INTRODUCTION

Thermal protective clothing (TPC) is primarily designed to protect occupational workers from potential thermal hazards, including radiant heat, flames, hot liquid splashes and gases, molten metals, hot steam, and other hazards. In the research area of TPC, much attention is paid to protection against heat and flame, whereas protection from hot steam is relatively unexplored. Pressurized steam is a common threat faced by firefighters and industrial workers in metallurgical, oil and gas industry, food processing and energy sectors. Different from heat and flame hazards, steam may result in much heat and mass transfer as it can easily penetrate clothing and release a considerable amount of thermal energy by phase change. In addition, during high-pressure steam exposure, TPC may get compressed with human skin and that could enhance conductive heat transfer from clothing to the body. It is estimated in an existing research that 65% of skin burn injury is resulted from hot steam and hot water penetration. There is considerable...
interest, therefore, in understanding the protective mechanisms under exposure to steam hazard.

Until now, there has been no international test standard available to evaluate the steam performance of clothing. Some researchers have developed their customized steam testing devices. Rossi et al. used a water recipient heated with a Bunsen burner to produce low-pressure steam and found that fabric’s water vapor permeability was the most important property in protection against steam. The test device developed by Desruelle and Schmid can be used to produce a steam jet or a steam atmosphere. Sati et al. used a cylinder test apparatus to mimic the high-pressure steam exposure and mentioned that steam pressure and distance to the skin could influence heat transfer. Ackerman et al. designed a novel user-friendly steam tester and reported that the steam protective performance could be influenced by many factors, including fabric’s thickness, density, and air permeability. Recently, Su et al. developed a numerical model to understand the heat and mass transfer in protective clothing under steam exposure.

These previous studies revealed the importance of TPC in the reduction of heat and mass transmission when exposed to hot steam. But in practice, TPC can cause some problems on the wearer, such as compromising wear’s comfort and/or reducing ergonomic properties. In addition, it has been reported that TPC may also have a thermal hazardous effect on human skin due to the discharge of stored energy. Along with impeding heat and mass transfer from the environment, TPC also stores large amounts of sensible heat when it contacts hot steam. Unlike the phase change material (PCM) that is capable of storing and releasing heat only when PCM reaches a certain temperature to activate the phase change or vice versa, protective clothing with sensible energy storage automatically becomes a passive heating source at the termination of exposure, posing thermal threats as stored energy continues to discharge to the skin. Although TPC may have a dual protective/hazardous performance on human skin, previous studies mainly focused on the thermal protective performance during exposure. Along with the increased attention to energy discharge, several new test methods, for example, ASTM F2703-08 and ASTM F2731-11, have been established to evaluate the overall protective performance under exposures to flame and radiant heat. Results from these test methods showed that approximately 40%-60% of the energy storage within protective clothing could discharge to human skin after exposure, significantly reducing the thermal protection expected from the clothing, and even resulting in more serious burn injuries. The comprehensive performance of TPC could be very complicated in consideration with the transmitted and stored energy. Song et al. reported that the multilayer and thick fabric systems enhanced thermal resistance to heat transfer during exposure, but they stored more thermal energy than a single layer or a thin fabric system and that may result in more energy discharge after exposure. The existing air gap between the fabric and skin has a similar complicate impact on the dual performance because it can decrease heat transfer during exposure but increase heat discharge to human skin when the fabric get contacted with human skin by compression. To ensure the reliability of TPC, therefore, it is critical to consider both the thermal protective performance and thermal hazardous performance throughout the test.

