-air conditions was tested and the number of participants was limited as the study was carried out during the COVID-19 pandemic period. However, these conditions were...
sufficient for validation purposes. During the experiment, all participants wore the same type of clothing: a short-sleeved cotton shirt, trousers, regular underwear, and Footwear A of the appropriate size with holes on the surface.

The foot and footwear geometric information of all participants was determined using the method described above, and the results are shown in Table 4. Based on Hardy and Dubois’s seven-point method (Hardy, Dubois, and Soderstrom 1938), local skin temperatures of the forehead, chest, posterior forearm, hand, anterior thigh, and anterior calf were monitored continuously at 1-min intervals using wireless iButtons (DS1923, Maxim Integrated, USA) that were pre-calibrated in a calibrated thermostatic chamber (SM-105-CB-WT, Sanwood, Guangdong, China) and then affixed to the skin with surgical adhesive tape. The local temperatures of foot skin were monitored using type-K thermocouples at eight positions on the left foot (big toe, middle instep, medial instep, lateral instep, medial ankle, first metatarsal, heel, and rear), as indicated in Figure 2(E). The average of these eight local temperatures was used to calculate the leg skin temperature, and the formula $0.6t_{\text{thigh}} + 0.4t_{\text{calf}}$ was used to calculate the leg skin temperature (Hardy, Dubois, and Soderstrom 1938). Three additional type-K thermocouples were placed at a horizontal distance of 0.3 m from the participants at a height of 1.2 m (eye level), 0.6 m (middle level), and 0.1 m (foot level), respectively, to measure the air temperatures around participants. These temperature data did not vary significantly during the experiment, which indicated that the vertical air condition around the participants remained relatively consistent. Two small heat-flux sensors (gSkin-XM-26-9C, greenTEG, Switzerland) were affixed to the surface of two regions of the tested foot of participants (the middle instep and the first metatarsal) to measure the average heat flux per skin area. This enabled the $l_{st}$ to be calculated for the participants based on the difference between the temperature of their foot skin and that of the adjacent air; the results are shown in Table 4.

The experimental protocol was as follows. Each participant, equipped with sensors as above, sat inside the chamber for a total of 120 min. No forced ventilation was applied for the first 50 min (the first stage), to allow participants’ temperatures to reach a stable state. Then, forced ventilation was applied to both sides of the participants’ footwear at a flow rate of 30 L/min for 30 min. Finally, the forced ventilation was switched off for 40 min, to allow the participants’ temperature to recover to a stable state. The average heat flux of foot skin for each participant was determined based on the data obtained during the last 20 min of the first stage, when a stable state was achieved. The experimental procedures were explained to the participants before obtaining their written informed consent, and the experiment was approved by the Human Research Ethics Committee of the University of Hong Kong.

### 3. Results

**Total insulation values obtained using the thermal foot-manikin system**

Figure 3 summarises the $l_{st}$ values of various footwear in the current study and those obtained in three other studies (Bergquist and Holmér 1997; Kuklane 1999; Nomoto et al. 2020), which were measured using different thermal foot-manikin systems. All data were obtained under static conditions with an $l_a$ in the range of 0.088–0.132 m$^2$·K·W$^{-1}$. The obtained $l_{st}$ values ranged from 0.074 to 0.198 m$^2$·K·W$^{-1}$ from sports shoes to safety boots, which are similar to the literature data of 0.120–0.189 m$^2$·K·W$^{-1}$ (Nomoto et al. 2020). Higher $l_{st}$ values were obtained in the other two previous studies, which tested cold-protective footwear, as such footwear has a larger heat-transfer resistance. The CV value obtained from the triplicate tests for each measurement ranged from 0.14% to 7.78% for all measurements, with an average of 3.24% and median of 2.92%; this indicates that the repeatability of measurements made using this thermal foot-manikin system was good.

