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Wildland Firefighter Helmet Air-Supply System for Reducing Smoke Exposure and Heat Stress

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ABSTRACT

The size and severity of wildfires worldwide have increased in recent years. Thousands of firefighters are needed to control these fires. The occupational health and safety risks associated with wildland firefighting are significant including physical injury, exposure to smoke and heat stress. A prototype helmet ventilation system was developed that can reduce such risks. The system uses multiple air ducts channeling filtered air into the firefighter's helmet promoting sweat evaporation from the head and directing air over the firefighter's breathing zone. The system is designed to provide a comfortable, discreet, and simple solution for reducing occupational exposure to smoke while also reducing heat stress.

Keywords: Wildland firefighters, Occupational health and safety, Respiratory protection, Heat stress reduction, Prototype technology

INTRODUCTION

Climate change has led to an increase in the frequency and severity of droughts worldwide, contributing to a global rise in wildland fires (Li, 2023; Aldersley, 2011; Aldersley, 2116). Since the 1980s, both the size and intensity of these fires have been steadily increasing. In the United States alone, more than 66,000 forest and wildland fires were recorded in 2022 (Burke, 2021; Earth Science Data Systems, 2024), requiring the deployment of thousands of firefighters to protect nearby communities. Wildland firefighting presents significant occupational health and safety challenges (Kondros, 2021; De Vos, 2009). Among the most critical risks are physical injuries, smoke inhalation, and heat stress (Budd 1, 1997; Budd 2, 1997; Budd 3, 1997). This project aimed to design and develop a prototype technology that reduces firefighters' exposure to smoke while also mitigating the effects of heat stress. A functional prototype system has now been developed to meet these objectives.

WORK ENVIRONMENT

The work environment of wildland firefighting differs significantly from that of structural firefighting. While structural firefighting involves intense physical effort, it typically occurs over shorter durations and involves exposure to known hazardous substances, necessitating the use of specialized respiratory protection such as self-contained breathing apparatuses (SCBAs) and full "turnout gear" (Aisbett, 2012). In contrast, wildland firefighting demands prolonged, high-intensity workloads in unpredictable and often remote environments. Firefighters in these settings are routinely exposed to smoke, dust, and diesel exhaust, yet they are not equipped with respiratory protection. To maintain mobility and endurance during extended operations, wildland firefighters wear much lighter clothing than their structural counterparts. For head and eye protection, they rely on standard hard hats and goggles. To mitigate smoke and particulate exposure, simple cloth face masks are commonly used, though these offer minimal respiratory protection.

SYSTEM DESIGN

To provide an alternative to the limited respiratory protection available to wildland firefighters, an air supply filtration system that also promotes sweat evaporation from the head was developed which can be integrated into existing helmets. The system includes a battery-powered variable-speed air filter that provides airflow directly to a firefighter's helmet. Tubing leading from the air filter to the helmet provides airflow to the firefighter's breathing zone while also providing airflow to the space between the helmet suspension straps and the helmet outer shell. This configuration promotes sweat evaporation directly from the head. The two air supply options can be operated independently of each other. The overall system design is shown in Figure 1. To evaluate the actual system performance, air flow was incrementally introduced in five steps ranging from 222 L/min to 680 L/min.

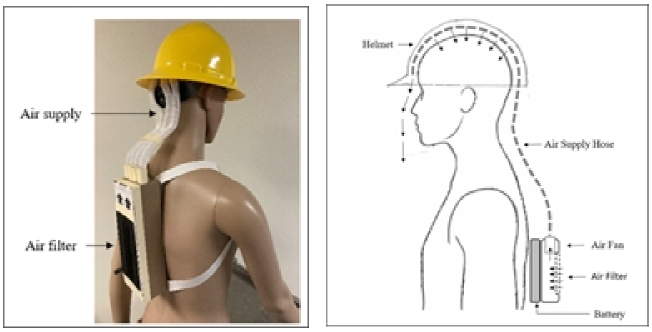

Figure 1: Illustration of the prototype wildland firefighter helmet air supply system designed to reduce smoke exposure and promote sweat evaporation from the head.