Steam protection is a rather complex case because TPC easily gets wet from internal and external sources. Moisture appears inside of clothing when the wearer perspires profusely due to intensive physical activity and harsh environment. Moisture can be generated externally by water spray from a fire hose or in rainy conditions. Moisture absorption strongly affects heat transfer as it changes thermal properties, that is, thermal conductivity and heat capacity of the fabric. The effects of internal and external moisture exposed to flame or radiant heat have been investigated by previous studies. Lawson et al. found that under flame exposure, external moisture decreased heat transfer through the fabric whereas internal moisture did the opposite, increasing heat transfer. Under low level radiant heat exposure, internal moisture decreased heat transfer. Barker et al. observed that approximately 15% moisture content reduced protective performance most severely under a radiant heat exposure. It was reported that under a flame exposure, 15% internal moisture content approached the minimum thermal protection but saturation moisture improved thermal protection. Taken together, the presence of moisture within fabrics has a complex effect on heat transmission and its effect is highly influenced by the type and intensity of thermal exposure, moisture amount, and moisture location. However, the above results were mainly obtained under the flame and radiant heat conditions and only considered the thermal protective performance during exposure but neglected the thermal hazardous performance after exposure. The need for knowledge about the impact of moisture on the dual performance of TPC under a hot steam condition is urgent.

The objective of this study was to investigate the impact of both external and internal moisture on the energy storage caused dual performance of a multilayer fabric system under a hot steam condition. The research findings will contribute to thoroughly understanding the mechanism associated with moisture effect on the dual performance in a steam condition and provide new insights into the development of functional textile materials.
2 | EXPERIMENTAL

2.1 | Materials

Aramid specimens selected for experiments in this study are commercially available. A three-layer protective fabric system consisting of an outer shell (OS), a moisture barrier (MB), and a thermal liner (TL) was constructed, as shown in Table 1. The OS material is the first layer exposed to thermal hazards and provides flame resistance and mechanical resistance to cuts, punctures, tears, etc. The MB with a microporous polytetrafluoroethylene (PTFE) membrane provides protection against the penetration of water and allows a limited amount of moisture vapor to dissipate. The TL with high insulation plays an important role in preventing heat transfer from hazardous environment to the skin. The fabric sample was 190 mm × 190 mm.

2.2 | Moisture preconditioning of test specimens

The OS and TL were chosen to be prewetted before the test, and four moisture levels were examined. The first moisture level was a relatively dry condition, in which the test specimen was preconditioned in a standard atmosphere of 21°C with 65% relative humidity for 24 hours prior to testing.14 The moisture contents of the fabric layers correspond to standard atmosphere were equal to the moisture regain of the fabrics, which were 4.2%, 3.8%, and 4.5% for the OS, MB, and TL, respectively. The other three wet condition levels for the OS (33%, 66%, and 84%) and for the TL (33%, 66%, and 100%) were selected according to a previous research.25 The OS cannot reach the highest moisture content 100% as the TL, because its woven structure had lower hygroscopicity compared to the needled felt.

The moisture content for the wet sample was achieved through the following procedure25: Fabrics were immersed in distilled water for at least 5 minutes to ensure the uniform distribution of the moisture within fabrics and then taken out to keep flat. Residual water within the fabric was absorbed by commercial blotter papers placed on both sides of the fabric until the moisture content reached a desire amount. The saturated amount of moisture (level 100%) for the OS and TL was 7.6 g and 10.4 g, respectively. Therefore, the amount of external moisture was 0 g, 2.5 g, 5 g, and 6.4 g, respectively, while the internal moisture was 0 g, 3.4 g, 6.9 g, and 10.4 g, respectively. The prepared sample was sealed in a plastic bag before testing to maintain the moisture content, and the test was conducted within 2 minutes after being taken out from the plastic bag to minimize moisture evaporation. Sixteen conditions for different moisture contents and locations are listed in Table 2.

2.3 | Testing apparatus and protocol

A steam and hot fluid tester (MYAC0001, MYAC Consulting Inc) was employed to simulate steam exposure at high pressures as shown in Figure 1.1,7 The tester consisted of an electric steam generator with a boiler, an electrically heated droplet separator, a steam spout, a fabric retainer, and a skin simulant sensor. In this device, the saturated and superheated steam at a temperature of 133.7°C and a pressure of 200 kPa was generated. The saturation temperature of the steam was maintained by the droplet separator. The steam jet positioned 60 mm above the specimen impinges directly on the specimen surface. The specimen retainer consisted of a PTFE ring to allow the steam escaping from above the top surface of the fabric during tests. A skin simulant sensor, developed by University of Alberta (Canada), was placed horizontally behind the specimen to determine the heat flux transferred through the fabric system. This sensor was made up of an inorganic material colorceran, and its heat transfer nature behaves similar to the human skin. In this sensor, a type-T thermocouple was used to measure the temperature history in any intensified thermal environment, and this temperature history was used to calculate the heat flux through the sensor using Duhamel’s theorem (Equation 2).26 In this study, the steam exposure duration was 20 seconds. Sensor data continued to be recorded for another 40 seconds after terminating the steam.

