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Nebulizer-Retrofitted Drone Deployment at Residential Construction Sites

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Abstract

A water-misting drone was deployed during the summer of 2021 at two residential construction sites in Utah. Area readings for Wet Bulb Globe Temperature (WBGT) and particulate matter (PM) concentrations were collected during 12 pilot test runs involving a 10-minute pre-flight stage, a 10-minute flight stage, and a 10-minute post-flight stage. The average WBGT values during the drone flight/misting stage were found to be 1.7 degrees F lower than those averages found for both the pre- and post-flight stages. This difference was statistically significant ($p < 0.001$, $\alpha = 0.05$). The particulate matter concentrations pre-flight and post-flight were not found to be significantly different. Future research should include the deployment of additional drones with nebulizers and potentially other sensors at residential sites, with an improvement in battery technology and resulting flight times under maximum payload conditions.

Key Findings

1. During the drone flight stage of the test runs, the WBGT averaged 1.7 F degrees lower than both the pre-flight and post-flight stages of the test runs. This appears to support previous studies employing stationary nebulizers at construction sites.
2. Temperatures during the drone flight stage were significantly different ($p < 0.001$, $\alpha = 0.05$) than both the pre-flight and the post-flight stages.
3. After the attempt at wet deposition of airborne particles during the drone flight stage of each of the test runs, the air was not statistically significantly cleaner than it was prior to the misting event.
4. The drone's battery life was a major constraint for all runs. This was due to the significant draining from a heavy water payload (22 pounds or 10 liters initially).
5. While the average WBGT values from the test runs were 1.7 degrees F lower for the drone flight stages compared to both pre-flight and post-flight sampling values, there were several times during the test runs when the WBGT values during the flight event were 3 degrees lower than that of both the pre-flight run values and post-flight run values.
6. While the particulate matter concentrations were not statistically significantly different between the pre-flight ("dirty" air) and the post-flight ("clean" air), at the beginning of the post-flight sampling the particulate concentrations were normally marginally lower than at the end of the pre-flight test run. Hence, some minor particulate matter cleaning appeared to result from the misting events.
7. To get significant WBGT reductions and marginal air particulate cleaning at a particular residential constructions site, it will be necessary to keep drone(s) deployed almost continuously. With current battery technology, this will be challenging but plausible.

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Introduction

Although construction workers remain vulnerable to occupational injury and fatalities from the Occupational Safety and Health Administration (OSHA)-defined "fatal four" (i.e., falls, struck-by objects, electrocution, caught in/between), the "silent" exposures of air pollution and heat stress also pose considerable, frequently overlooked occupational burdens. Construction workers often experience heightened air pollution on job sites, particularly in the form of particulate matter sized 2.5 µm (PM2.5) or ultrafine particles (UFP) of less than 200 nanometers, which can permeate deep into the alveoli [1]. Air sampling during tasks such as plastering, concrete mixing, and masonry has revealed high levels of PM2.5 associated with lower lung function [2]. Both PM2.5 and UFP have been associated with the development of cardiovascular, pulmonary, and respiratory illness and early mortality [3, 4]. Current dust suppression controls are not, based on the new OSHA permissible exposure limits (PELs), fully effective, while personal respiratory protection (i.e., wearing of a respirator) can be difficult to implement [5].

Heat stress is another occupational exposure where the current strategies for protecting workers are frequently inadequate. The temperature at which heat stress affects a worker is highly individualized, as heat stress is a complex interaction of metabolic heat, environmental conditions, temperature, humidity, velocity of air, and radiant heat [6]. However, construction workers are commonly exposed to extreme weather conditions without access to shade or water and are especially vulnerable to heat stress, particularly as the number of extreme hot days rise [7]. One study found that construction workers were 13 times more likely to die from heat stress than workers in other industries [8]. Like air pollution, mitigation of the risk of heat stress is currently inadequate, particularly when rest periods and access to water/shade are merely suggested rather than mandated [7].

Recent experiments suggest that water spray may offer considerable benefits in areas of both air pollution and heat stress. Wet deposition, or the process in which precipitation moves pollutants out of the atmosphere and to the earth, has been observed to be more efficient in the removal of particulate matter (PM) than the more gradual dispersal of pollutants via dry deposition [9]. This principle has long been understood in construction, as thorough wetting of soil prior to work reduces the risk of airborne dust contamination [10]. Water spray offers the possibility of an effective, swift, and low-cost reduction of airborne PM exposures [11]. Additionally, evaporative spray cooling systems have been used to great benefit (even in humid, subtropical areas) to reduce heat stress at large events [12]. Past studies have indicated that elevated temperatures in work zones have been reduced 10-15% when using misting fans [12-14]. Specifically, one of these studies used a misting device, capable of dispersing 86 liters/hour of water mist (25 micron mean diameter), to bring down a significant outdoor area's temperature by a maximum of 2.5 °C [13]. Highly polluted urban areas (e.g., Bangkok, Thailand) have begun to use drone aircraft for the dispersal of water spray [15]. This study used this method in order to examine the potential of a simple, low-cost intervention for two pressing construction site occupational health concerns. Along with the obvious benefits to workers, another collateral benefit of the project is the reduction of dust on occupied homeowner properties near to the construction events.