Air Flow

Airflow through the helmet tubing was measured using a digital precision thermoanemometer probe positioned within the manifold chamber, upstream between the air fan and the tubing connector (manifold). Average airspeed values were calculated based on three-minute sampling periods, during which the thermoanemometer recorded air velocity once per second, yielding 180 individual measurements per trial. Each test was conducted four times, and the results were averaged. To assess airflow reaching the breathing zone, the tubing designated for head sweat evaporative cooling was sealed. Conversely, to measure airflow for head cooling only, the tubing to the breathing zone was blocked. For total airflow measurements—including both the breathing zone and head cooling—all tubing remained open. Air volume (L/min) was calculated by multiplying the average airspeed (cm/min), as recorded by the thermoanemometer, by the cross-sectional area of the tubing (cm^2).

Evaporative Cooling

Evaporative cooling from the head was evaluated using the thermal manikin shown in Fig. 2. This system measures heat loss from the head (in watts) and changes in head surface temperature (°C). Three test configurations were used: 1. Control – dry manikin head, 2. Wet – manikin head moistened with water, 3. Sweating + Helmet – a simulated sweating manikin head wearing a helmet. Sweating was simulated by placing a high-absorbency paper towel, saturated with water, over the manikin's head to mimic sweat evaporation. The three configurations are illustrated in Fig. 3. Each test was repeated four times, and the results were averaged. Manikin head temperatures were monitored using four thermocouple probes symmetrically taped to the top of the head. All tests were conducted with an air supply rate of 550 L/min and all helmet air ducts open.

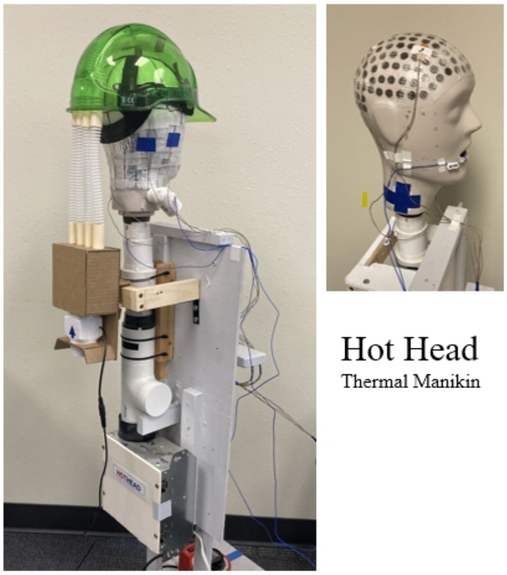

Figure 2: Illustration of the thermal manikin used in determing the evaporative heat loss from the head while wearing a construction helmet.

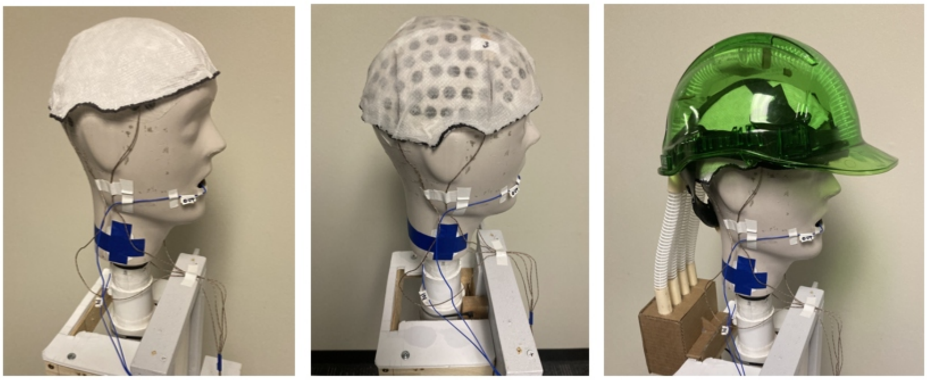

Figure 3: Illustration of the thermal manikin head configurations evaluated using a dry paper cap as a control, a wet paper-cap without a helmet, and a wet paper-cap worn underneath the helmet.

