Total Heat Loss of Firefighters’ Protective Clothing

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Received 26 September 2014; accepted for publication 10 October 2014

Abstract

We examined the total heat loss, which is the summation of heat loss and evaporation loss, for the firefighters’ protective clothing and the combined clothing samples which were prepared from the firefighters’ protective clothing, the working wear clothing and the commercial T-shirts as determined by a test method specified in ASTM F 1868 part C. We compare the total heat loss, heat loss and evaporation loss obtained from firefighters’ protective clothing and combined clothing samples with those of the commercial T-shirts and a working wear using in a fire station. We confirmed that the total heat loss of firefighters’ protective clothing and combined clothing samples were approximately 2.5 times less and approximately 2.9 times less than those of clothing materials such as T-shirts and working wear clothing, respectively. It was found that very strong correlation existed between total heat loss and evaporation loss. We suggested that the total heat loss determined according to ASTM F 1868 part C could be estimated from the values of evaporation loss.

Key Words: Clothing material, Total heat loss, Heat loss, Evaporation loss

1. Introduction

Clothing materials prevent heat loss and evaporation loss from human skin. The heat loss and evaporation loss can be calculated from thermal resistance and evaporative resistance of clothing materials. It is well known that thermal resistance and evaporative resistance are especially important properties for firefighter’s protective wear using under severe condition such as a fire accident environment [1-3].

Many test methods have been developed to investigate the thermal properties of clothing materials, and several test methods on thermal and evaporative resistances have been established by ISO, ASTM, NFPA and JIS [4-8].

ASTM test method F 1868 part C has specified the total heat loss as the summation of the heat loss calculated from thermal resistance and the evaporation loss calculated from evaporative resistance measured in a standard environment. This test method is applicable to fabrics, films, coatings, forms, leathers, and multi-layer fiber assemblies under steady-state conditions [6].

We examined the total heat loss, which is the summation of heat loss and evaporation loss, as determined by a test method specified in ASTM F 1868 part C using four types of firefighters’ protective clothing and twelve types of combination samples of the firefighters’ protective clothing, the working wear clothing and commercial T-shirts clothing. And we compared the experimental results of the total heat loss, heat loss and evaporation loss obtained from firefighters’ protective clothing and the combination samples with the results of general wears such as commercial T-shirts, and working wear clothing using in a fire station.

2. Experimental

2.1 Samples

The clothing materials used as experimental samples were four types of commercial T-shirts as general wears, one type of working wear worn in a fire station, and four types of firefighters’ protective wear clothing. The firefighters’ protective clothing consisted of three layers, of which the outer layer was material having heat and flame resistance, the middle layer was material having a liquid barrier, and the innermost layer was material having a heat insulation property. The layered materials of the firefighters’ protective clothing were considered proprietary information by the manufacturers.

Preparation of samples was performed by cutting out materials from the commercial T-shirts, a working wear worn in a fire station...
and the four types of firefighters’ protective clothing. Additional samples were a combination (hereinafter, “combined clothing sample”) of the three-layered firefighters’ protective clothing, the working wear clothing, and the commercial T-shirts combined in that order.

2.2 Apparatus

In the experiment, a hot plate with attached wind tunnel was used to measure the thermal and evaporative resistances described in ASTM F 1868. The size of the hot plate was 200 mm×200 mm. To measure the evaporative resistance, the hole on the surface of the hot plate was opened and the water barrier material specified in ASTM F 1868 was used to keep the sample in the wet condition.

2.3 Calibration of Apparatus

For each thermal resistance measurement, calibration of the apparatus was performed. To measure the thermal resistance, several layers (from single to four-fold) of calibration fabric were placed on the test plate and several total thermal resistances were measured. We confirmed that the apparatus conditions satisfied constraints a) through d), as follows.

a) A graph of total thermal resistance versus number of layers of calibration fabric was linear for the bare-plated value.

b) The slope of the linear regression was 0.0195 K·m²/W ± 10%.

c) No individual data measurement was outside ± 10% of the value predicted by the linear regression.

d) The intrinsic thermal resistance of the four layers of calibration fabric was 0.078 K·m²/W ± 10%.

For each evaporative resistance measurement, we calibrated the apparatus by the same procedure used for heat resistance. We showed that the apparatus conditions satisfied constraints e) to h), as follows.

e) A graph of apparent total evaporative resistance versus the number of layers of calibration fabric was linear for the bare-plated value.

f) The slope of the linear regression was 0.0043 kPa·m²/W ± 10%.

g) No individual data measurement was outside ± 10% of the value predicted by the linear regression.

h) The intrinsic thermal resistance of four layers of calibration fabric was 0.0172 kPa·m²/W ± 10%.

2.4 Procedure

The temperature of the hot plate was 35.0 ± 0.5 °C, the air temperature was 25.0 ± 0.5 °C, the air velocity was 1.0 ± 0.1 m/s and the relative humidity was 65 ± 4%.

The average intrinsic thermal resistance (K·m²/W) and the average apparent intrinsic evaporative resistance of a sample (kPa·m²/W) were measured.