During this pilot project, we tested the efficacy of water-dispersing drones at residential construction sites in the St. George, Utah, area (characterized by year-round warm temperatures and summers in regular excess of 38°C) [16] and in the Salt Lake City, Utah, area. Initially, we anticipated conducting sampling at three large home construction events, each four consecutive days long and that involve site excavation and ancillary activities, to be characterized for NUFP levels and heat WBGT values. However, due to significant challenges imposed by the pandemic, including travel restrictions, we modified this sampling protocol to fewer days and fewer sites. Still, the same number of test runs were completed as was initially proposed. During each of these events, a sophisticated and durable agricultural-based spray drone was deployed to disperse water. The sampling protocol included quantitative, real-time characterization of WBGT and particulate matter concentrations before (i.e., pre-flight), during (i.e., flight), and after (i.e., post-flight) the deployment of the drone. The sampling/monitoring occurred between the end of June 2021 and the final week of July 2021 at two residential construction sites, one in Salt Lake City, Utah and one in the St. George, Utah area. This pilot project fulfills the CPWR's strategic goals of 1) establishing best practices that improve worker safety adopted on constructions sites (r2p), 2) addressing emerging issues and exploring new technologies, 3) exploring innovative or new directions in construction sciences, and 4) reaching high-risk sectors.

We addressed goal #1 through the development and pilot testing of a protocol that may effectively and efficiently improve the thermal comfort level of site workers during extreme temperatures while reducing potential exposures to significant concentrations of dust. Goals #2 and #3 were accomplished through the use of a relatively new technology (portable drones) to explore an innovative direction to reduce or eliminate potential occupational exposures and illnesses in the residential construction industry. Goal # 4 is realized because a sector that is underserved and at significantly high risk (Hispanic males) makes up approximately 50% of the residential construction industry in both southwest and northeast Utah.

Objectives/Specific Aims

There were two specific aims for this project:

Specific Aim #1: Develop and assess the effect of water-dispersing drones on air quality at residential construction sites. The hypothesis is that particulate matter concentrations (PM), measured on residential construction sites immediately after water-dispersing drones are deployed during the excavation process, will be statistically significantly lower than the concentrations measured without the water-dispersing drones being deployed during similar residential construction excavation events.

- From Progress Report (December 2020): "While the current pandemic has hindered significant progress in addressing and attaining this specific aim, preliminary field work and validation studies have been conducted with the project instrumentation and drone technology. Construction partners in both St. George and Salt Lake City, Utah have been secured for Spring/Summer 2021 field data collection."

Specific Aim #2: Develop and assess the effect of water-dispersing drones on air temperature at residential construction sites. The hypothesis is that wet bulb globe temperatures (WBGT), measured on residential construction sites immediately after water-dispersing drones are deployed during the excavation process, will be statistically significantly lower than the WBGT measured without the water- dispersing drones being deployed during similar residential construction excavation events.

- From Progress Report (December 2020): "While the current pandemic has hindered significant progress in addressing and attaining this specific aim, preliminary field work and validation studies have been conducted with the project instrumentation and drone technology. Construction partners in both St. George and Salt Lake City, Utah, have been secured for Spring/Summer 2021 field data collection.

Methods

The main instrumentation/equipment used on this project included two heat stress monitors, one particulate monitor, and one DJI agricultural misting drone. In addition, an infrared distance measuring device, a tripod, and a tall stepstool were required during each sampling event. Please see Figure 2 for additional details on the field set-up.

The misting drone traversed at the two sites (Family Housing construction site on the University of Utah campus; in St. George, at The Ledges residential community) at an altitude of 20 feet. It misted its 10-liter payload at 1 liter per minute for a duration of 10 minutes. WBGT and PM data were collected at the center point of a 50' x 50' plot (250 ft^2) site. The area WBGT was placed on a tripod at 3.5' and the PM monitor was placed at approximately 5' above ground level. For each of the 12 test runs, data for both WBGT and PM was collected for 10 minutes to get a baseline (*pre*), during a 10-minute flight (*flight*), and for 10 minutes to get a post-flight condition (*post*).

The traversing protocol is shown in Figure 1 below. Other site specifics are provided in Table 1. Figures 2-6 show other site sampling details.

