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Revisiting the use of globe thermometers to estimate radiant temperature in studies of heating and ventilation

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ABSTRACT

The globe thermometer has been considered a reliable instrument to quantify mean radiant temperature (MRT) since Bedford & Warner isolated its readings from air movement in their 1934 paper so that radiation could be quantified. Recent expanded use of radiant heating and cooling systems has presented new challenges for the usage of globe thermometers in the built environment by causing additional radiant asymmetries and performance expectations. Therefore, we replicate the original Bedford & Warner work to reconsider and develop a more holistic understanding of black globe performance and the determination of MRT in buildings. We recreate the MRT and air temperature separation to investigate the accuracy of globe thermometers on measuring MRTs. A radiantly heated open-plan laboratory and a radiantly cooled conference room were selected and measured with multiple globe thermometers and non-contacting infrared sensors. The globe temperature results were then corrected with air movement to produce MRTs and compared against MRTs simulated from measured surface temperatures. We demonstrate a significant impact of air speed on the MRTs obtained from globe thermometers. We also illustrate a less-investigated non-graybody emissivity variation and spatial variation of MRTs of up to 5 °C at the same height. We believe the increasing temporal and spatial resolution of digital sensors may create new challenges for using globe thermometers to measure MRTs, since fluctuating readings may camouflage potential MRT changes. Through a validation of our spatial MRT distribution with experimental results, we believe there is a need for better sensors that could spatially resolve MRTs, and recognize issues with both air speed and emissivity.

1. Introduction

Motivated by increased popularity of high performance radiant heating and cooling systems today, we revisit the study by Bedford & Warner in 1934 [1] because it presented the original method of determining mean radiant temperature (MRT) from a globe thermometer. Presently, the globe thermometer is the most common method of measuring MRT [2]. MRT is a widely used and important variable that helps quickly characterize the radiant heat transfer potential. MRT is defined in standards as the uniform temperature of a hypothetical and homogeneous black sphere that surrounds and exchanges the same amount of heat with a human body as the actual surroundings [3].

Bedford & Warner's work was the first to use globe thermometer readings to indicate MRT to represent radiant heat exchange while accounting for convective heat losses[1]. Such losses had challenged the initial developers of the globe itself [4]. Bedford & Warner's 1934 paper has been widely cited by some of the most prominent thermal comfort researchers as the seminal work to define this technique, including Fanger's comfort work in the 1970s [5] and in a contemporary extensive review of thermal radiation and comfort by Halawa [6]. This seminal paper has become so influential to the field that globe temperatures have become synonymous with MRT. In this original work with globe thermometers, much emphasis was placed on its sensitivity to convective air movement, but less so on emissivity or spatial variations. We aim to replicate the basic measurements done in the Bedford & Warner paper, and to use those results to produce critical new analyses of globe thermometer performance that address new aspects relating to convection, emissivity, and spatial variations.

To identify what could cause errors in replicating the original Bedford & Warner paper, we have structured our analysis as follows:

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- MRT measurements and errors presented by Bedford & Warner [1] and from our replication are compared.
- The influence of air speed measurements on corrections for convection are analyzed.
- The influence of the spectral complexity and variation of surface emissivity are measured.
- The spatial variation of MRT is derived analytically from surface temperature measurements and confirmed by multiple globe readings.

The motivation to replicate the MRT experiments stems from our own use of the same globe thermometers, and our desire to better understand the errors we have encountered as well as those we have observed in other contemporary work. We would like to situate these errors in the context of the origins of the measurement technique [1].

We provide a new critical perspective on the first model used by Bedford & Warner [1], correcting globe thermometer readings for air speed. There are many nuances to convective impacts on MRT as determined with globe measurement that should be considered.

Second, we believe emissivity of globe thermometers is not studied critically enough in the literature. Globe thermometers' emissivities were originally, and still often are, assumed to be a constant value based on grey-body emissions, which we critique through experimental analysis using modern IR imaging and analysis tools.