Measurements were taken three times, and the average intrinsic thermal resistance of each sample \( R_{cf} \) and the average apparent evaporative resistance of each sample \( R_{ref} \) were obtained. Total heat loss \( Q_t \) was calculated by the summation of heat loss \( Q_d \) and evaporation loss \( Q_w \) according to the following formula (1) in ASTM F 1868 part C.

\[
Q_t = Q_d + Q_w = \frac{10^0C}{R_d + 0.04} + \frac{3.57kPa}{R_{ref} + 0.0035} \cdot \cdot \cdot (1)
\]
3. Results and Discussion

Explanations of the sample numbers are shown in Table 1. The experimental results for all samples are shown in Table 2. The ranges of $R_{cf}$ and $R_{fa}$ taken from T-shirts and working wear samples (No. 1–No. 5) were 0.012 K m$^2$/W to 0.024 K m$^2$/W and 0.0015 kPa m$^2$/W to 0.0022 kPa m$^2$/W, respectively. The ranges of $R_{cf}$ and $R_{fa}$ of the firefighters’ protective clothing samples (No. 6–No. 9) and those of the combined clothing samples (No. 10–No. 21) were 0.079 K m$^2$/W to 0.144 K m$^2$/W, 0.0080 kPa m$^2$/W to 0.0156 kPa m$^2$/W. These ranges of $R_{cf}$ and $R_{fa}$ of all samples differ from each other greatly.

Fig. 1 is the bar graph of $Q_d$, $Q_w$, and $Q_t$. As is apparent from Fig. 1, the values obtained from T-shirts and working wear samples (No. 1–No. 5) were higher than those of firefighters’ protective clothing and combined clothing samples (No. 6–No. 21). The averages of $Q_d$, $Q_w$, and $Q_t$ of T-shirts and working wear samples were 172.2 W/m$^2$, 685.5 W/m$^2$, and 857.7 W/m$^2$, respectively. The averages of $Q_d$, $Q_w$, and $Q_t$ of firefighters’ protective clothing samples (No. 6–No. 9) were 76.0 W/m$^2$, 265.6 W/m$^2$, and 341.5 W/m$^2$. Those of the combined clothing samples (No. 10–No. 21) were 70.3 W/m$^2$, 221.1 W/m$^2$, and 291.4 W/m$^2$.

It was found that the values of the $Q_t$ obtained from firefighters’ protective clothing and combined clothing samples were approximately 2.5 times and approximately 2.9 times less than those of T-shirts and working wear samples, respectively. Therefore, the firefighters’ protective clothing is superior in prevention of total heat loss to other samples.

Fig. 2 and Fig. 3 are indicative of the relationship between $Q_d$, $Q_w$ and $Q_t$ obtained from firefighters’ protective clothing and combined clothing samples. The correlative coefficients calculated from the firefighters’ protective clothing and combined clothing samples were 0.888 for $Q_t$ and $Q_d$, and 0.977 for $Q_t$ and $Q_w$. Satisfactory correlations were indicated from these results.

The correlations between $Q_d$, $Q_w$ and $Q_t$ for T-shirts and working wear samples were shown in Fig. 4 and Fig. 5. The linear correlative coefficients of T-shirts and working wear samples were 0.852 for $Q_t$ and $Q_d$, and 0.965 for $Q_t$ and $Q_w$ as shown in Fig. 4 and Fig. 5.

On the other hand, the relationship between $Q_t$ and $Q_d$ for all samples is shown in Fig. 6. Two sample groups bounded by
a dotted line indicate T-shirts and working wear samples, and firefighters’ protective clothing and combined clothing samples. The linear correlative coefficient calculated for \( Qt \) and \( Qd \) was 0.979. Fig. 7 shows the relationship between \( Qt \) and \( Qw \) for all samples. The correlative coefficient was 0.997. We confirmed that the strong correlations existed between \( Qd \), \( Qw \) and \( Qt \) for all samples. The \( Qw \) has very close relationship with \( Qt \) exceptionally \((r=0.997)\). Therefore, it was considered that the \( Qt \) could be estimated from the value of \( Qw \) or \( R_{av}^d \) directly.

4. Conclusion

In this paper, we examined the total heat loss (\( Qt \)), heat loss (\( Qd \)) and evaporation loss (\( Qw \)) that was established by ASTM test method F 1868 part C using mainly firefighters’ protective clothing as test samples. Experiments were carried out using the firefighters’ protective wear, and clothing made from combinations with three sheets of firefighters’ protective clothing, working wear clothing worn in a fire station and commercial T-shirts combined in that order, and the clothing material samples cut from commercial T-shirts and a working wear in a fire station. We confirmed that the average of total heat losses (\( Qt \)) of firefighters’ protective clothing materials, and clothing prepared by combinations of three sheets of firefighters’ protective clothing, working wear clothing in a fire station and commercial T-shirts were approximately 2.5 times smaller and approximately 2.9 times smaller than those of clothing materials such as T-shirts and working wear clothing.

We examined on the relationship between total heart loss (\( Qt \)), heat loss (\( Qd \)), and evaporation loss (\( Qw \)). It was found that a strong correlation existed between total heat loss (\( Qt \)) and heat loss (\( Qd \)), and between total heat loss (\( Qt \)) and evaporation loss (\( Qw \)) for all samples. The evaporation loss (\( Qw \)) has very close relationship with the total heat loss (\( Qt \)) exceptionally. Therefore, it was considered that the total heat loss (\( Qt \)) could be estimated from the value of evaporation loss (\( Qw \)) or average apparent intrinsic evaporative resistance (\( R_{av}^d \)) directly. On this point, the correlations between heat loss (\( Qd \)), evaporation loss (\( Qw \)) and total heat loss (\( Qt \)) that are observed from many clothing materials including general garments such as suit, sweater, office wear and spots wear also will need to be discussed in more detail for the future.

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