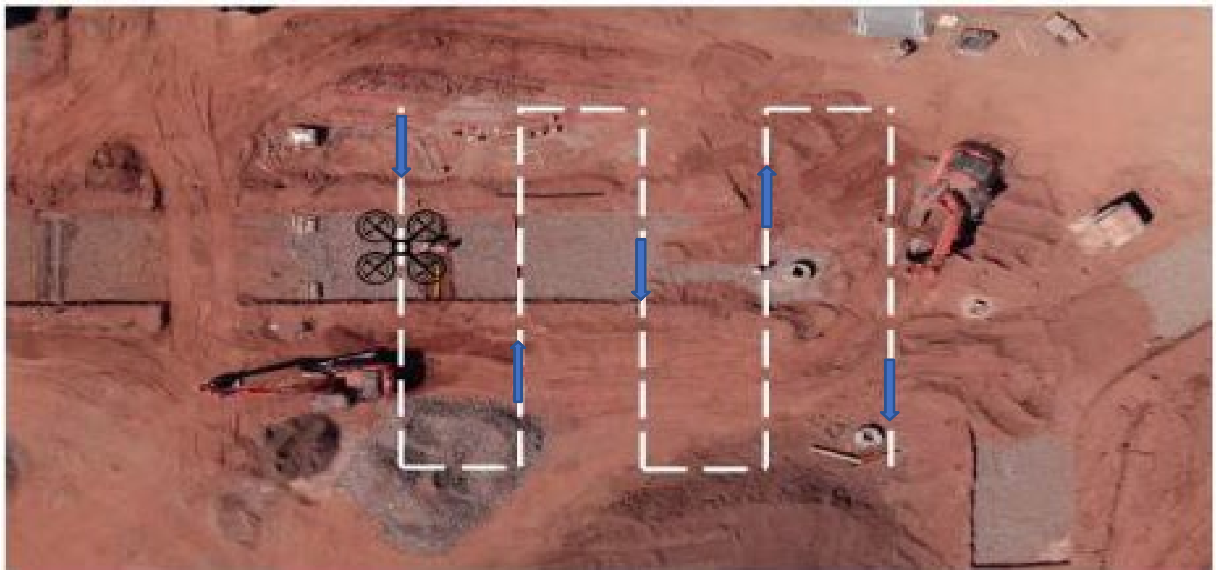

Figure 1 – Misting Drone Traversing Pattern

Table 1. Data Collection at Salt Lake City (SLC) & St. George (StG) Sites

Test Run #	Date/Start Time	Location	Weather Conditions
1	6/28 – 1:15PM	SLC	Mostly sunny @ 86°F and RH=23% w/light wind (W)
2	6/28 – 2:10PM	SLC	Mostly sunny @ 88°F and RH=18% w/ light wind (W)
3	6/29 – 1:00PM	SLC	Mostly sunny @ 85°F and RH=20% w/light wind (V)
4	6/29 – 2:00PM	SLC	Mostly sunny @ 86°F and RH=22% w/light wind (V)
5	7/27 – 10:10AM	StG	Mostly sunny @ 81°F and RH=48% w/light wind (SW)
6	7/27 – 11:15AM	StG	Mostly sunny @ 86°F and RH=35% w/light wind (SW)
7	7/27 – 2:05PM	StG	Mostly sunny @ 93°F and RH=31% w/light wind (W)
8	7/27 – 2:50PM	StG	Mostly sunny @ 95°F and RH=33% w/light wind (W)
9	7/28 – 10:10AM	StG	Sunny @ 85°F and RH=28% w/light wind (V)
10	7/28 – 11:00AM	StG	Sunny @ 88°F and RH=22% w/light wind (V)
11	7/28 – 2:00PM	StG	Sunny @ 95°F and RH=19% w/light wind (W)
12	7/28 – 2:50PM	StG	Sunny @ 97°F and RH=16% w/light wind (W)

Figure 2 – Sampling location and set-up.

Figure 3 – Drone in flight and misting at 20' altitude.

Figure 4 – Weather conditions similar during each test run.

Figure 5 – Salt Lake City sampling location at university family housing construction site.

Figure 6 – Multiple construction activities going on during site sampling events.

Accomplishments and results, including their relevance and practical application

<u>WBGT Data and Results</u>

The following graphs and tables provide the data and results for area WBGT values from the 12 pilot test runs. Since during one of the test runs there was a significant weather front that passed through during the post-flight stage, it was considered an outlier and not included in the following graphical assessments. Figure 7 shows the temperature difference over time, by drone test run, for 11 of the 12 total test runs, while Figure 8 provides a kernel density diagram of temperature change. Figure 7 reveals a major reduction in WBGT temperatures during the flight/misting stage of the test runs when compared with both the pre-flight and the post-flight stages. Specifically, Figure 8 shows the distribution of temperature changes for each flight stage, with “flight” temperatures shifting left compared to other time periods.