Finally, we believe spatial variation should be considered in MRT measurements. Historically, assuming MRT is invariant in a space has been a reasonable assumption. The reliance in this assumption is reinforced by commercial buildings with deep plans that are conditioned with all-air systems bringing the many internal partition walls and their resulting MRT close to equilibrium with the air. More recent buildings have begun to incorporate radiant heating and cooling systems, narrower floor plans with larger glass facades. This has led to complex sets of radiant environments that cannot be evaluated by the measurement from a single globe thermometer, and motivate our analysis of variation which considers both multiple globes in the context of Bedford & Warner and a novel contemporary computational analysis based on surface temperatures and room geometry.

Our objective is to improve our understanding of the dependability of MRT globe thermometer measurements by revisiting the first study that demonstrates the reliability of globe thermometers to account for MRT from Bedford & Warner in 1934 [1].

2. Background

Unlike its predecessors, i.e. the kata-thermometer [7] or the eupatheoscope [8], the globe thermometer was introduced by Vernon in 1932 [4] intended for measuring combined radiative and convective heat exchange with its environment. Vernon proposed a 6-in. (approximately 15 cm) diameter hollow copper sphere coated with matte black paint with a thermometer fixed at its center after comparing several options [9]. Intending to indicate a combined effect, Vernon did not attempt to quantify the convection individually in his research. Bedford & Warner addressed this topic by allowing the globe temperatures to be corrected with air velocity and air temperature to produce the mean black body temperature, which was widely cited afterwards for their work [10].

A globe thermometer is considered settled when it is in thermal equilibrium with its surrounding environment. Analytically speaking, this is a balance achieved between Q_{therm}, its heat exchange with the surrounding air and thermal environment, and the sum of radiative Q_{rad}, as well as convective Q_{conv}, heat exchanges, or as Eq. (1) states:

$$Q_{therm} = Q_{rad} + Q_{conv} \tag{1}$$

The net rate of radiative heat transfer between one surface with area A_S at temperature T_S, emissivity ε enclosed in a much larger surface at temperature of T_{surr} can be described with Eq. (2) [11]. The net rate of convective heat transfer can be described by Eq. (3) for an object with surface area A and a surface temperature T_a in contact with fluid at temperature T_b, using H_C to denote the convective heat transfer coefficient.

$$Q_{rad} = \varepsilon \sigma A_S (T_S^4 - T_{surr}^4) \tag{2}$$

$$Q_{conv} = H_c A (T_a - T_b) \tag{3}$$

Vernon also recognized that the time for his 6-in. copper globe thermometers to settle (or reach equilibrium) was roughly 15 min [4]. Smaller diameters were found to be helpful to reduce this settling/response time down to approximately 4 min. This significant decrease was believed to be caused by reduced heat capacity [12], but was also found to make globe thermometer readings more susceptible to changes in air temperature and velocity [13].

The concept of MRT was introduced in order to quantify the effects of complex radiant environments so that all radiation fluxes towards a human body could be accounted for. MRT is defined as the 'uniform temperature of an imaginary enclosure in which the radiant heat transfer from the human body equals the radiant heat transfer in the actual non-uniform enclosure' [3]. Mathematically, MRT can also be defined with Eq. (4), where the MRT for any point p in a given space can be calculated from the surface temperatures (T_i) and view factors (F_{p-i}) towards a surrounding surface i:

$$MRT^4 = T_1^4 F_{p-1} + T_2^4 F_{p-2} + T_3^4 F_{p-3} + \ldots + T_n^4 F_{p-n} \tag{4}$$

Bedford & Warner demonstrated the globe thermometer as a reliable piece of instrumentation to evaluate a radiant environment in 1934, when they used the globe thermometer to estimate the MRT and the equivalent temperature, an estimation of the combined effect of convection and radiation on an occupant [1]. Previous measurements of equivalent temperature and radiation effects required more complicated and bulky equipment such as the eupatheoscope, which is the size of a seated human. The scale and simplicity of the globe thermometer made it a valuable apparatus to account for incoming radiation for the thermal comfort studies all the way up through the 1970s [14], and it gained significant recognition among thermal comfort researchers when de Dear published a mathematical model that accounts for globe diameter as an input to obtaining MRT in 1987 [15]. de Dear's model was further validated and improved in 2007 [16].