### Table 1 Basic properties of the selected fabrics

| Fabric code | Layer            | Component                        | Structural features                                      | Mass (g/m²) | Thickness (mm) | Thermal conductivity at 300 K (W/m/K) |
|-------------|------------------|----------------------------------|---------------------------------------------------------|-------------|----------------|---------------------------------------|
| OS          | Outer shell      | 98% meta-aramid/2% para-aramid   | Twill                                                   | 210.5       | 0.49           | 0.047                                 |
| MB          | Moisture barrier | 100% meta-aramid/PTFE film       | Water thorn felt with PTFE                             | 116.3       | 0.85           | 0.034                                 |
| TL          | Thermal liner    | 100% meta-aramid                | Needle punched nonwoven with meta-aramid woven face cloth | 288.1       | 2.06           | 0.035                                 |

Abbreviation: PTFE, polytetrafluoroethylene.
exposure. The sampling rate was ten samples per second. Three replications of the experiment were conducted with good consistency between replications.

2.4 | Performance evaluation indices

1. Thermal protective performance during exposure

Three indices including the 2nd degree burn time ($t_{2\text{nd}}$), the 3rd degree burn time ($t_{3\text{rd}}$), and the absorbed energy of the sensor during exposure (EAE) were used to evaluate the thermal protective performance of fabrics during exposure. The skin burn time was predicted by the Pennes three‐layer skin model and Henrique's Burn Integral model according to standard ASTM F2731‐11.\textsuperscript{19}

Skin’s energy absorption of EAE was derived by integrating the heat flux of the skin simulant sensor with the corresponding exposure time:

$$EAE = \sum_{0}^{t_{\exp}} q_{\text{sens}}(t) \cdot \Delta t \quad (t \leq t_{\exp})$$  \hspace{1cm} (1)

where $q_{\text{sens}}(t)$ and $t_{\exp}$ refer to sensor heat flux at time $t$ in kW/m² and exposure time, respectively.

The heat flux of the sensor ($q_{\text{sens}}$) can be calculated as,$^{26}$

$$q_{\text{sens}}(t) = \sqrt{\frac{k \rho c}{\pi}} \left[ \frac{1}{2} \int_{0}^{t} T_s(t) - T_i \frac{1}{t^{1/2}} \right]$$  \hspace{1cm} (2)

where $k$, $\rho$, and $c$ are the sensor’s thermal conductivity in W/(m °C), the density in kg/m³, and the specific heat capacity in kJ/(kg °C), respectively. $T_i$ is the initial uniform surface temperature in °C, and $T_s(t)$ is the surface temperature at time $t$ (s).

Thermal hazardous performance after exposure

After exposure, the thermal hazardous performance caused by the heat discharge from the fabric to the skin was also directly recorded by the sensor. Here, the energy discharge amount or energy absorption during cooling (CAE) was calculated as:

$$CAE = \sum_{t_{\exp}}^{t_{\exp}+t_{\text{col}}} q_{\text{sens}}(t) \cdot \Delta t \quad (t_{\exp} < t \leq t_{\exp}+t_{\text{col}})$$  \hspace{1cm} (3)

where $t_{\text{col}}$ refers to the cooling time.

