Research Article

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Evaluating air-gap effects on fabric moisture vapor transmission using a modified simple dish method

Abstract

Moisture vapor transfer through clothing plays a significant role in wearer comfort, particularly when sweat needs to evaporate from the body and pass through the fabric. In clothing systems, the space between the skin and the fabric is not fixed. It changes with garment fit, body shape, posture, and movement. However, the air-gap is not usually considered in a simple dish test. In this study, a modified simple dish method was used to examine how different air-gap thicknesses affect moisture vapor transmission through fabrics. Three fabrics were selected: two cotton/polyester denim fabrics, one untreated fabric (W-CP1) and one with stone washed (W-CP2) and one wool knitted fabric (K-W4). The air-gap between the water surface and the fabric was set at 3, 9.5, and 16 mm, and each fabric was evaluated with both sides facing the water surface. The results showed a decrease in moisture vapor transmission as the air-gap increased which suggests that a thicker air layer adds resistance to vapor movement. The wool knitted fabric showed the highest moisture vapor transmission because of its lower thickness and higher porosity compared with the woven denim fabrics. Fabric side did not have a major effect on moisture vapor transmission under these test conditions. The modified simple dish results were also compared with sweating guarded hot plate results, and both methods ranked the fabrics in a similar order. However, the measured values were different because the two methods use different test conditions.

Keywords: moisture vapor transmission, air-gap thickness, modified simple dish method, evaporative resistance, sweating guarded hot plate

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Introduction

Moisture vapor transport is one of the main fabric-level factors controlling moisture-related comfort in clothing. When sweat evaporates from the skin, the vapor must pass through the skin-clothing microclimate before it reaches the fabric and surrounding air. If vapor movement is restricted, humidity can accumulate near the skin and increase the feeling of dampness and discomfort.[1] For next-to-skin clothing, this comfort depends strongly on a fabric's ability to transmit moisture vapor away from the skin and release it to the surrounding atmosphere, thereby maintaining a dry skin microclimate.[2] Therefore, moisture vapor transmission is an important parameter for evaluating the comfort performance of apparel and protective clothing materials.

In real clothing systems, the space between the skin and the fabric is not fixed. This air-gap changes with garment design, fit, body shape, posture, movement, and body location. The air-gap forms part of the clothing microclimate and can influence the distance over which water vapor must travel before reaching the outer environment.[3] Air-gap thickness, wind speed, ventilation, and fabric air permeability can interact during heat transfer through fabric systems.[4] Li et al.[5] reported that clothing thermal insulation increased with air-gap size initially. However, it decreased when the air-gap thickness exceeded approximately 1 cm because natural convection increased heat transfer. Therefore, the 9.5 and 16mm gaps in the present study are near or above this range where convection-related effects may become possible.

Because water vapor must pass through this microclimate before reaching the fabric and outer environment, changes in air-gap thickness can alter the transport pathway for moisture vapor. In addition, Havenith et al.[6] showed that the cooling benefit of sweat evaporation depends on where evaporation occurs relative to the skin, with evaporation farther from the skin providing less effective cooling.

Moisture vapor transport through fabrics is commonly evaluated using dish methods and sweating guarded hot plate methods.[7] The simple dish method measures mass loss and reports moisture vapor transmission rate, while the sweating guarded hot plate measures evaporative resistance under controlled heat and moisture transfer conditions. Although both methods describe vapor transport through textiles, their results are not directly interchangeable because they use different boundary conditions, air movement, vapor pressure gradients, and reporting units.[8]

Despite the importance of the clothing microclimate, the effect of controlled air-gap thickness is not usually examined in a standard simple dish test. ASTM E96/E96M-24a specifies the distance between the water surface and specimen as part of the test configuration.[9] However, this spacing is not typically varied to evaluate its influence on measured fabric moisture vapor transmission. This creates a gap in understanding how the air-gap between the water surface and fabric affects measured fabric-level moisture vapor transmission (MVTR). Additionally, the process of moisture vapor transfer is not only measured via the MVTR method, but also with a sweating guarded hot plate through the measurement of the evaporative resistance of fabrics (R_{et}). Both MVTR and R_{et} address the transport of water vapor through the fabric, based on a specific vapor pressure difference, either at room temperature (MVTR) or at body temperatures (R_{et} at 35^{0}C). But such temperature differences are not expected to affect vapor diffusion very much, so both properties should not only be correlated, but there is an analytical relationship between them.