Figure 4 shows the modelled and experimentally measured changes in $l_a$ at various ventilation rates. In each of the 20 cases, there were 100 sets of model...
outputs, corresponding to the 100 values of $\beta$ depicted in the figure. It can be seen that the larger the value of $\beta$, the smoother the decrease in the curve of $I_t$ values with increasing ventilation rate. Moreover, the larger the $\delta$ value (as listed in Table 3), the greater the range of curves. The curve representing the data with the lowest
RMSE for each set of conditions is clearly visible in the figure, which enabled the appropriate $\beta$ value to be determined. In the 20 cases, the RMSE ranged from 0.00293 to 0.00699 m$^2$·K·W$^{-1}$ for cases without holes, and from 0.00182 to 0.00340 m$^2$·K·W$^{-1}$ for cases with holes. This indicates that there was a smaller deviation between the experimental data and model predictions for footwear with holes distributed on the surface. There was also a smaller deviation between the experimental data and model predictions for larger sizes of footwear without holes on the surface; however, no such correlation was observed for footwear with holes on the surface. These results demonstrate that our model effectively predicted the change in $I_t$ for most of the tested types of footwear under various forced ventilation conditions, especially footwear of a larger size or with holes on the surface.

**Determination of the $\beta$ value as a model constant**

As discussed above, the required $\beta$ value was that which corresponded to the lowest RMSE for the experimental data and model predictions. Therefore, this parameter was result-dependent: it could not be determined before the experiment was conducted (i.e. in advance). However, as $\beta$ is an input for our model, it had to be determined in advance as a model constant.

The relationships between the $\beta$ value and the RMSEs for all of the cases are depicted in Figure 5, which shows that $\beta$ ranges from 0.01 to 1. Specifically, in most cases, the RMSE curve first decreases continuously until it reaches its lowest point, and then increases continuously thereafter. The lowest point of each RMSE curve is circled, and indicates the required $\beta$ value for each case. The required $\beta$ value was further from 1 for the larger-sized footwear than for the smaller-sized footwear, which correlates with the larger dead space in the former than in the latter. The required $\beta$ value was also slightly decreased for footwear with holes on the surface, which may be attributable to a small portion of the forced flow being able to take a ‘shortcut’ via these holes, thereby increasing the dead space.

Since the 20 cases were divided into four subgroups (A, B, C, and D) based on the sizes and the presence of holes, mean RMSE values of five footwear were calculated under the same $\beta$ value for each subgroup. The $\beta$ value corresponding to the lowest mean RMSE value was found out for each subgroup ($\beta = 0.87, 0.75, 0.60$, and 0.51 for groups A, B, C, and D respectively). When these $\beta$ values were used as the model inputs, the RMSE ranges for each subgroup of tested footwear range were 0.00564 – 0.00708, 0.00191 – 0.00440, 0.00338 – 0.00631, and 0.00201 – 0.00361 m$^2$·K·W$^{-1}$.

---

**Figure 5.** Relationships between the $\beta$ value and the RMSE for 20 cases, divided into four subgroups based on size and the presence of holes.
respectively. These RMSEs are acceptable, especially those for footwear with holes on the surface.

**Determination of \( t_s \) and \( t_a \) values as model constants**

The above validation process was based on temperature settings of \( t_s = 34^\circ C \) and \( t_a = 22^\circ C \), and thus we compared 190 sets of \([t_s, t_a]\) combinations to determine whether temperature settings would affect the model outputs. The model generated a series of \( I_t \) data for each set of combinations that corresponded to various \( V_a \) data. For example, if the model output for the combination \([34^\circ C, 22^\circ C]\) was regarded as a reference, the comparison between this reference and the output for the other 189 sets of combinations was performed by calculating the corresponding RMSE for \( I_t \):

$$
\text{RMSE} = \sqrt{\sum (I_t - I_t')^2 / n}
$$

Supplementary Figure S2 shows a comparison of the results for the five types of footwear, with and without holes. The RMSEs ranged from 0 to 0.00081 m\(^2\) K\(\cdot\)W\(^{-1}\), with an average of 0.00018 m\(^2\) K\(\cdot\)W\(^{-1}\) and a median of 0.00014 m\(^2\) K\(\cdot\)W\(^{-1}\), which was two to three orders of magnitude smaller than the \( I_t \) value. This shows that the \( t_s \) and \( t_a \) values of 25 – 40 \(^\circ C\) and 20 – 35 \(^\circ C\), respectively, had little effect on the model output. The combination \([34^\circ C, 22^\circ C]\) was therefore selected as the model input for the next analysis.

