Characterizing a Firefighter's Immediate Thermal Environment in Live-Fire Training Scenarios

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Introduction

Background

In 2013, over 7,500 firefighter were injured during training related activities including high-risk, but necessary, live-fire training[1]. Little physical data have been collected from a firefighter's immediate thermal environment during live-fire training. Acquiring such data would allow for the evaluation and improvement of live-fire training evolutions and standards as well as the standards for firefighter personal protective equipment (PPE).

In order to gather data from a firefighter's immediate thermal environment in a live-fire training exercise, a portable heat flux and gas temperature measurement system was created and integrated into firefighter PPE. The system was tested and calibrated in a laboratory setting at the National Institute of Standards and Technology (NIST) and then used to measure the ambient temperature and incident heat flux of a firefighter's immediate environment in live-fire scenarios. Data were collected from 28 live-fire training evolutions conducted during seven different training scenarios.

Measuring the Thermal Training Environment

Over the years, a variety of thermal environment classification systems have been developed by researchers. Many of these systems define three or four different thermal classes based on temperature and heat flux. In 2006, NIST reviewed the existing thermal environment data and proposed four thermal classes, listed below in Table 1, for use in defining standardized test criteria for electronic safety equipment used by firefighters.

Table 1: NIST Thermal Classes

Thermal Class	Maximum Time (min)	Maximum Temperature (°C)	Maximum Heat Flux (kW/m²)
I	25	100	1
II	15	160	2
III	5	260	10
IV	< 1	> 260	> 10

[1] Karter, M. J., Jr. and Molis, J. L., Fire fighter Injuries in the United States, NFPA, National Fire Protection Association, Quincy, MA (November 2014).

Methods

Portable Data Measurement and Acquisition System

In order to effectively obtain data from a firefighter's immediate thermal environment in a live-fire setting, a portable data measurement and acquisition system was developed. The system, pictured in Figure 1, is composed of two main parts: the helmet and the pack.

Figure 1: Portable data measurement and acquisition system

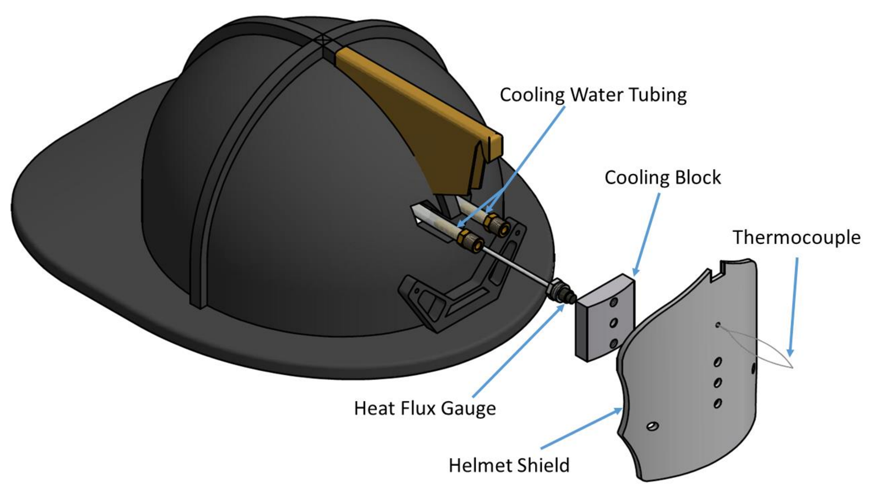

Figure 2: CAD model of helmet portion of portable measurement system

Helmet

The helmet portion of the system, shown in Figure 2, consists of a fire helmet, a bare bead thermocouple, a heat flux microsensor (HFM), and a custom cooling block for the sensor that is attached to the aluminum helmet shield. To control the temperature of the heat flux sensor, water is pumped through the cooling block. The wires of the HFM and thermocouple and the tubing for the cooling water pass through an access port cut into the helmet behind the shield, along the underside of the helmet's dome, out the back end of the helmet, and to a 2.07 L (70 fl oz) hydration backpack.