In the literature, very few studies have systematically varied air-gap thickness in a dish-based moisture vapor transmission test and directly compared the resulting SDM-derived vapor resistance with evaporative resistance measured using a sweating guarded hot plate. Therefore, this study used a modified simple dish method to evaluate moisture vapor transmission through selected woven and knitted fabrics at three air-gap thicknesses. Fabric orientation was also examined by testing both fabric sides facing the water surface. Finally, the modified simple dish results were compared with sweating guarded hot plate results to determine whether the two methods provide a similar ranking of fabric vapor transport performance and whether indeed the expected analytical relationships between MVTR and R_{et} hold in the experimental data.

Objective

The objective of this study was to evaluate the effect of controlled air-gap thickness on fabric moisture vapor transmission using a modified dish method. The study examined how MVTR changed with air-gap thickness for selected woven and knitted fabrics, whether fabric orientation affected MVTR under modified test conditions, and whether SDM-derived vapor resistance provided a similar fabric ranking to and a clear analytical relationship with evaporative resistance measured using a sweating guarded hot plate (SGHP).

Materials and methods

Materials

Three fabrics were selected to represent different fabric structures and vapor transport behaviors as summarized in Table 1. W-CP1 and W-CP2 were cotton/polyester denim woven fabrics with similar construction, where W-CP1 was untreated and W-CP2 was stone-washed. K-W4 was a single jersey wool knitted fabric with lower thickness and higher porosity than the denim fabrics.

Table 1 Physical and structural properties of the tested fabrics

Fabric code	Fabric type	Composition	Structure	Mass, g/m²	Thickness, mm	Porosity
W-CP1	Denim woven	Cotton/polyester	2/1 RHT twill	499	0.76	0.55–0.60
W-CP2	Denim woven	Cotton/polyester	2/1 RHT twill	467	0.9	0.53–0.58
K-W4	Knitted wool	100% wool	Single jersey	146	0.42	0.79

These fabrics provided contrasting fabric structures and vapor transport behavior for evaluating whether controlled air-gap thickness affected measured MVTR in the modified simple dish method. Therefore, the results should be interpreted as a method-focused comparison using selected representative fabric structures.

Modified simple dish method

According to ASTM E96/E96M-24a, the water level in the dish should be maintained at a distance of 19 ± 6mm from the specimen.[9] The modified simple dish test was conducted based on ASTM E96/E96M-24a, but the air-gap thickness was intentionally varied to examine the effect of evaporative distance. The experimental setup is shown schematically in Figure 1. In the present study, three air-gap thicknesses were selected: 3, 9.5, and 16mm. The 9.5mm gap was selected as the midpoint condition. The 3mm gap was selected as the lower practical limit because it was the minimum distance that could be maintained without wetting the fabric during sample handling. The 16mm gap was selected as the upper practical limit because the dish depth was 19mm, leaving a minimum water depth of 3mm in the dish.

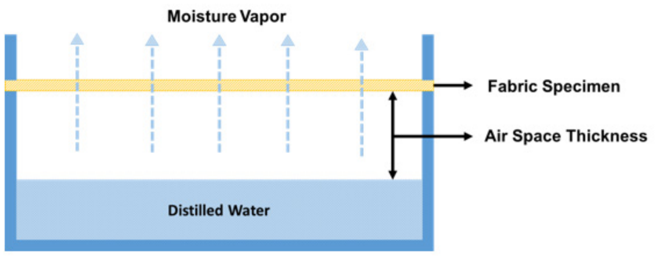

Figure 1 Schematic diagram of modified simple dish test.

Each fabric was evaluated in two orientations, with either the skin side or the outer side facing the water surface. Three replicate specimens were evaluated for each condition, giving a total of 54 measurements. All specimens were conditioned at 20 ± 2°C and 65 ± 5% RH for 24 h before testing. The air-gap thickness was controlled by adjusting the water depth in the dish, and the required water amount was calculated from the dish geometry.

The assembled specimen dish was weighed immediately after preparation to maintain the intended initial air-gap thickness. After 24 h, the final mass was recorded. Moisture vapor transmission rate was calculated from the mass loss using Equation 1:

$$MVTR = \frac{W_1 - W_2}{\pi \times r^2} \quad (1)$$

Where MVTR is the rate of moisture vapor transmission (g/m²·24 h), W_1 is the initial weight of assembled specimen dish (g), W_2 is the ending weight of assembled specimen dish (g) after 24 hours and r is the radius of the exposed test area (m).