**Validity of the footwear cavity model when applied on wet footwear**

As footwear may become wet due to the absorption of sweat during daily use, we examined whether our model could be applied to wet footwear. A study demonstrated that a sweat rate of 3 g/h reduced footwear insulation by 9–19% (with socks included), and that the magnitude of this reduction increased with the sweat rate and the level of dry insulation of the footwear (Kuklane, Holmér, et al. 1999). These researchers also developed the equation below, which predicts the reduction in the total insulation of wet footwear under static conditions \(I_{t, st, wet}\) after 1.5 h:

$$
I_{t, st, wet} = 0.00087 + 0.012 \cdot SW - 0.00064 \cdot SW^2 + I_{t, st, dry} \cdot (1 - 0.093 \cdot SW + 0.0047 \cdot SW^2)
$$

(15)

where \(I_{t, st, dry}\) is the original dry insulation of the footwear under static conditions and \(SW\) is the sweat rate per foot. It was estimated that sweat rates under occupational conditions are generally 3 – 6 g/h (Rintamäki and Hassi 1989), but during activities can increase to 23–32 g/h (Smith et al. 2013).

We investigated whether the forced ventilation of wet footwear would first cause a decrease or an increase in the total insulation (with the latter resulting from the drying of footwear fabric). Figure 6(A) depicts two extreme scenarios used to evaluate the applicability of our model to wet footwear. The first scenario involves forced ventilation not affecting the accumulation of sweat within the footwear fabric materials; this scenario was examined by using \(I_{t, st, wet}\) as the model input to predict the changes in total insulation under various ventilation rates. The second scenario involves the forced ventilation causing all of the sweat to evaporate from the footwear fabric and preventing further sweat absorption; this scenario was examined by using \(I_{t, st, dry}\) as the model input. As indicated in the figure, the curves depicting the actual change in the total insulation for wet footwear should
be between the curves for each of these extreme scenarios, but it was difficult to determine which of the 'actual change' curves was most realistic. If \( I_{st,wet} \) was used as the model input, the maximum possible relative error (MPRE) between the model prediction and the actual situation under a given forced ventilation rate was calculated as follows:

\[
MPRE = \frac{I_{t,dry} - I_{t,wet}}{I_{t,dry}} \times 100\%
\]

EU 42-sized Footwear C was examined further, due to its having the largest measured \( I_{t,st,dry} \) value (0.198 m\(^2\) · K · W\(^{-1}\)), which suggested that it had the largest reduction in insulation under these wet conditions. As we focussed on at-rest conditions, only sweat rates of 3, 4, 5, and 6 g/h were considered; when these were used in Equation (15), the \( I_{t,st,wet} \) values after 1.5 h were found to be 0.182, 0.178, 0.174, and 0.171 m\(^2\) · K · W\(^{-1}\), respectively.

We also calculated a series of MPRE values for each of these sweating rates under various ventilation rates, which afforded the results in Figure 6(B). The lower the sweat rate, the lower the MPRE when \( I_{t,st,wet} \) was used as the model input. When the sweat rate was 3 g/h, the MPRE was 1.56 – 7.94%, which is acceptable. The MPRE was also inversely proportional to the forced ventilation rate: when the ventilation rate was greater than 6.40 L/min, the MPRE was less than 10% for all sweating rates; when the ventilation rate was greater than 32.06 L/min, the MPRE was less than 5% for all sweating rates. These results demonstrate that the MPRE of the model predictions for wet footwear was acceptably low at sufficiently low sweating rates or sufficiently high ventilation rates. The MPRE of footwear with smaller \( I_{t,st,dry} \) values would be even lower. Moreover, the actual error would be less than the MPRE, and would be further reduced if the wet footwear were worn for less than 1.5 h and if little sweat accumulated within the footwear fabric.

**Prediction of changes in foot skin temperature caused by forced ventilation**

Based on the footwear cavity model, \( I_t \) at a ventilation rate of 30 L/min was calculated to be 0.080 m\(^2\) · K · W\(^{-1}\) using the average \( I_{t,st} \) value (0.180 m\(^2\) · K · W\(^{-1}\)) and the average geometry data of the eight participants (as shown in Table 4). The value of \( \beta \) was set as 0.76, to represent the use of Footwear A of an appropriate size and with holes on its surface. Input of these insulation data into the thermoregulation model gave the temperature changes on the skin in six body regions as shown in Figure 7, which were compared with the average measured data for these regions for the eight participants. The RMSEs for these comparisons (0.1601–0.2933 °C) reveal that the model
effectively predicted the changes in skin temperature. These RMSEs were further reduced if the data measured before the stable state were omitted from the comparison. Notably, the calculated and measured results both show that 30 L/min of forced ventilation applied to footwear decreased the skin temperature of the feet by approximately $2^\circ C$ after 30 min. However, this was not the case in the other five regions of the body. These results are consistent with a previous study that showed the skin temperatures of central parts of the body were not influenced by warming or cooling of the extremities (Heising and Werner 1985).