Figure 9 provides a box plot of the WBGT data, excluding SLC day 2 test run 2 data (the outlier). While this box plot shows the same data provided in Figures 7 and 8, it is in a format that makes differences in mean, median, interquartile range (IQR), and outliers more apparent. An omnibus one-way analysis of variance (ANOVA) test showed a highly significant difference in means between at least two stages of the pre-, post-, and during- flight temperature change ($F(2, 987) = 73$, $p < 0.001$). Tukey’s Honest Significant Difference (HSD) post-hoc test for multiple comparisons found that the mean value of temperature change was significantly different between during-flight and pre-flight, and during-flight and post-fight with adjusted p-values < 0.001. There was no difference between pre-flight and post-flight. Of interest is that with ambient temperature rising, during- flight temperature was reduced by an average of 1.7 degrees (F) from the pre-flight time period. This has all been summarized in Table 2 and graphically represented in Figure 10.

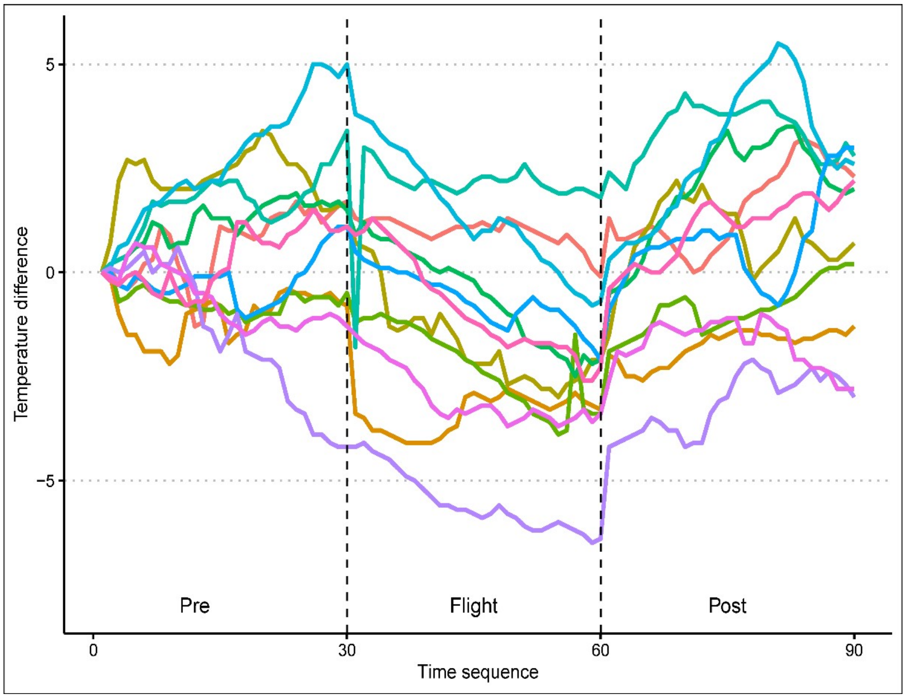

Figure 7 - Temperature difference over time by drone test run (for 11 of 12 total runs).

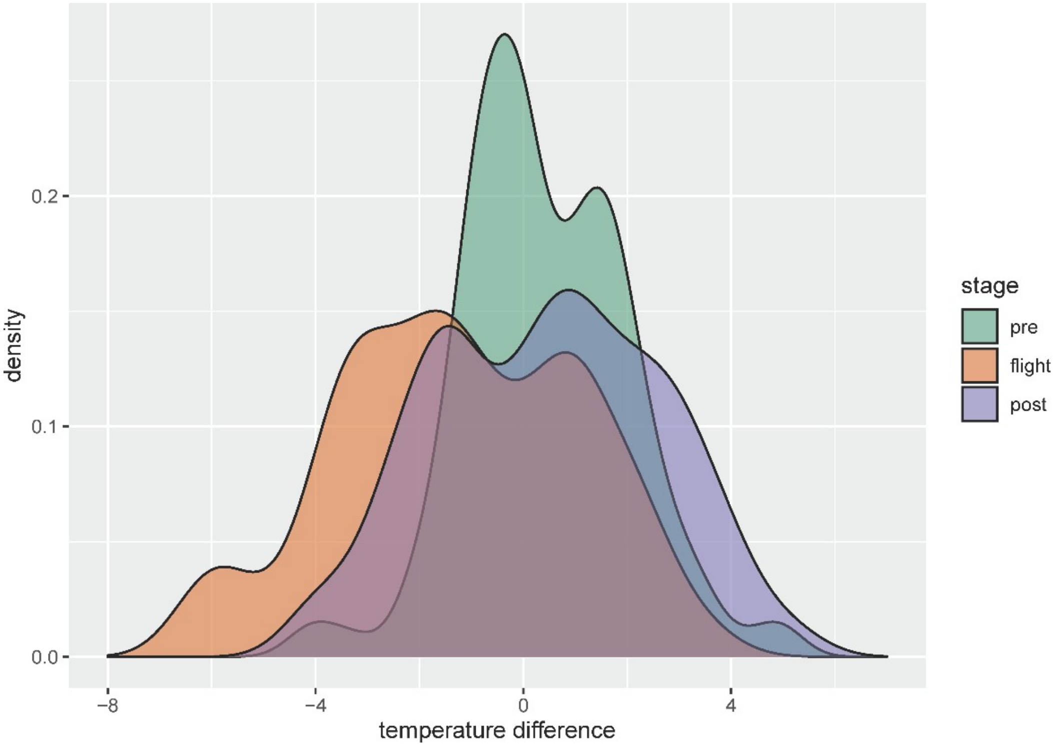

Figure 8 - Kernel density of temperature change (excluding SLC day 2 run 2).