Sweating guarded hot plate

Evaporative resistance was measured using a sweating guarded hot plate according to ASTM F1868-2023, Part B.[10] The same three fabrics, W-CP1, W-CP2, and K-W4, were evaluated. Specimens were conditioned at 20 ± 2°C and 65 ± 5% RH for 24 h before testing, and three replicate specimens were evaluated for each fabric.

The sweating guarded hot plate setup is shown schematically in Figure 2. The specimen size was 0.508 m × 0.508m. During testing, the specimen was placed on the test plate, which was surrounded by a guard heater to reduce lateral heat loss. A bottom heater was used to minimize downward heat loss, so heat and moisture transfer occurred in the upward direction through the specimen.

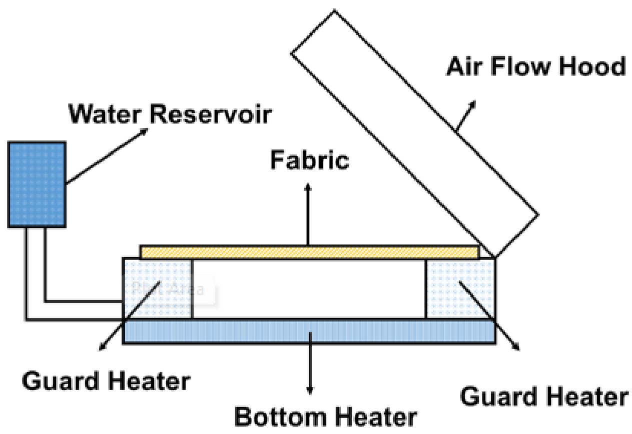

Figure 2 Schematic diagram of the sweating guarded hot plate test.

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The test was conducted under isothermal conditions, with both the plate temperature and air temperature maintained at 35°C. The relative humidity was set at 40%. Under these conditions, dry heat exchange is minimized, and the measured heat loss is primarily associated with evaporation. The total evaporative resistance was calculated using Equation 2:

$$R_{et} = \frac{(P_s - P_a) \times A}{H_e} \quad (2)$$

where R_{et} is the evaporative resistance provided by the fabric system and air layer (kPa·m²/W), P_s is the water vapor pressure at the plate surface (kPa), P_a is the water vapor pressure in the air (kPa), A is the area of the plate test sections (m²), and H_e is the power input (W).

Theoretical basis for comparing SDM and SGHP

The simple dish method (SDM) and sweating guarded hot plate method (SGHP) evaluate moisture vapor transport using different measurement principles. SDM measures mass loss and reports moisture vapor transmission rate (MVTR, g/m²·24 h), whereas SGHP measures evaporative heat loss and reports evaporative resistance, R_{et} (kPa·m²/W). Because the two methods use different boundary conditions, air movement, vapor pressure gradients, and reporting units, their results cannot be directly compared without conversion and careful interpretation.

In this study, a diffusion-resistance approach was used to relate the SDM results to the SGHP results. Based on Fick's law, steady state moisture vapor flow can be expressed as a function of the concentration difference and the resistance to diffusion.[7,11]

$$\frac{Q_v}{A \times t} = \frac{\Delta C}{R_d} \quad (3)$$

Where Q_v is the mass of water vapor passing through the system (g), A is the diffusion area (m²), t is the diffusion time (s), ΔC is the water vapor concentration difference (g/m³), and R_d is the diffusion resistance (s/m), related to the diffusion coefficient D_v (m²/s).

Since water vapor concentration is related to vapor pressure under fixed temperature conditions, the driving force can also be expressed using the water vapor pressure difference, ΔP. In this study, water vapor pressure was calculated from temperature and relative humidity using psychrometric relationships; relative humidity is defined as the ratio of actual vapor pressure to saturation vapor pressure at the same temperature.[12] Therefore, the SDM data were used to calculate a resistance term from the relationship between ΔP/MVTR and air-gap thickness. The intercept of this relationship represents the combined contribution of fabric resistance and boundary air-layer resistance.

This approach is consistent with Islam et al.,[13] who described latent heat transfer in skin-clothing-environment system as being controlled by total evaporative resistance. In that framework, the total resistance includes contributions from the enclosed air layer, fabric layer, and boundary air layer.

This SDM-derived resistance was then converted using the latent heat of evaporation and compared with R_{et} from the sweating guarded hot plate. The comparison was used to determine whether the two methods ranked the fabrics in a similar order of evaporative performance, rather than to claim exact numerical equivalence.