Pack

The data logger, water reservoir, and miniature water pump are contained in various pockets of the hydration backpack (Figure 3). The data logger rests in the front pocket of the pack and is used to collect and store data from the HFM and the thermocouple. The water reservoir, located in the rear pocket of the pack, serves as the storage unit for the cooling water. Finally, the water pump used to pump water from the reservoir through the helmet portion of the system and its battery pack are located in a side pocket of the pack.

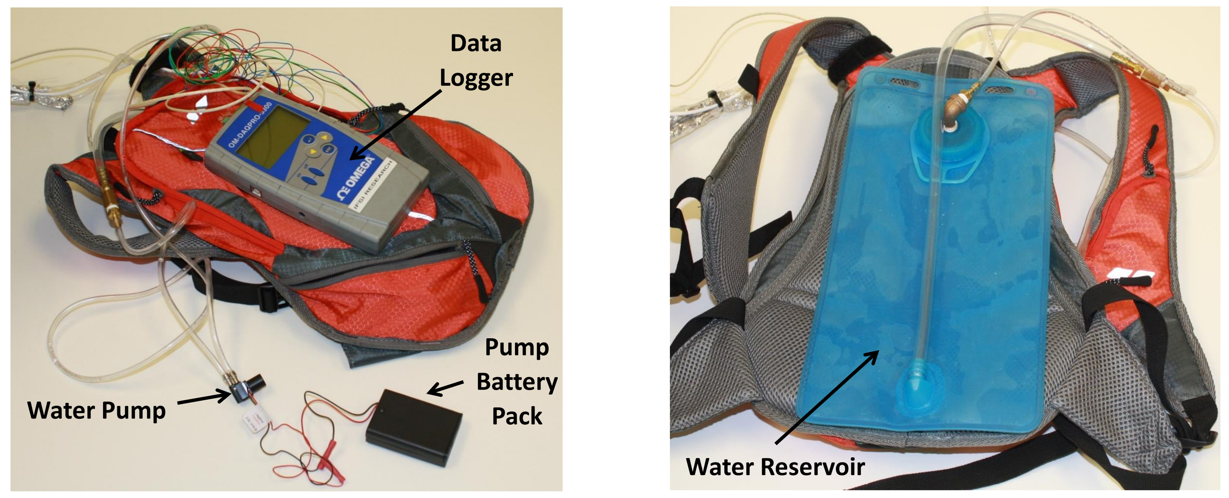

Figure 3: Pack portion of portable measurement and data acquisition system

Results

Laboratory Calibrations

Multiple laboratory experiments were conducted at NIST to compare the HFM module from the portable measurement and data acquisition system to a standard NIST-calibrated Schmidt-Boelter total heat flux gauge (SBG). As shown in Table 2 and Figure 4 below, there were no statistically different results between the two sensors.

Table 2: Laboratory calibration results

Approximate Incident Heat Flux (kW/m²)	Average SBG Heat Flux (kW/m²)	Average HFM Heat Flux (kW/m²)
1	1.08 ±0.02	1.28 ±0.09
3	3.26 ±0.02	3.24 ±0.10
5	5.27 ±0.03	5.23 ±0.10