RESULTS

Table 1 summarizes the airflow rates into the breathing zone, the helmet and the combined breathing zone and helmet. Input airflow was increased stepwise from 222 L/min to 608 L/min. The corresponding increases in air flow for the three regions, relative to the input air flow, are illustrated in Fig. 4. Table 2 summarizes the relative heat loss (watts) and skin temperature changes observed for the manikin head and the dry-cap, manikin head with the wet-cap and the manikin head with the wet-cap and construction helmet. The dry-paper cap configuration served as the “control” against which the wet-cap and the three configurations were compared. Airflow was introduced into the helmet and the breathing zones simultaneously at a constant flow rate.

Table 1: Summary of airflow values observed for the three ventilation configurations at five different air-input velocities.

System Air Input (l/min)	Airflow to Face (l/m)	Airflow to Head (l/m)	Air Flow to Face + Head (l/m)
222	135	94	174
385	240	215	305
475	300	283	384
555	363	326	420
608	393	372	489

Table 2: Summary of evaporative cooling associated with the dry-paper cap, wet paper-cap and wet paper-cap and helmet.

Thermal Manikin Head Configuration	Relative Change in Heat Loss (Watts)	Relative Change in Temperature (°C)
Dry Cap (Control)	0	0
Wet Cap	+ 3.2%	−16.6%
Wet Cap + Helmet	+ 17.2%	−42.0%

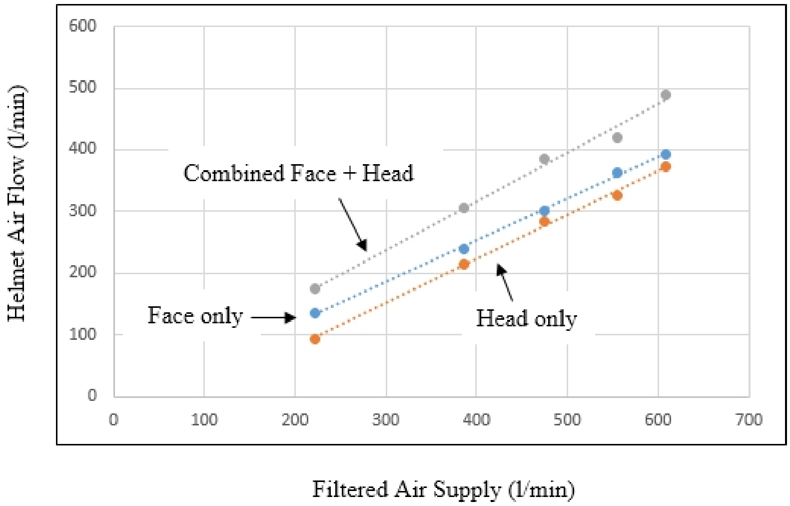

Figure 4: Illustration of the linear relationship between system air input and airflow in the breathing zone (face), the internal helmet space (head) and the combined face and head combination.

DISCUSSION

The findings of this study demonstrate that the prototype system delivers filtered air to the firefighter's breathing zone at a rate exceeding the maximum anticipated respiratory demand of 200 L/min during heavy exertion (Budd 3, 1997). With a flow rate of 400 L/min, the system provides a surplus of filtered air capable of effectively displacing smoke and airborne pollutants from the breathing zone. Additionally, the airflow directed into the helmet enhances evaporative cooling from the head, offering further physiological relief. This dual-function capability—combining respiratory protection with thermoregulatory support—is not currently available in any commercial product.

CONCLUSION

The development and testing of the prototype firefighter respiratory protection system demonstrated the potential for improving the health and safety of wildland firefighters significantly. Although the tests were conducted inside a laboratory, the fundamental principle of providing filtered air to a firefighter's breathing zone that then displaces smoke and particulate matter, while also providing cooling of the head by sweat evaporation appears technologically feasible. Ultimate commercial development of this technology may lead to further performance improvements making this technology attractive not only for wildland firefighters but also for workers in other fields that require use of protective head ware. While laboratory testing provides a controlled environment to evaluate fundamental performance and feasibility, real-world testing scenarios will be essential to fully validate the effectiveness, durability, and usability of the firefighter respiratory protection system.