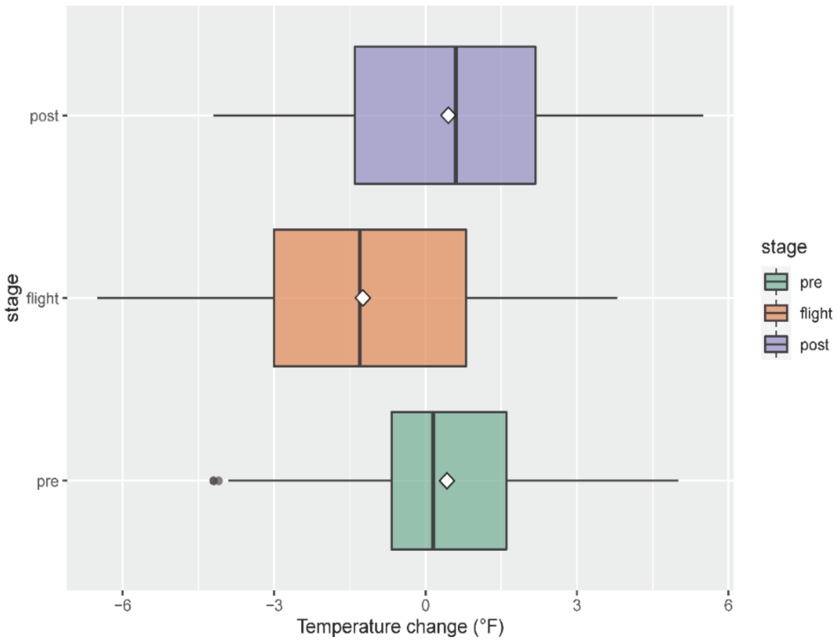

Figure 9 – Box plot of WBGT change, excluding SLC day 2 test run 2 (outlier).

Table 2. Tukey multiple comparisons of means with 95% family-wise confidence level

Stage	Temperature change	95% CI	Adjusted p-value
During Flight-Pre Flight	-1.7	-2, -1.3	< 0.001
Post Flight-Pre Flight	0.03	-0.35, 0.4	Approaching 1
Post Flight-During Flight	1.7	1.3,	< 0.001

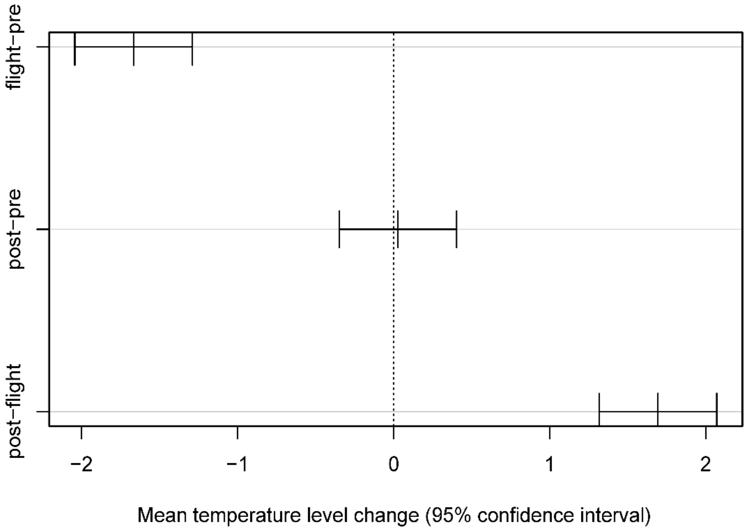

Figure 10 – Graphical representation of Table 2 data.

Particulate Matter Data and Results

The following graphs and tables provide the data and results for area PM values from the 12 pilot test runs. Figure 11 shows the area particulate matter concentration changes over time, by drone test run (for 12 of 12 total runs), while the kernel density of concentration changes is shown in Figure 12. As can be discerned from Figure 11, the PM values were all over the place, with no distinct trend or pattern. Figure 12 shows the distribution of particulate changes for each flight stage. 'Flight' particulates shift right compared to other time periods while demonstrating considerable variability.