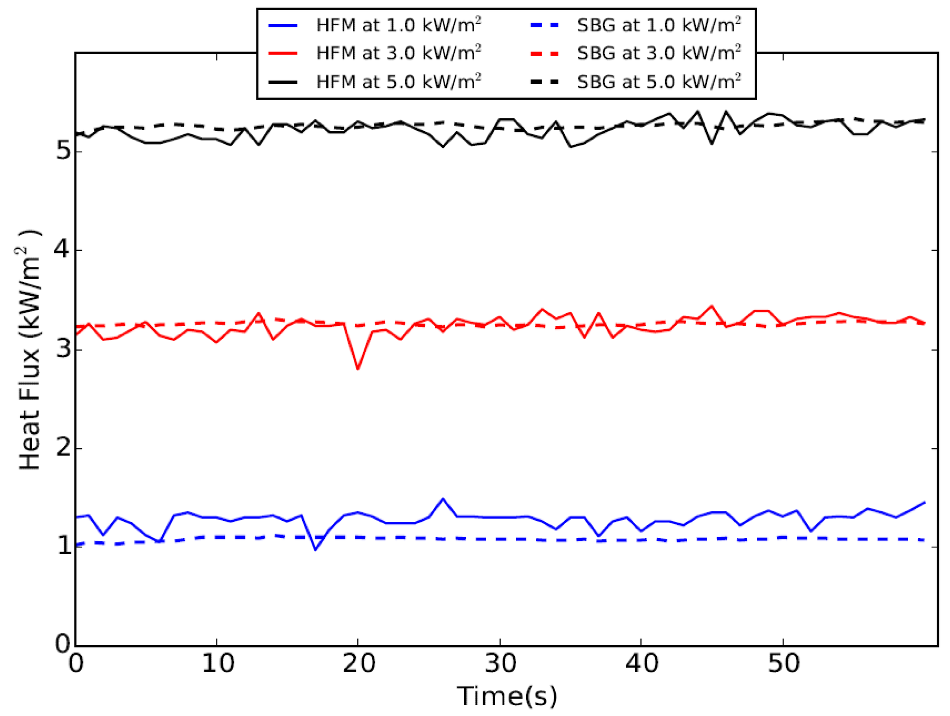

Figure 4: HFM module (solid lines) vs. Schmidt-Boelter (dashed lines) at each incident heat flux

Live-Fire Training Exercises

Tables 3 and 4 list the number of exposures from which data were collected during each of the five training exercises and the average and maximum heat fluxes and temperatures for each of the five sets of experiments, respectively. Additionally, Figure 5 contains a plot comparing the temperature and heat flux measured in a more severe environment to the temperature and heat flux measured in a moderate environment encountered during the training exercises. Throughout the live-fire exposures, a more severe thermal environment included temperatures between 150°C and 225°C and incident heat fluxes generally between 3 kW/m² and 6 kW/m², while a moderate environment consisted of ambient temperatures between 50°C and 75°C and incident heat fluxes around 1 kW/m².