MRT is recognized in the outdoor environment domain as an indicator of thermal comfort and energy balance [17], urban environment [18,19], and is a predictor of mortality [20]. Its spatial variation has been modeled to evaluate urban environment [21], which is important since outdoor globe thermometer measurements must also account for highly variable solar radiation at much shorter wavelengths. The lack of analysis of globe thermometer variation in the indoor environment could be partially attributed to the nature of indoor surfaces being lower temperatures and seeing much smaller fluctuation of temperatures. Walikewitz et al. investigated the differences between air temperature and MRT under different solar irradiation scenarios and looked at temporal rather than spatial change of MRT [22]. Even for research that focused specifically on the globe thermometer and the MRT it measures, the authors referred to their results as 'the enclosure MRT', hinting at their assumption of MRT being singular to a given 3D space regardless of the point of measurement [23].

Within the thermal comfort domain, it is increasingly common to conduct Fourier Transform Infrared (FTIR) Spectroscopy to fully characterize the radiant exchange of non-gray body emitters with their surroundings. The tool allows for the precise quantification of a material's absorption, transmission, and reflection of radiation within the measured domain. For a black globe, the precedent has been to measure the hemispherical emissivity, as described in the Bedford & Warner [1] paper, the value of which is used to back calculate the MRT when air velocity is present. However, emissivity is sensitive to a number of components lost when computing onlt the hemispherical averages such as the temperature and wavelength dependence of emissivity in general. Thus, it becomes something not quantitatively considered in the literature even when including additional transparent materials to isolate globes from convection [24]. In general, the sensitivity of a black globe to spectral properties appears to be unstudied, and is another important source of error that could be considered.

MRT has been widely used in indoor [25] and outdoor environments [16]. Generally in both outdoor and indoor environments it is difficult to assess the wide variety of potential spatial variations in MRT. Tredre [26] suggested it was unnecessary to investigate the MRT with multiple globe thermometers in a space, if its MRT variation is below 2 °F (1.1 °C). For outdoor environments, spatial MRT variation could be anywhere from 10 to 20 °C [27] and could go as high as 38 °C[28]. For indoor environments, MRT variations are usually much smaller and very close to air temperature [22,29], particularly in cases without radiant asymmetry [30].

The definition of MRT clearly states that different locations in spaces will lead to different surface view factors that impact MRT. More recent works have also considered spatial variations, but require significant computation [31], and are hence rarely pursued further beyond localized thermal comfort studies in full-scale experiments such as desk-based investigations [32]. MRT remains limited by the sensors used to measure it. Additionally, the semantics of a *mean* radiant temperature led a significant number of researchers to misinterpret MRT as a value representative of an entire space. Similarly, those more familiar with MRT assumed that the variation through space was very small and it was not necessary to take multiple measurements with globe thermometers [26].

3. Methodology

3.1. Original setup

Bedford & Warner used data they had collected in factories "with various systems of heating and ventilation" from globe thermometers of 6 in. diameter copper spheres painted matte black. A variety of measurements were taken in both cold and warm environments in proximity to various types of heat sources. At each observation point, a globe thermometer was set to obtain readings along a silvered kata-thermometer to derive air movement and a mercury thermometer to measure air temperature. A Moll thermopile was used to validate the performance of the globe thermometer. The Moll thermopile, as described by Bedford & Warner, was directed "in turn to every part of the sphere surrounding the observation point," and had its readings averaged for the mean intensity of radiation. These values were then used to calculate the "mean intensity of radiation," which Bedford & Warner considered representative of the mean black body temperature through correlations and graphical tools described in their paper. With 221 sets of observations comparing the globe and thermopile, Bedford & Warner managed to support their argument that the globe thermometer is a reasonably reliable instrument to estimate the mean radiation from its surroundings. We attempt to replicate this setup with contemporary tools and to further question the sensitivity of the device.

3.2. Replication experimental setup

We perform a replication of the investigations described in the Bedford & Warner studies by setting up globe thermometers in radiantly heated and cooled real building spaces. We have access to digital temperature data loggers along with digital air speed sensors and air temperature sensors in order to correct for convective exchanges, which were not available in the 1930s.