The box plot in Figure 13 shows the same data but in a format that makes differences in mean, median, IQR, and outliers more apparent. The omnibus one-way analysis of variance (ANOVA) test shows a highly significant difference in means between at least two stages of the pre-, post-, and during- flight particulate change ($F(2, 2157) = 14.22$, $p < 0.001$). Tukey's HSD post-hoc test for multiple comparisons found that the mean value of particulate change was significantly different between during- flight and pre-flight ($p = 0.005$), and during-flight and post-flight ($p < 0.001$). There was no difference between pre-flight and post-flight. This is summarized in Table 3. In addition, a graphical representation of Table 3 is provided in Figure 14.

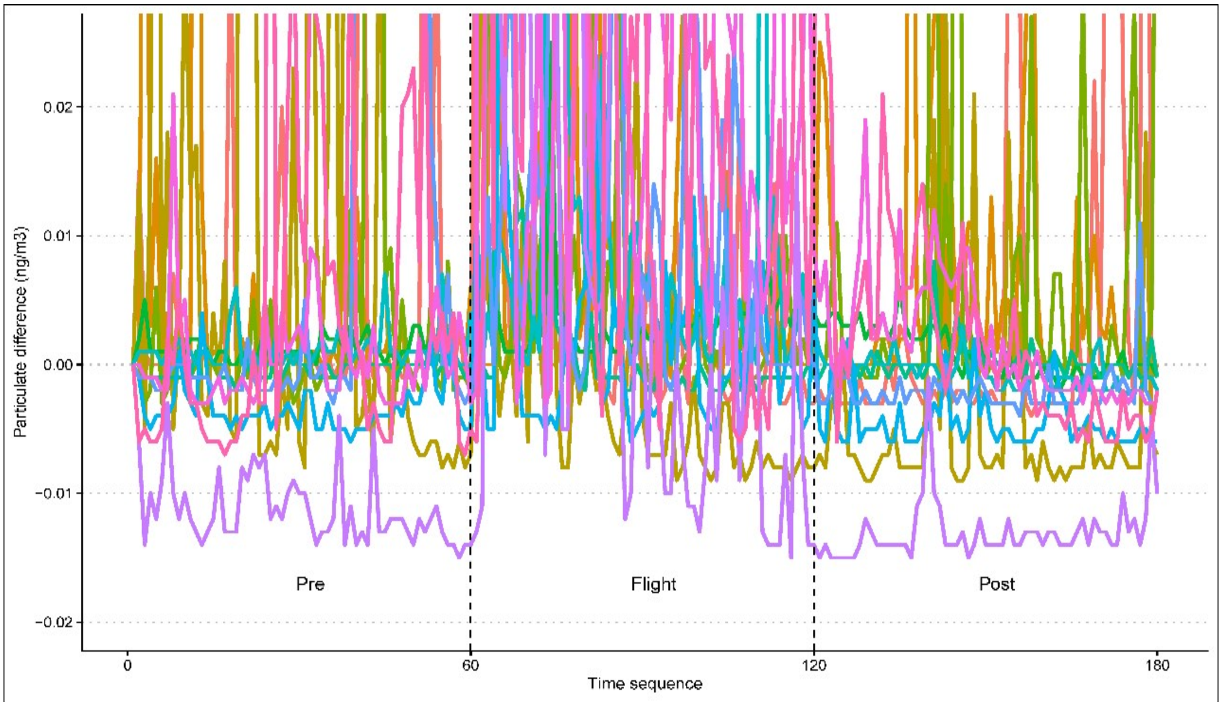

Figure 11 – Area PM concentration changes over time, color-coded by test run.