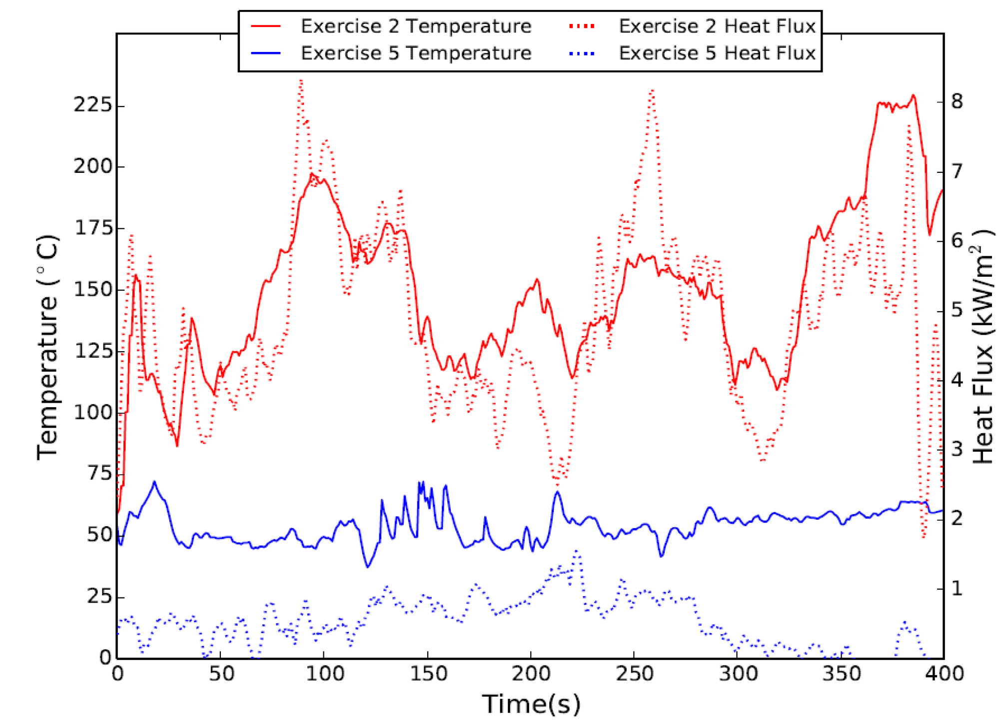

Figure 5: Comparison of a severe thermal environment (Exercise 2) and a moderate thermal environment (Exercise 5) encountered during the live-fire exposures

Table 3: Average heat flux results for Exercises 1-5

Training Exercise	Number of Exposures	Average (kW/m²)	Maximum (kW/m²)	NIST Thermal Class Average Duration *mm:ss* (Heat Flux *kW/m²* ± StdDev)			
				I	II	III	IV
1	4	2.4 ±1.4	11.1	10:31 (2.4 ±1.4)	08:58 (2.7 ±1.3)	06:08 (3.2 ±1.3)	00:01 (10.8 ±0.3)
2	3	2.5 ±1.7	10.0	08:52 (2.5 ±1.7)	08:21 (2.7 ±1.7)	04:05 (3.9 ±1.6)	00:00 (-)
3	2	1.4 ±1.3	12.7	14:14 (1.4 ±1.3)	08:46 (2.1 ±0.8)	03:43 (2.9 ±1.0)	00:01 (12.7 ±0.0)
4	9	1.0 ±1.1	7.0	09:37 (1.0 ±1.1)	04:41 (1.8 ±0.8)	01:21 (2.8 ±0.9)	00:00 (-)
5	7	1.0 ±0.7	8.8	12:48 (1.0 ±0.7)	04:52 (2.4 ±1.4)	01:09 (2.4 ±1.4)	00:00 (-)

Table 4: Average temperature results for Exercises 1-5

Training Exercise	Number of Exposures	Average (°C)	Maximum (°C)	NIST Thermal Class Average Duration *mm:ss* (Temperature *°C* ± StdDev)			
				I	II	III	IV
1	4	119 ±28	180	10:31 (119 ±28)	06:59 (133 ±23)	01:18 (167 ±4)	00:00 (-)
2	3	113 ±45	230	08:52 (113 ±45)	05:11 (145 ±29)	01:34 (181 ±16)	00:00 (-)
3	2	115 ±47	238	14:14 (115 ±47)	07:26 (154 ±27)	03:01 (180 ±17)	00:00 (-)
4	9	42 ±102	170	09:37 (42 ±102)	03:34 (112 ±12)	00:02 (161 ±1)	00:00 (-)
5	7	59 ±12	137	12:48 (59 ±12)	00:14 (110 ±8)	00:00 (-)	00:00 (-)

Conclusions

A portable measurement and data acquisition system has been developed, tested, and proven effective in collecting data from the immediate thermal environment of a firefighter in a live-fire setting.

The system was used to characterize the thermal environment of various live-fire training scenarios. It was found that a more severe thermal environment included temperatures between 150°C and 225°C and incident heat fluxes generally between 3 kW/m² and 6 kW/m², while a moderate environment consisted of ambient temperatures between 50°C and 75°C and incident heat fluxes around 1 kW/m².

Using the heat flux criteria from the NIST Thermal Classes to classify a firefighter's immediate thermal environment in a live-fire training setting produces longer durations in higher thermal classes than when the temperature criteria are used to characterize the same environment. It was determined that temperature is not enough to fully monitor the thermal environment; heat flux measurements are also needed to adequately characterize the live-fire environment.

Additional research is needed to develop a more complete understanding of the thermal environments encountered by firefighters in live-fire training scenarios. The portable measurement and data acquisition system that has been developed and proven effective during this project may play a significant role in future research.

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