Field testing in active wildland firefighting operations introduces variables that cannot be fully replicated in the lab, such as extreme temperatures, variable humidity, physical exertion, prolonged use, terrain challenges, and dynamic smoke concentrations. These factors can significantly influence the system's ultimate performance and firefighter comfort. Deploying a fully functional prototype system into the field will allow the assessment of how well the system can be integrated into existing firefighting gear, its ease of use during high-stress operations, and its impact on communication, mobility, and situational awareness. It also enables the collection of feedback from end-users—the firefighters themselves—which can lead to iterative design improvements that enhance both functionality and user acceptance. For instance, issues related to fit, noise, weight distribution, or cooling efficiency may only become evident after extended deployment in the field. Furthermore, environmental exposure to dust, ash, rain, and mechanical impacts during real firefighting scenarios can reveal important insights about the system's durability and maintenance requirements. Field testing will also provide critical data on how the technology performs over time, helping to establish maintenance intervals, cleaning protocols, and component longevity—all of which are essential for eventual commercialization. Finally, by testing the system in varied geographical locations and under different wildfire conditions, manufacturers can ensure that the technology is adaptable across a wide range of operational contexts. This comprehensive validation approach will be able to strengthen the case for broader adoption not only by wildland firefighters but also by other professionals in hazardous or high-heat environments, such as industrial workers, construction crews, or emergency responders.

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REFERENCES

Aisbett, B., Wolkow, A., Sprajcer, M., Ferguson, S. A. (2012). "Awake, smoky, and hot": Providing an evidence-base for managing the risks associated with occupational stressors encountered by wildland firefighters. Applied Ergonomics, 43, 5, 916–925.

Aldersey, S. Williams, A. (2016). Impact of anthropogenic climate change on wild fires across wester US forest. Proc Natl Acad Sci USA, 113, 11770–11775.

Aldersey, S., Murray, J., Corneel, S. (2011). Global and regional analysis of climate and human drivers of wildfire, Science of the Total Environment, 409, 18: 3472–3481.

Budd, G. M., Brotherhood, J. R., Hendrie, A. L., Jeffery, S. E., Beasley, et al. (1997). Project Aquarius 5. Activity distribution, energy expenditure, and productivity of men suppressing free-running wildland fires with hand tools. International Journal of Wildland Fire, 7, 2, 105–118.

Budd, G. M., Brotherhood, J. R. Hendrie, A. L., Jeffery, et al. (1997). Project Aquarius 6. Heat load from exertion, weather, and fire in men suppressing wildland fires. International Journal of Wildland Fire, 7. 119–131.

Budd, G. M., Brotherhood, J. R., Hendrie, A. L., Jeffery, S. E., et al. (1997). Project Aquarius 7. Activity distribution, energy expenditure, and productivity of men suppressing free-running wildland fires with hand tools, Wildland Fire, 7, 2, 113–144.

Burke M., Driscoll, A., Heft-Neal, S., Xue, J., Burney, J., Wara, M. (2021). The risk and burden of wildfire in the United Sates, Proc. Natl. Acad. Sci. 2021, 118, 2.

De Vos, A. J., Cook, A., Devine, B., Thompson, P. J., Weinstein, P. J. (2009). Effect of protective filters on fire fighter respiratory health: Field validation during prescribed burns, 52, 1:76–87.

Kodros, JK, O'Dell, K, J, Samet, JM, L'Orange, C, C., Pierce, J. R., Volckens, J. (2021). Quantifying the Health Benefits of Face Masks and Respirators to Mitigate Exposure to Severe Air Pollution. GeoHealth, 5, 9.

Li, T., Cui, L., et al., (2023). Advances in the study of global forest wildfires. J. Soil Sediments, Vol. 23. pp 2654–2668.

National Aeronautics and Space Administration (NASA), (2024). Website: https;//www.earthdata.nsa.gov/topics/hazards/wildfires.