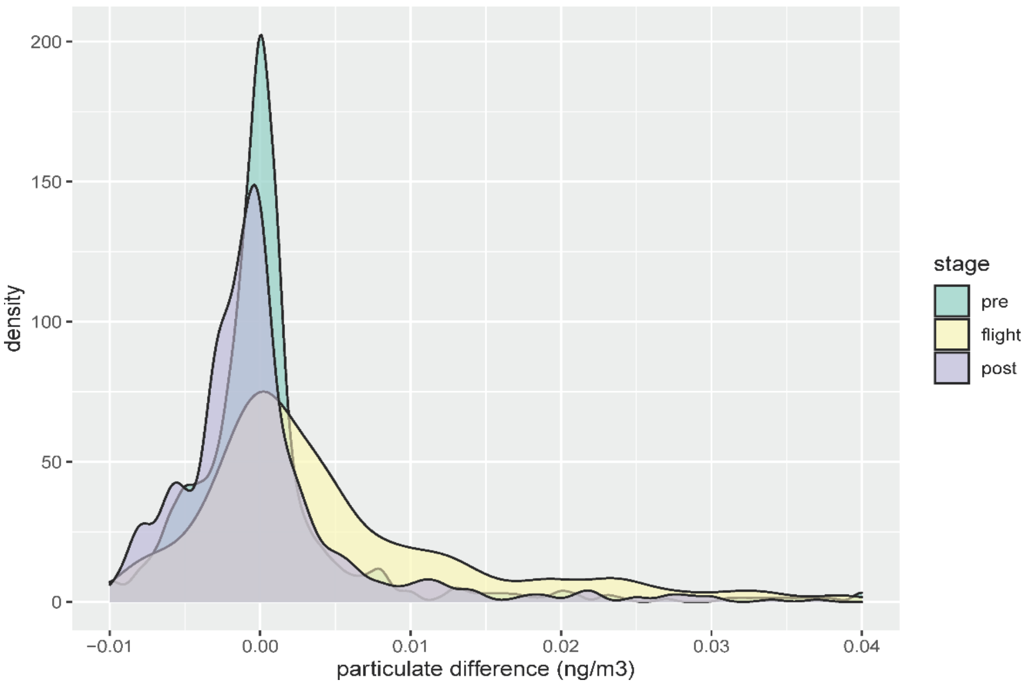

Figure 12 – Kernel density of PM concentration change.

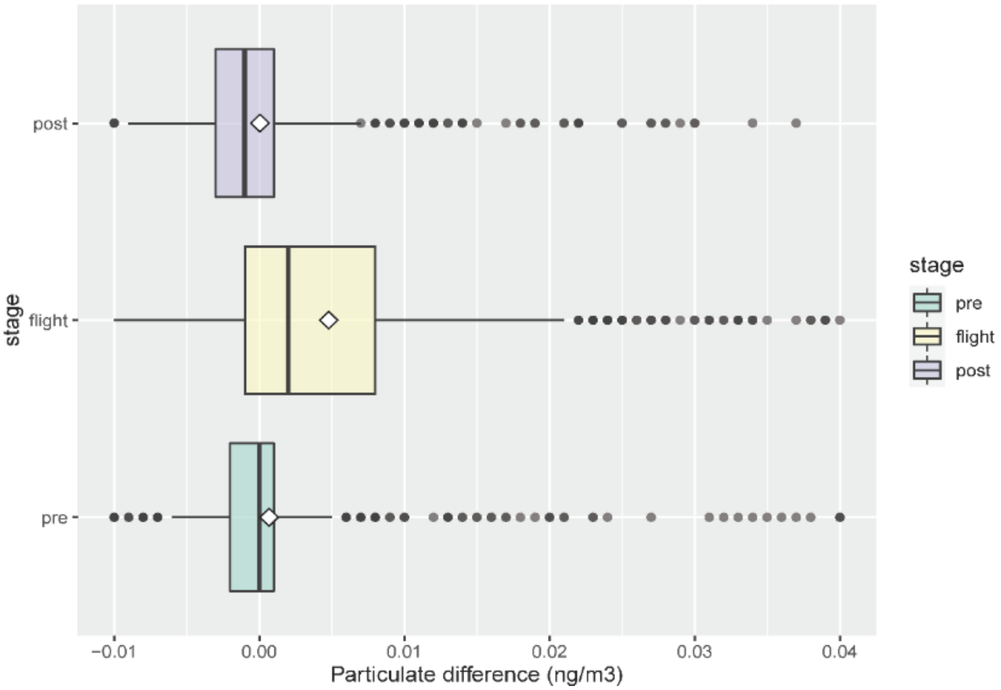

Figure 13 – Box plot of PM concentration change.

Table 3 - Tukey multiple comparisons of means with 95% family-wise confidence level

Stage	Particulate change	95% CI	Adjusted p-value
During Flight-Pre Flight	0.008	0.002, 0.014	0.005
Post Flight-Pre Flight	-0.006	-0.011, 0.0004	0.07
Post Flight-During Flight	-0.013	-0.019, -0.007	< 0.001

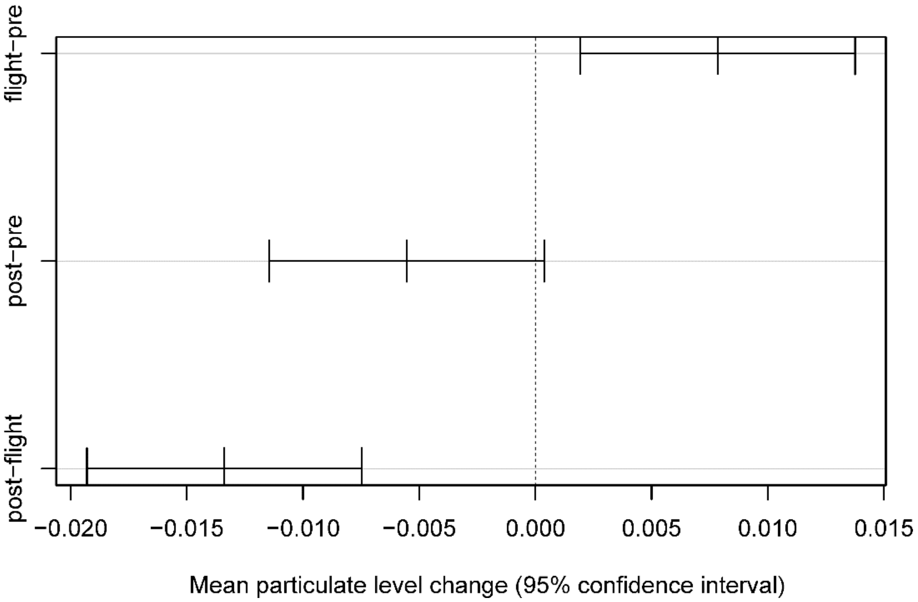

Figure 14 – Graphical representation of Table 3 data.