Statistical analysis

MVTR values were calculated from mass loss and reported as mean values from three replicate specimens for each condition. R_{et} values were obtained from sweating guarded hot plate measurements and reported as mean ± standard deviation. Paired t-tests were used to compare MVTR between the two fabric orientations because measurements were paired within the same fabric and air-gap condition.

Linear regression was used to evaluate the relationship between ΔP/MVTR and air-gap thickness. The SDM-derived resistance values were converted and compared with sweating guarded hot plate R_{et} values to evaluate whether both methods ranked the fabrics similarly. Statistical significance was evaluated at $\alpha = 0.05$.

Results and discussion

Effect of air gap thickness on MVTR

The MVTR results from the modified simple dish test are summarized in Table 2. For all three fabrics, MVTR decreased as the air-gap thickness increased from 3 to 16 mm. The decrease in the MVTR with increasing air-gap thickness shows that the air layer added resistance to vapor movement in the modified dish method. As the gap became thicker, vapor had to travel through a longer air path before reaching the fabric, which reduced the measured MVTR.

Table 2 Moisture vapor transmission rate of fabrics measured at different air-gap thicknesses

Fabric code	Air-gap thickness (mm)	MVTR (g/m²·24 h) Skin side up	MVTR (g/m²·24h) Skin side down
W-CP2	3	1181	1164
W-CP2	9.5	812	821
W-CP2	16	632	622
W-CP1	3	1016	1022
W-CP1	9.5	734	746
W-CP1	16	577	583
K-W4	3	1575	1581
K-W4	9.5	1030	999
K-W4	16	732	706

This agrees with previous work showing that the size of the clothing microclimate can affect heat and moisture transfer. Moisture diffusion may decrease as the microclimate thickness increases.[3] The study by Młynarczyk et al.[14] showed that small air-gaps are dominated by conduction, while larger gaps may allow natural convection. Islam et al.[13] also described water vapor transfer below the convection threshold as mainly diffusion controlled. In the present study, however, MVTR continued to decrease even at larger gaps. This suggests that any convection-related effect was limited, and that the longer vapor diffusion distance through the air layer remained the main factor of controlling MVTR up to 16mm.

Among the three fabrics, K-W4 showed the highest MVTR at all air-gap levels, while W-CP1 showed the lowest. The higher MVTR of K-W4 is consistent with its lower thickness and higher porosity since fabric structure is known to influence thermophysiological comfort and moisture-related transport behavior.[15] W-CP2 showed higher MVTR than W-CP1, suggesting that the stone-washing treatment may have improved vapor transport by changing the fabric structure.

Effect of fabric orientation

Fabric orientation did not significantly affect MVTR under the tested conditions. The 54 MVTR measurements were matched into 27 paired values based on fabric type and air-gap thickness. The paired t-test gave a p-value of 0.63, which is greater than 0.05. Therefore, there was no statistically significant difference between the two fabric orientations. This result suggests that, under steady-state dish testing, vapor transport was governed by the vapor pressure gradient and total diffusion resistance of the fabric–air-gap system rather than by fabric side orientation.

Regression between ΔP/MVTR and air-gap thickness

Based on the MVTR results and the theoretical relationship described in Section 2.4, linear regression was used to evaluate the relationship between ΔP/MVTR and air-gap thickness for each fabric. The regression models are shown in Figure 3. All three fabrics showed strong linear relationships, with $R^2 = 0.999$. This supports that the increase in air-gap thickness produced a proportional increase in vapor transport resistance in the modified simple dish system. However, because the regression was based on only three air-gap levels, the results should be interpreted as a description of the experimental trend rather than a universal linear relationship.

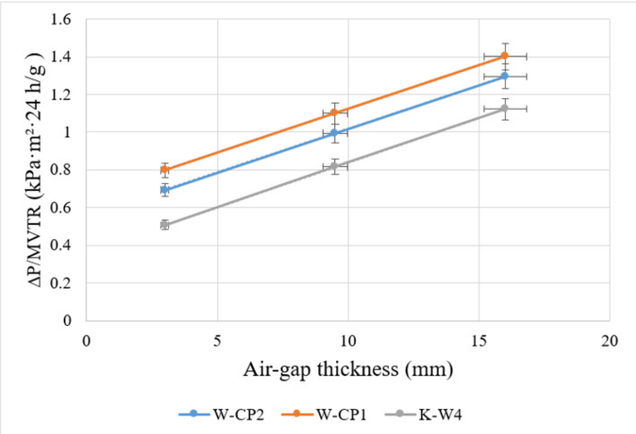

Figure 3 Linear relationship between ΔP/MVTR and air-gap thickness for the tested fabrics.