The above validation results indicate that the footwear cavity model and the thermoregulation model effectively predicted changes in the foot skin temperature due to forced ventilation. The two models were thus used to examine the effects of footwear with various $I_{t, st}$ values under various ventilation rates. As fitted footwear with holes on the surface was tested, the $I_{t, st}$ values ranged from 0.10 to 0.20 m² $K^{-1} W^{-1}$ (based on Table 3) and the geometry parameters were the average for the five footwear in fitted conditions. The value of $\beta$ was set to 0.75, based on Figure 5. Figure 8(A) shows the temperature changes as a function of time when forced ventilation was applied; as can be seen, the higher the ventilation rate, and the smaller the $I_{t, st}$ value, the longer it took for the skin temperature to stabilise. Figure 8(B) showed the percentage of temperature reduction as a function of time at a forced ventilation rate of 90 L/min.

Figure 9(A) shows the foot skin temperatures after 150 min at various forced ventilation rates. It can be seen that the larger the $I_{t, st}$, the higher the rate of forced ventilation had to be to reduce the skin temperature to a certain level. For example, if 32 $^\circ C$ was regarded as the upper temperature of the foot thermal-comfort zone, the minimum required forced ventilation rates were 5.4–24.6 L/min for $I_{t, st}$ values of 0.10–0.20 m² $K^{-1} W^{-1}$. Figure 9(B) shows the temperature reduction at various forced ventilation rates based on the results from Figure 9(A). The maximum temperature reduction was from 3.1 to 4.3 $^\circ C$ for the $I_{t, st}$ values of 0.10 to 0.20 m² $K^{-1} W^{-1}$ when the forced ventilation rate was within 90 L/min. A fitting equation was obtained, as shown in the figure, to reveal the mathematical relationship between the temperature reduction, $I_{t, st}$, and the forced ventilation rate. This equation fits the calculated data well, as its coefficient of determination ($R^2$) is greater than 0.998.

Thus, the forced ventilation rate required to achieve foot thermal comfort can be calculated using the following equation:

$$V_a = 45.45 \cdot \ln \left( 1 - \frac{t_s - t_{s, tc}}{5.40 - 7.36 \cdot e^{-14.0 I_{t, st}}} \right)^{-1}$$

(17)

where $t_{s, tc}$ is the defined thermal comfort temperature for foot skin. Equation (17) can therefore be used in
situations where the actual foot skin temperature is monitored on a person wearing a certain type of footwear ($I_{\text{st}} = 0.10 – 0.20 \text{ m}^2 \cdot \text{K} \cdot \text{W}^{-1}$), and a certain thermal comfort temperature is required. The applicable total insulation range covers footwear used in everyday situations, such as sports shoes, leather shoes, and safety shoes, as indicated in Figure 3. Cold-protective footwear has $I_{\text{st}}$ values greater than 0.20 m$^2 \cdot \text{K} \cdot \text{W}^{-1}$, but cannot have ventilation, as this would decrease its cold-protective abilities. Similarly, footwear with $I_{\text{st}} < 0.10 \text{ m}^2 \cdot \text{K} \cdot \text{W}^{-1}$ requires relatively weak forced ventilation, as under these conditions the skin temperature is already very close to (or less than) the thermal comfort value (as can be seen in Figure 9(A)), and thus no further reduction in temperature is required.

Equation (17) is only applicable if an individual is at rest in a calm environment, as both movement and wind will also reduce the total insulation (ISO 2004a). When applying the forced ventilation on footwear cavities when there is wind or movement, these multiple effects on total insulation reduction will be considered in future work.

Validity of Equation (17) if the air temperature is not 26.4 °C

Equation (17) is derived from the relationship between the reduction in foot skin temperature and forced ventilation rate at various $I_{\text{st}}$ values. However, the temperature-reduction values were calculated from the temperature data that were obtained for an air temperature and relative humidity of 26.4 °C and 62.5%, respectively. Thus, the obtained relationship between the temperature reduction and forced ventilation is only valid at this air temperature and relative humidity. This is because the higher the indoor-air temperature, the smaller the reduction in foot skin temperature due to forced ventilation, as less heat exchange between the skin and the force-ventilated air exists due to the reduced temperature difference between them.