Overall thermal protective performance throughout the test

Total energy transmission (TAE) throughout the test was calculated by using Equation (4) or by the sum of EAE and CAE:

$$TAE = \sum_{0}^{t_{\exp}+t_{\text{col}}} q_{\text{sens}}(t) \cdot \Delta t = EAE + CAE \quad (0 \leq t \leq t_{\exp}+t_{\text{col}})$$  \hspace{1cm} (4)

2.5 | Statistical analysis

Descriptive statistics (means and standard deviations) were calculated for all dependent variables: $t_{2\text{nd}}$, $t_{3\text{rd}}$, EAE, CAE, and TAE during the test. One-way analysis of variance (ANOVA) using SPSS version 20.0 (SPSS Inc) was conducted to explore the difference of the indicators due to moisture precondition. Post hoc analysis was performed using a least significant difference (LSD) test to assess the parameters that displayed significant differences in the ANOVA analysis.

3 | RESULTS AND DISCUSSION

3.1 | Effect of external moisture only

The results for four levels of external moisture are described in Table 3. Except for CAE, all indicators were highly dependent on the external moisture content. The lowest protection time $t_{2\text{nd}}$ and $t_{3\text{rd}}$ was observed for the dry fabric system.
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N0, showing 7.4 seconds and 11.3 seconds, respectively. As the moisture was saturated in N3, \( t_{2nd} \) and \( t_{3rd} \) were increased by 100% and 88.5%, respectively. It was noted that the \( t_{3rd} \) for N3 is higher than the exposure duration, which demonstrated the contribution of stored energy to skin burn injury. For the absorbed energy, indicators of EAE and TAE were decreasing as a result of absorbing more water. Results from the protection time and absorbed energy all demonstrated that the thermal protective performance during steam exposure was increased with the external moisture content. This result was consistent with those found in the flame or high radiant heat exposures,\(^{23,24}\) showing that external moisture enhanced thermal protective performance.

To further explain the effect of external moisture on heat transfer, heat flux profiles obtained by the skin simulant sensor were examined in Figure 2. The heat flux increased immediately when steam exposure started and then reached a peak value in 1.4-2 seconds. A previous study by Zhang\(^{24}\) has shown that under flame exposure, the heat flux of the sensor behind a three-layer fabric system with moisture preconditioned, arrived at the maximum value in approximately 10-20 seconds. The steam exposure greatly accelerated the occurrence of the peak heat flux, indicating that the steam imposed a much quicker heat transfer at the beginning of exposure comparing to the flame exposure. This observed increase in heat transfer rate was not only due to the intrinsic high transfer rate of steam in micro-porous fabric,\(^4\) but also due to the reduction of the fabric thickness and the increasing contact area between the fabric and the skin when the high pressure of steam was applied to the fabric.\(^1\) The steam pressure compressed fabric layers during the test and decreased the space between fabric layers and between the fabric surface and the sensor surface where still air had been contained to provide resistance to heat transfer. After the initial increase, heat flux curves shown in Figure 2 were greatly decreasing as exposure continued. This following decrease should be more attributed to the condensation occurring inside the fabric layers, especially in the MB. The condensed liquid water blocked the micropores of the waterproof breathable MB, thereby greatly resisting the penetration of steam together with heat into the sensor. At the end of exposure, thermal energy storage within the fabric system continued to transfer and the heat flux was decreased remarkably as a result of fabric cooling.

It can be seen that heat flux curves varied considerably among different moisture treatments. The heat flux during the exposure period was decreased with the increasing of external moisture content, but exhibited small changes in the cooling period. The greater moisture content reduced the heat transfer during exposure, because the heat storage capacity of the fabric system was increased by the presence of moisture.\(^{20}\) The specific heat capacity of water is approximately three times as high as the dry fabric.\(^{27}\) When exposed to steam, the OS that contained more moisture increased the stored energy within it, consequently reducing the heat transmission to the skin. It should be noted that