Changes/problems that resulted in deviation from the methods

The COVID-19 pandemic made the data collection aspects of this project very difficult. The University of Utah was on a travel restriction from almost the onset of this project up until July 1, 2021. Student and faculty travel was strictly prohibited for the majority of the time, allowed only under certain conditions and sign-offs. Thus, since St. George, Utah, is approximately 300 miles from the University of Utah campus, project activity was continued sporadically in the Salt Lake City area.

In addition to the pandemic and travel restrictions, the project had additional setbacks. Specifically, one of the graduate students working on the project unfunded had to leave our academic program due to family issues. Another significant setback involved one of the drones crashing, which demolished it. A second drone was lost in transit by FedEx and never found; it was determined to be theft. The final project drone used for the collection of field data arrived in the spring of 2021. The funded graduate students/drone pilots had to assemble and get comfortable with this drone for the summer 2021 data collection. We decided at that point to concentrate our efforts on a smaller construction area and to deploy only one drone per test run.

The sampling events conducted in Salt Lake City, at a residential construction site in university family housing, were accomplished successfully during the last week of June 2021. After travel restrictions were lifted on July 1, 2021, sampling was accomplished successfully during the last week of July 2021. While we did not get to sample during the hottest days/weeks of the year, we do feel that the days represent a good cross-section of the weather conditions normally experienced in southwest Utah and northeast Utah during the typical summer months.

To satisfy the data collection aspect of our original plan, we were also able to collect the same number of samples for both WBGT and PM by conducting multiple sampling test runs on the same days. While this was not what we originally planned to do, making these modifications helped to alleviate the risks associated with potentially not collecting the necessary data points because of ever-changing constraints imposed by the pandemic.

Future funding plans. If the findings appear to justify expansion of the research, the investigator(s) should indicate plans for such research and possible sources of additional funding

From the results of this pilot study, it seems reasonable to pursue additional funding for a more comprehensive study involving heat stress and construction workers. This is further backed up by recent issues involving global climate change, outdoor workers, and recent increases in chronic kidney disease manifested in workers employed in outdoor occupations [17]. Thus, it is the intention of this research team to use the findings of this project to support a NIOSH-CDC R21 submission in the near term (possibly November 2021 cycle, likely February 2022 cycle). At this time, it is not anticipated that PM characterization will be included as a part of this submission.

List of presentations/publications, completed and/or planned

Initially, there were two engineering doctoral students and one industrial hygiene master's student working on this project. As was mentioned earlier, the unfunded master's student had to leave the university because of family issues. Thus, the paper required from this student will not be submitted. The PI plans to at least submit one manuscript involving this study. This will be submitted to a journal in the Spring of 2022. The results from this pilot study will also be presented as a poster at a University of Utah graduate research event in the Spring of 2022. It is also anticipated that the engineering students will present their work at a civil engineering conference in the near term. The journal that will be chosen for the PI to present the findings of this pilot study will be *Construction and Engineering.* If the IH student returns to school in the near future, another submission to *Journal of Student Research* or the *Journal of Occupational and Environmental Health* (JOEH) will be made.

Dissemination plan

While the plan is to continue with this research, especially the WBGT portion, it is anticipated that this effort will be pursued over the next 5-7 years in various stages. This plan should allow for the advancement and improvement of drone battery technology. However, the following dissemination plan and potential dates of completion also includes this pilot project as well (1-2 years).

Plan Step	**Who/What/How/When?**
Purpose of the outreach?	To reach Construction Engineering and Management Professionals, Occupational Health and Safety professionals through conferences, trade shows, trade magazines, and peer-reviewed journals
The audience for the outreach?	Construction Safety, Occupational and Environmental Health, Occupational Medicine, Construction Engineering, Construction Management professionals
The message or messages to be shared?	Misting drones can be used to reduce the thermal stress experienced by construction workers during the hottest months of the year.
The methods for sharing the messages?	Health and Safety conferences and journals, Construction Safety conferences and journals, Occupational Medicine conferences and journals, trade magazines, trade shows
The timing for the outreach?	5-7 years; however, articles, presentations, and posters will be presented in the next 1-2 years
The process for evaluating the success of the dissemination effort?	The dissemination effort will be evaluated based upon the success of being able to secure additional funding from public or private resources (R21 to be submitted in February 2022) and the number of publications and presentations over the near-term (1-2 years) and long-term (5-7 years)

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