As the heat lost by foot skin to the environment is $q = (t_s - t_a)/h_t$, the reduction in skin temperature due to forced ventilation can be written as:

$$\Delta t_s = q_0 \cdot I_{\text{st},0} - q_x \cdot I_{\text{st},x}$$  \hspace{1cm} (18)

where the subscripts ‘0’ and ‘x’ denote situations in which the forced ventilation rates are 0 L/min and x L/min, respectively. When the air temperature changes from 26.4 °C to a certain value, the ratio of the skin-temperature reduction at these two forced ventilation rates can be expressed as:

$$\gamma = \frac{\Delta t_s'}{\Delta t_s} = \frac{q_o' \cdot I_{\text{st},0} - q_x' \cdot I_{\text{st},x}}{q_0 \cdot I_{\text{st},0} - q_x \cdot I_{\text{st},x}}$$  \hspace{1cm} (19)

where the total insulation under various ventilation rates is regarded as independent of the ambient air temperature when this is 20–35 °C, as shown earlier. If it is assumed that $q_o'/q_0 = q_x'/q_x = \varphi$, the ratio of the skin temperature reduction $\gamma$ equals the ratio of the
heat loss $\varphi$ for the two air temperatures. The relationship between the ambient air temperature and the heat loss of foot skin has been investigated in several studies. Kuklane et al. measured the heat-loss values of bare feet at rest at air temperatures of 13, 18, and 23 °C as 73.3, 56.9, and 49.5 W·m$^{-2}$, respectively (Kuklane, Afanasieva, et al. 1999). Yao et al. found that foot skin temperature increased from 27.3 to 32.3 °C when the air temperature was 21–29 °C, and calculated that the corresponding heat-loss of feet was 55.7 to 31.0 W (Yao et al. 2007). A fitting equation $q = -2.86t_a + 113.9$ was therefore obtained based on the calculated data; this has an $R^2 = 0.89$, and $\gamma$ was thus calculated as shown in Figure 9(C). When the air temperature was 21–29 °C, the corresponding $\gamma$ value was calculated to be 1.4–0.8. This demonstrates that the higher the air temperature, the smaller the $\gamma$ value; this is intuitive, because the higher the air temperature, the less heat is exchanged between foot skin and the force-ventilated air, due to the reduced temperature difference between them.

Equation (17) can therefore be modified by adding a $\gamma$ as a coefficient, as follows:

$$V_o = 45.45 \cdot \ln \left(1 - \frac{t_s - t_{s, tc}}{\gamma \cdot (5.40 - 7.36 \cdot e^{-14.0 \cdot h \cdot m})}\right)^{-1}$$

(20)

Equation (20) satisfies the conditions of various indoor-air temperatures. For example, if the air temperature increases to 29 °C, Equation (20) reveals that the maximum temperature reduction is 2.5–3.5 °C, which corresponds to $l_{s, st}$ values of 0.10–0.20 m$^2$·K·W$^{-1}$ when the ventilation rate is 90 L/min. If the skin temperature is higher than $t_{s, tc} + 3.5$ °C, a ventilation rate greater than 90 L/min may be required to further reduce the foot skin temperature. The efficiency of forced ventilation gradually decreases, as shown by the temperature reduction curve becoming smooth at forced ventilation rates greater than 90 L/min (Figure 9(B)). At a surrounding air temperature of 29 °C and an infinite rate of forced ventilation, the maximum temperature reduction was calculated to be 4.0 °C. Therefore, for indoor-air temperatures above a certain value, other methods may be needed to ensure foot skin within footwear remains at a comfortable temperature, such as the use of PCMs or a combination of forced ventilation and PCMs, as was previously studied for cooling clothing (Kang et al. 2018).