### Table 3: Results for external moisture only

| Code | \( t_{2nd} \) [s] (SD) | \( t_{3rd} \) [s] (SD) | EAE [kJ/m\(^2\)] (SD) | CAE [kJ/m\(^2\)] (SD) | TAE [kJ/m\(^2\)] (SD) |
|------|-----------------|-----------------|-----------------|-----------------|-----------------|
| N0   | 7.4 (0.4)       | 11.3 (0.6)      | 206.7 (5.9)     | 100.6 (8.5)     | 307.3 (2.6)     |
| N1   | 10.2 (0.2)      | 14.4 (0.3)      | 185.0 (3.2)     | 94.3 (3.6)\(^a\) | 279.2 (6.8)\(^b\) |
| N2   | 11.8 (0.9)      | 16.7 (1.0)      | 170.2 (6.7)     | 96.0 (5.0)\(^a\) | 266.2 (11.7)\(^b\) |
| N3   | 14.8 (0.1)      | 21.3 (0.4)      | 148.1 (0.9)     | 95.6 (5.8)\(^a\) | 243.6 (4.9)     |

Note: a, b—testing samples with the same superscript letter do not differ significantly from each other \((P > .05)\); otherwise, significant differences were determined between each sample using LSD post hoc tests \((P < .05)\).

Abbreviations: Emc, the effect of moisture content; NS, no significant effect; SD, standard deviation.

\(*P < .01.*

\(* * P < .001.*

**FIGURE 2** Heat flux histories of the sensor at four levels of external moisture
although thermal stored energy within the dry fabric system should differ from that within the wet ones, the energy discharge, indicated by CAE in Table 3, was not significantly different among the testing samples \((P > .05)\). This should be attributed to the fact that the increasing thermal stored energy within the OS was located at the external layer of the system, making the energy discharge need to transfer through the OS, the MB as well as the TL before reaching to the sensor.\(^{11}\) This long-distance heat discharge transferring from the external fabric layer to the internal fabric layer reduced the discrepancy of heat absorption of the sensor during cooling.

### 3.2 Effect of internal moisture only

The data for the effect of internal moisture are displayed in Table 4. The internal moisture content had a significant impact on protection time, EAE, and CAE. Similarly to the situation in Table 3, N0 without any moisture treatment had the lowest protection time. When N5 had 66% internal moisture, it resulted in more than 60% and 40% increases in \(t_{2nd}\) and \(t_{3rd}\), respectively. This enhanced thermal protection can be explained by the increasing energy storage capacity of the moisture containing fabric system. The positive effect of the internal moisture can be also proved by the data of EAE, showing that the energy transmission during exposure was decreased from 206.7 kJ/m\(^2\) to 173.9 kJ/m\(^2\) as the moisture content was increased to 66%. However, with further increasing the moisture content to the maximum level 100% in N6, the protection time and the EAE showed no significant changes onward. The reason may be that this greatest internal moisture content considerably increased the thermal conductivity of the innermost fabric layer, increasing heat transfer from this layer to the sensor. The thermal conductivity of water is nearly 0.6 W/m/°C, which is several times as great as that of aramid fiber (0.13-0.179 W/m/°C).\(^{4,28}\) With this great moisture amount, heat conduction from the wet TL to the skin was obvious, counteracting the positive effect of the moisture's heat capacity in reducing heat transfer. Results from this study demonstrated that that the positive effect of the internal moisture during exposure seemed to be complicated under a steam condition. The thermal protection was enhanced by the initial increase in the internal moisture, but if the moisture content was increased to a very high level, such as 100%, the risk of heat conduction from the innermost wet fabric to the sensor was pronounced, probably restricting the enhancement of thermal protection. And the largely wet TL decreased comfort sensation of the wearer.\(^{21}\)

It can be seen from heat flux profiles (Figure 3) that heat transfer during the first 10 seconds of exposure was largely impeded by the internal moisture. The peak heat fluxes with different internal moisture contents were lower than that in a dry condition, and the occurrence of peak heat flux was postponed for N5 and N6. However, interestingly, the greatest heat flux during cooling was observed for N5 and N6 that had higher moisture contents. Samples N5 and N6 lead to approximately 133 kJ/m\(^2\) of CAE (Table 4), which was nearly 1.3 times as much as N0 and N4. The high moisture content within N5 and N6 increased their stored energy and thermal conductivity, resulting in a greater energy discharge to the sensor when the exposure was ended. It was demonstrated that although the internal moisture could have a positive effect in reducing heat transfer during exposure, it would result in a negative effect during cooling through enhancing energy discharge to the sensor. For this reason, the total energy absorption of the sensor, indicated by TAE in Table 4, had no significant differences across the testing samples.