The regression equations are:

$$\frac{\Delta P}{MVTR} = 0.3662 + 0.0473d\left(K - W4\right)$$

$$\frac{\Delta P}{MVTR} = 0.6580 + 0.0464d\left(W - CP1\right)$$

$$\frac{\Delta P}{MVTR} = 0.5547 + 0.0463d\left(W - CP2\right)$$

Where ΔP/MVTR is the SDM-derived vapor pressure resistance (kPa·m²·24 h/g), and d is the air-gap thickness (mm). The intercepts represent the combined fabric and boundary air-layer resistance estimated from the modified simple dish method. The intercept values followed the order W-CP1 > W-CP2 > K-W4, indicating that W-CP1 had the highest vapor transport resistance and K-W4 had the lowest. This ranking is consistent with the MVTR results in Table 2.

Sweating guarded hot plate results

The sweating guarded hot plate results are summarized in Table 3. K-W4 showed the lowest total evaporative resistance, with a R_{et} value of 0.009 kPa·m²/W, and the lowest intrinsic evaporative resistance, with a R_{ef} value of 0.004 kPa·m²/W. W-CP1 showed the highest R_{et}, while W-CP2 showed an intermediate value. This ranking agrees with the modified simple dish results, where K-W4 showed the highest MVTR and W-CP1 showed the lowest MVTR.

Table 3 Evaporative resistance of fabrics measured using the sweating guarded hot plate

Fabric code	Ret (kPa · m²/W)		Ref (kPa · m²/W)	
	Mean	SD	Mean	SD
W-CP2	0.012	0.0002	0.006	0.0002
W-CP1	0.014	0.0003	0.009	0.0003
K-W4	0.009	0.0002	0.004	0.0002

Comparison between SDM and SGHP

The SDM-derived resistance values and SGHP-derived resistance values are compared in Table 4 and Figure 4. Both methods ranked the fabrics in the same order of evaporative resistance: W-CP1 showed the highest resistance, W-CP2 showed intermediate resistance, and K-W4 showed the lowest resistance. This agreement suggests that the modified simple dish method can provide useful comparative information about fabric vapor transport performance.

Table 4 Comparison of SDM-derived evaporative resistance and sweating guarded hot plate R_{et}

Fabric code	Simple dish test	Sweating guarded hot plate test
	Ref + Rba (kPa · m²/W)	Ret (kPa · m²/W)
W-CP1	0.023	0.014
W-CP2	0.019	0.012
K-W4	0.013	0.009

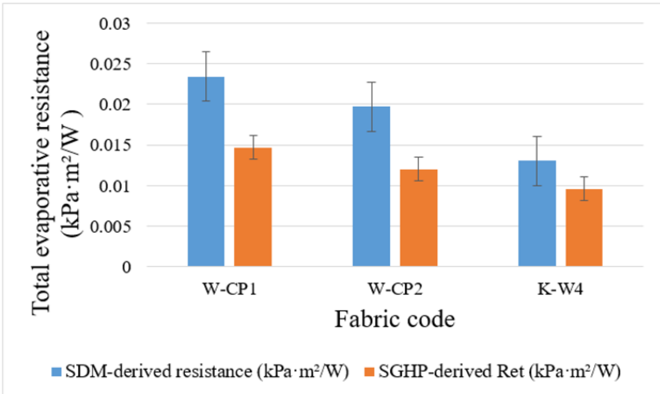

Figure 4 Comparison of SDM-derived evaporative resistance and SGHP-derived evaporative resistance (R_{et}).

Although the ranking was consistent, the SDM-derived resistance values were higher than the corresponding SGHP-derived resistance values for all three fabrics. For example, K-W4 had an SDM-derived resistance of 0.013 kPa·m²/W, while its SGHP-derived resistance was 0.009 kPa·m²/W. This difference is expected because the two methods use different air velocities and boundary-layer conditions. In the sweating guarded hot plate test, the air velocity was 1m/s, whereas the air velocity near the specimen in the simple dish test was approximately 0.034 m/s. Higher air velocity reduces boundary-layer resistance and can result in lower evaporative resistance values.

A paired comparison of the three fabric-level values gave p = 0.055. Because this comparison included only three fabric-level paired values, agreement between the two methods was evaluated from the consistency in fabric ranking rather than from the p-value alone.