4. Discussion

To the best of our knowledge, this paper describes the first study of forced ventilation as a possible means for controlling the thermal microenvironment of a footwear cavity. The required forced ventilation rates were found to be 5.4–24.6 L/min for various types of footwear at the air temperature of 26.4 °C. Higher forced ventilation rate was required for footwear with higher insulation. However, previous studies indicated that the existing ventilation rate could be in the range of 4.6–9.4 L/min during exercise (Satsumoto, Takeuchi, and Havenith 2011; Shimazaki, Matsutani, and Satsumoto 2016; Miao et al. 2021), which seems to satisfy the ventilation requirement for some footwear types. But such ventilation requires exercise to support, without exercise, the natural ventilation inside footwear could be less than 1 L/min (Shimazaki, Matsutani, and Satsumoto 2016). Therefore, forced ventilation is still necessary for footwear thermal environmental control, especially during resting conditions.

However, there is a limit to such forced ventilation, as it was achieved by directly exchanging the air inside the footwear cavity with the ambient air using a mechanical fan. Other cooling methods will be needed when the ambient air temperature is high. Also, though forced ventilation rate up to 90 L/min has been theoretically discussed in this paper, it is almost impossible to achieve in practical applications. Other cooling methods will be necessary when the calculated required forced ventilation rate is too large.

Besides, several questions remain to be answered when considering the mechanical ventilation of footwear. The first question is whether it is feasible to install a mechanical fan within footwear. Micro fans have been developed for face masks, and their application to footwear should not be difficult. Moreover, we have installed a micro-electrical fan in a shoe. However, the optimal location of such a fan, and consumer acceptance of such a shoe, has yet to be determined. Also, the weight of the fan and its power source needs to be carefully considered since it is reported that weights on the feet require up to seven times more energy compared to weight on the torso during activities (Dorman and Havenith 2014). The second question is whether such ventilation of shoes will release polluted air into the environment, which could be a concern in public spaces. This seems unlikely to occur, as the odour of footwear is a result of microbial growth in the humid footwear cavity, which would be reduced or prevented by ventilation.

This work defined the rate of forced ventilation required to achieve foot thermal comfort in several types of footwear. However, the optimal ventilation rate to minimise or prevent moisture accumulation in a footwear cavity remains to be determined. There are
also two limitations to applying Equation (20). First, it was derived based on the assumption that the ratio of heat loss $\varphi$ for two air temperatures remains constant under various footwear insulation conditions, but this may only be valid under certain conditions. Second, the relationship between the air temperature and the heat loss of foot skin was only validated using data from tests under one indoor-air condition, i.e. $t_a = 26.4^\circ\text{C}$. Future studies should directly acquire a series of equations corresponding to various air temperatures by conducting more experiments with greater numbers of participants. These equations could then be used to validate our integrated foot-wear-cavity–thermoregulation model at various indoor-air temperatures and relative humidity.

5. Conclusion

In this study, we developed a novel and simple mathematical model of the thermal microenvironment of footwear that considers forced ventilation of the foot-wear cavity, with a focus on the effective total thermal insulation of footwear. This model considers both the heat balance of the footwear cavity and the thermoregulation of the entire body. A comparison of the experimental data of five footwear types using a newly developed thermal foot-manikin measuring system with the predictions of the footwear cavity mathematical model show that the latter effectively predicted the footwear total insulation at forced ventilation rates of $0 – 90\text{L/min}$.

The predicted changes in foot skin temperature due to forced ventilation also agreed well with the data obtained from studies of human participants. At the tested air temperature of $26.4^\circ\text{C}$ and a foot thermal comfort temperature of $32.2^\circ\text{C}$, the required minimum forced ventilation rates were found to be $5.4–24.6\text{L/min}$, corresponding to $I_{t,ST}$ values of $0.10–0.20\text{m}^2\cdot\text{K}\cdot\text{W}^{-1}$. The maximum reduction in skin temperature was $3.1–4.3^\circ\text{C}$ when the ventilation rate was within $90\text{L/min}$. When the air temperature increased to $29^\circ\text{C}$, the maximum reduction in skin temperature was $2.5–3.5^\circ\text{C}$. As the ambient air temperature further increased, the reduction in skin temperature due to forced ventilation became negligible, suggesting that other cooling methods will be necessary at higher temperatures.

A ventilation equation was devised for determining the forced ventilation rate required to achieve foot thermal comfort. Although this equation only applies to the test conditions examined in this study, this equation could be easily extended to other situations if they can be examined using similar tests. In the future, the application of the ventilation equation must be further validated by performing more human trials under various indoor and outdoor thermal conditions.

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