It should be noted that the increasing external moisture also improved the energy storage, but it did not induce significantly higher energy discharge (Table 3). It seemed to indicate that under steam exposure, internal moisture increased heat discharge toward the skin whereas external moisture had little impact on heat discharge. To elucidate the reasons, the

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**Table 4**  Results for internal moisture only

| Code | \(t_{2nd}\) [s (SD)] | \(t_{3rd}\) [s (SD)] | EAE [kJ/m\(^2\)] (SD) | CAE [kJ/m\(^2\)] (SD) | TAE [kJ/m\(^2\)] (SD) |
|------|-------------------|-------------------|----------------|----------------|----------------|
| N0   | 7.4 (0.4)         | 11.3 (0.6)        | 206.7 (5.9)   | 100.6 (8.5)   | 307.3 (2.6)   |
| N4   | 10.1 (0.1)        | 14.0 (0.1)        | 187.8 (1.0)   | 102.2 (4.0)   | 290.0 (3.0)   |
| N5   | 12.0 (0.3)\(^a\)  | 15.9 (0.1)\(^b\)  | 173.9 (0.0)\(^c\) | 133.8 (7.1)\(^f\) | 307.7 (7.1)\(^f\) |
| N6   | 12.1 (0.1)\(^a\)  | 15.9 (0.2)\(^b\)  | 174.3 (2.0)\(^c\) | 133.3 (5.7)\(^f\) | 307.5 (7.7)\(^f\) |

Note: a, b, c, d, e, f—testing samples with the same superscript letter do not differ significantly from each other \((P > .05)\); otherwise, significant differences were determined between each sample in the same column using LSD post hoc tests \((P < .05)\).

Abbreviations: Emc, the effect of moisture content; NS, no significant effect; SD, standard deviation.

\(*P < .05. \\
**P < .01. \\
***P < .001. \)
Figure 3 illustrates the results of the combined effect of external and internal moisture. Comparing the data in Figure 4 with those in Tables 3 and 4, we can find that the combined action normally had a significantly greater impact on thermal protective performance during exposure than the action of external or internal moisture alone (P < .05). Furthermore, the combined action led to a greater impact on thermal hazardous performance during cooling than the action of external moisture alone (P < .05), but had an approximately equivalent impact to the action of internal moisture alone (P > .05). For instance, the fabric system N8 that had 33% external moisture and 66% internal moisture showed 13.6 seconds to reach the 2nd degree burn when exposed to hot steam, which approximated 34% higher than N1 and 14% higher than N5 that, respectively, had 33% external and 66% internal moisture only. The CAE discharged from N8 during the cooling period was 44% higher than that from N1, but was not significantly different from N5.

When the external moisture was maintained at 33% as shown in Figure 4A, there was an increasing trend in $t_{2nd}$, $t_{3rd}$, and CAE but a decreasing trend in EAE as the internal moisture was increased to 100%. This increasing trend in both the protective performance and hazardous performance was similar to that which was observed in Table 4, showing that the dual performance of the fabric system was enhanced by the increasing of the internal moisture. This result demonstrated that if the external moisture was maintained at a relatively low level, the changing trend of the dual performance mainly depended on the internal moisture content.

When the external moisture was maintained at 66% as shown in Figure 4B, the greatest protection time and the lowest EAE were observed for N11 that had 66% internal moisture. The 66% internal and external moisture decreased the EAE through increasing the stored energy within the fabric system and consequently resulted in the highest CAE discharged from the fabric system N11 during the cooling. However, further increasing of internal moisture to 100% as for N12, the protection time was significantly decreased and the EAE was significantly increased. This thermal protection reduction can be explained by the increasing thermal conductivity of the wet innermost fabric layer. When the innermost TL had 100% moisture, heat conduction through this much moisture was increased to exceed the heat absorption within it, reducing the thermal protection of the fabric system. The increasing thermal conductivity of the TL also functioned during the cooling when N12 discharged the stored energy to the sensor, maintaining the CAE at a high level that was significantly higher than that from N2 and N10.