These results suggest that the modified SDM may be useful for preliminary fabric screening where the goal is to compare relative

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vapor transport behavior under controlled air-gap conditions. However, it should not replace SGHP when absolute evaporative resistance (R_{et}) values, standardized thermophysiological comfort metrics, or controlled heat-transfer and airflow conditions are required. The R_{et} variable and methodology provide a more stable and controlled environment to measure water vapor transfer through fabrics and will provide better insights in calculating human heat loss or as input for thermophysiological models to predict thermal strain.

Limitations and future work

This study has several limitations. First, only three fabrics were investigated. These fabrics were selected as model materials with contrasting structures to evaluate the modified simple dish method, rather than to represent the full range of apparel textiles. Therefore, the results should be interpreted as a method-focused comparison and should not be expanded to predict vapor transfer in other fabrics without further testing. Still, this paper, being focused on the measurement methodology, and as it addresses different levels of vapor transfer, demonstrates the clear effect of the air-gap and the analytical relationship between MVTR and R_{et} to better understand their relationship.

Secondly, air permeability was not included as a supporting structural property. The three selected fabrics were of a regular woven and knit structure, without any laminate, coating or other finishes and thus may be expected to show normal air permeability for such fabrics, with lower air permeability for the woven and higher for the knit fabric. Some limited control measurements in our lab confirmed these assumptions. The absence of air permeability data limits direct comparison of airflow-related structural effects among all three fabrics. Especially, with higher air speeds the MVTR method may show deviating results from our linear relationships when the air-gap increases as related research has demonstrated.[4] Furthermore, only three air-gap thicknesses were examined; therefore, the regression results should be interpreted within the tested range only. Finally, the comparison between the modified simple dish method and the sweating guarded hot plate was based on a limited number of fabric-level values. As a result, the agreement in fabric ranking should be considered preliminary evidence of comparative consistency rather than a direct calibration between the two methods. Yet, the analytical relationship that was used to create the high correlation in Figure 3 is fundamental to the measurement methodologies and independent of fabrics. With the limitations of air permeability effects aside, these methodological relationships between MVTR and R_{et} can be expected to hold under normal testing conditions.

Future work may include a broader range of woven, knitted, nonwoven, and multilayer fabrics with complete physical characterization, including air permeability for all materials to further explore when air permeability and air-gap will have an effect on the MVTR predicted from R_{et}. Additional air-gap levels, environmental conditions, and controlled air velocity conditions may be investigated, however a separate study showed that these effects seem minimal on horizontal configurations as used here.[4] Further studies should evaluate whether the method can be extended to multilayer clothing systems and garment-relevant microclimate conditions.

Conclusion

This study evaluated the effect of air-gap thickness on fabric moisture vapor transmission using a modified simple dish method. For all three fabrics, MVTR decreased as the air-gap thickness increased from 3 to 16 mm, indicating that a thicker air layer added resistance to vapor movement. Among the tested fabrics, K-W4 showed the highest MVTR, while W-CP1 showed the lowest. This behavior was attributed to the lower thickness and higher porosity of the knitted wool fabric compared with the denim woven fabrics.

Fabric orientation did not significantly affect MVTR under the tested conditions, supporting that vapor transport was dominated by the vapor pressure gradient and total resistance of the fabric–air-gap system rather than by the side of the fabric facing the water surface. The regression analysis showed a strong linear relationship between ΔP/MVTR and air-gap thickness, supporting the use of the modified simple dish method to estimate air-gap-dependent vapor resistance.

The SDM-derived resistance values and sweating guarded hot plate R_{et} values ranked the fabrics in the same order: W-CP1 > W-CP2 > K-W4. However, the SDM-derived resistance values were consistently higher than the sweating guarded hot plate values because of differences in air velocity and boundary-layer conditions between the two methods. Therefore, the modified simple dish method can be useful for comparative screening of fabric vapor transport behavior, but it should not be used as a direct numerical substitute for the sweating guarded hot plate without further calibration.

These findings show that the air-gap between the water surface and fabric will influence MVTR values measured using a simple dish method as expected from their predicted effect. Therefore, controlling this distance is important when using dish-based methods to compare fabric moisture vapor transport. The modified simple dish method may be useful as a low-cost screening approach during early-stage fabric selection or method development, especially when the goal is to compare relative vapor transport behavior among fabrics. However, for further analysis of thermal strain evaporative resistance values would be required, as it provides better quality data and direct inputs for predictive models. Thus, sweating guarded hot plate testing remains necessary for appropriate evaluation of sweat evaporation and thermal strain.

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Conflicts of interest

The authors declare no conflict of interest.

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