When the external moisture was maintained at 84% as shown in Figure 4C, there was no significant difference in $t_{2nd}$, $t_{3rd}$, and
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EAE among N3, N13, and N15. Also, the CAE was no longer significantly different between the fabric systems with different levels of internal moisture. It was indicated that if a relatively high moisture content, for example, 84%, was absorbed by the OS, heat transmission during both exposure and cooling mainly depended on this high amount of external moisture, rather than the internal moisture amount. This was because the external moisture absorbed a lot of thermal energy when exposed to steam, greatly decreasing the temperature of the TL and the impact of its internal moisture on heat transmission. It was found that N14 with 66% internal moisture had significantly lower \( t_{3rd} \) and higher EAE than N3 and N13 with lower internal moisture, but it had significantly higher protection times than N15. The reduction of thermal protection as the increasing internal moisture to 66% can be explained by the increasing thermal conductivity through the TL. This meant that the increasing of external moisture to 84% in Figure 4C accelerated the negative effect of the high internal moisture to be detected, because in Figure 4B the reduction of thermal protection was observed only when the internal moisture was increased to 100%. However, when the internal moisture increased to 100% in N15, the positive effect of the increasing specific heat capacity by moisture compensated its negative effect of the increasing thermal conductivity, and thereby improving the thermal protection.

**FIGURE 4** Results of the combined effect of external and internal moisture: A, external moisture is 33%, while internal moisture changes from 0% to 100%; B, external moisture is 66%; C, external moisture is 84%. Note: * = significant difference was observed at \( P < .05 \); otherwise, no significant differences were determined between each sample using LSD post hoc tests (\( P > .05 \)); NS = no significant difference was observed at \( P > .05 \); otherwise, significant differences were determined between each sample using LSD post hoc tests (\( P < .05 \)).
3.4 The relationship between moisture and thermal protective performance

The above discussion demonstrated that the impact of moisture on thermal protection was highly dependent on the moisture location and moisture amount. Therefore, it was necessary to explore the specific corrections between the moisture and the performance of the fabric system. The relationships between the internal moisture, external moisture and $t_{2nd}$, $t_{3rd}$, and EAE, and CAE, respectively, are displayed in Figure 5. Here, the two-dimensional polynomial function was successfully used to establish their relationships, as shown in Equations (5)-(8) ($t_{2nd}$: $R^2 = 0.683$, $t_{3rd}$: $R^2 = 0.641$, EAE: $R^2 = 0.705$, CAE: $R^2 = 0.723$). The indicator of the goodness of fit ($R^2$) for $t_{2nd}$ and $t_{3rd}$ was lower than that of EAE and CAE, probably because the burn injury time was a discrete indicator rather than a continuous one such as the absorbed energy that can provide more distinguishable information on thermal protection. These equations all indicated that the thermal protective performance and the thermal hazardous performance under steam exposure were not only affected by the external and internal moisture, but also affected by their interaction.

It can be seen from Figure 5A,B that the $t_{2nd}$ and $t_{3rd}$ were normally increased with the increasing of the external and internal moisture, but showed a decrease when both...
the external and internal moisture reached a high amount. The EAE, as shown in Figure 5C, had an opposite change trend to the $t_{2nd}$ and $t_{3rd}$. The CAE shown in Figure 5D was raised with the increasing of internal moisture, but in general it had a slight decrease with the increasing of external moisture.

$$t_{2nd} = -0.07x^2 - 0.03y^2 - 0.08xy + 1.51x + 0.89y + 7.18$$  \(\text{(5)}\)

$$t_{3rd} = -0.07x^2 - 0.03y^2 - 0.11xy + 1.88x + 0.91y + 10.8$$  \(\text{(6)}\)

$$\text{EAE} = 0.62x^2 + 0.24y^2 + 0.63xy - 12.15x - 6.54y + 208.16$$  \(\text{(7)}\)

$$\text{CAE} = -0.33x^2 - 0.24y^2 - 0.21xy + 2.2x + 6.82y + 92.05$$  \(\text{(8)}\)

where $x$ and $y$ refer to the external moisture content and internal moisture content, respectively.

Equations (5)-(7) indicated that the increase in external moisture resulted in a greater changing rate in $t_{2nd}$, $t_{3rd}$, and EAE as compared to the increase in internal moisture. For instance, $\frac{dt_{2nd}}{dx}$ was $1.51 - 0.14 * x - 0.08 * y$, which was higher than $\frac{dt_{2nd}}{dy}(\frac{dt_{2nd}}{dy} = 0.91 - 0.11 * x - 0.06 * y)$. This result demonstrated that $t_{2nd}$, $t_{3rd}$, and EAE, which were indicative of the thermal protective performance, were more affected by the external moisture than by the internal moisture. The amount of sensible heat of the moisture ($Q_{\text{sensible}}$) during exposure could be determined by:

$$Q_{\text{sensible}} = cm\Delta T$$  \(\text{(9)}\)

where $c$ is the specific heat capacity of moisture, $m$ is the mass of moisture, and $\Delta T$ is the temperature fluctuation of moisture during exposure.

According to Equation (9), the sensible heat amount of moisture depended on the change of its temperature. The external moisture that was closer to the heating source had higher temperature in comparison with the internal moisture, and thereby increasing stored energy and decreasing transmitted energy to the sensor.

However, CAE in Figure 5D, which was indicative of the thermal hazardous performance, was more affected by the internal moisture because the difference between $\frac{\partial \text{CAE}}{\partial y}$ ($\frac{\partial \text{CAE}}{\partial y} = 6.82 - 0.21 * x - 0.48 * y$) and $\frac{\partial \text{CAE}}{\partial x}$ ($\frac{\partial \text{CAE}}{\partial x} = 2.2 - 0.66 * x - 0.21 * y$) was $4.62 + 0.45 * x - 0.27 * y$ (Equation 8), which was always a positive value. This meant that $\partial \text{CAE}/\partial y$ was much higher than $\partial \text{CAE}/\partial x$. This was because the stored energy within the internal moisture could discharge directly to the sensor after exposure, while the amount within the external moisture needed to transfer through the MB and the TL before reaching to the sensor. It should be noted that these empirical equations on the influence of internal and external moisture were established by using the limited data obtained in this study, and their validation is needed in the future work.

4  |  CONCLUSIONS

This study investigated the impact of internal and external moisture on the performance of a multilayer fabric system under a pressurized hot steam condition. The results showed that moisture distribution was a key parameter to consider in the reliability of TPC since the moisture content and location have a complex influence on both the thermal protective performance and the thermal hazardous performance.

External moisture increased the thermal protective performance of the fabric system through energy storage, but did not have significant effect on the thermal hazardous performance. Internal moisture generally had a positive effect in reducing heat transfer during exposure, but during cooling it did the opposite, increasing heat discharge to the sensor. The combined action of external and internal moisture normally had a greater influence on thermal protective performance than the action of external or internal moisture alone. This combined action had a greater impact on thermal hazardous performance during cooling than the action of external moisture alone. In addition, relationships between external moisture, internal moisture, and the dual performance of the fabric system were successfully established using two-dimensional exponential functions. It was found that thermal protective performance was more influenced by the external moisture. It generally increased with the rising external and internal moisture, while it decreased when both the external and internal moisture reached a high amount. The thermal hazardous effect during cooling, however, was more affected by the internal moisture rather than by the external moisture, and it showed an increase with the rising of internal moisture.

The results suggested that thermal media to store the heat such as the moisture should be located in the external layer of the system. In addition, the internal moisture normally resulted from perspiration should be transferred from the body to the atmosphere as much as possible in order to reduce the discharge of stored energy. These results could be brought to research institutions to develop new fabric combinations in order to minimize the heat transmission to the skin. With all this knowledge, future efforts could be made to investigate the optimizing configuration of fabric layers, the effects of fabric thermophysical properties, fabric structures, and air gap size on the dual performance of TPC.
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