In this experiment, we constructed three globe thermometers with the 6-inch copper spheres spray-painted matte black (245198, Rust Oleum) on the outside. A 100K thermistor (NTC 3950, Artillery) was fixed inside the sphere with analog temperature data being read back into a micro-controller board. This micro-controller board also collected data from an air temperature (DHT22/AM2302) and wind speed sensor (MD055, Modern Device).

The three globe thermometers were first placed in a room where the airflow was minimal ($v_a < 0.01$ m/s) with a negligible change of surrounding surface temperatures to calibrate against each other. The readings from the globe thermometers were fairly consistent and had acumulative 0.8% accuracy when compared at a by-the-minute scale, and an even better 0.3% when compared against each other with five-minute intervals.

We investigated the reliability of globe measurements in a similar manner to Bedford & Warner by averaging radiation from all directions, but using a more contemporary digital thermopile system. We measured surface temperatures with non-contacting infrared thermometers (MLX90614, Melexis). Beford & Warner described their method for using a single Moll thermopile in a 1933 paper to measure MRT, "The thermopile is mounted on a suitable stand and observations are made with the instrument pointing in turn to all parts of the sphere surrounding the point of observation" [33]. The same method is referred to in the subsequent globe thermometer paper that we are replicating [1], but did not provide elaborate explanation on the timing, mechanical control, or geometry of the environments scanned. We expand this technique in our analysis by specifically measuring surface temperatures as output directly from the Melexis sensor and combining them with the known geometry of the space. This enabled us to directly calculate MRTs to be compared with the corrected MRTs from globe thermometers at their known locations in the experiment locations, providing a similar final comparison for validation as was done by Bedford & Warner [1].

3.3. Replication location

We did not have access to highly variable thermal environments of factory settings from the 1930′s, but instead used two spaces with contemporary radiant heating and cooling systems. A workshop-style laboratory space was selected (as indicated in Fig. 1) to best replicate their experimental setup in several factories back in 1934. The laboratory is 90 ft (27 m) long, 50 ft (15 m) wide and 12.75 ft (4 m) tall with radiantly heated floors on both sides of the central loading area. The multiple globe locations are shown in 1. For a cooling scenario, a conference room with ceiling panels for radiant cooling was selected, measuring 5.2 m wide, 7.3 m long and 2.9 m tall. In this case a simpler setup in the standard conference room was used with a single globe.

During the heating scenario measurements, to provide additional variation of the air temperature profile of the space, we opened the front and rear hangar doors of the laboratory intermittently during measurements to increase the separation between the air temperature and globe thermometer readings. We acknowledge the potential errors that can be caused by the resulting convection and attempted to minimize those errors through extended settling periods ($\geq$ 15 min).

Fig. 1. Laboratory space for a majority of the heating experiments (photo), schematic indicating locations of globe thermometers (top left inset), and schematic of globe thermometer (right).

3.4. Black globe analysis of sensitivity to air velocity

Bedford & Warner adopted an empirically derived relationship between convective heat exchange and air velocity using data from a 6 inch silvered globe (low emissivity, mostly convective exchange) and a 6 inch blackened globe (high emissivity, mixed radiant and convective exchange). The relationship was developed using IP units as described in their paper [1], and is shown in Eq. (5) where T_S represents Bedford & Warner's MRT in absolute Fahrenheit scale (i.e. Rankine scale), T_G is the absolute temperature measured at the globe (also in Rankine scale), V is the air speed in fpm, and $(t_g - t_a)$ is the temperature difference measured between the air and the globe in Fahrenheit.

$$T_S^4 \times 10^{-9} = T_G^4 \times 10^{-9} + 0.1028\sqrt{V}(t_g - t_a) \quad (5)$$

We compared the method above to a contemporary method suggested by de Dear [15] that does not simply correlate to the root of air velocity, but takes the velocity to its 0.6 power, and includes a correction for globe diameter. The MRT, or $\mathrm{T_{mrt}}$, can be calculated as a function of globe temperature $\mathrm{T_g}$, air temperature $\mathrm{T_a}$, globe's mean convection coefficient ($\mathrm{h_{cg}} = 1.1 \times 10^8 \times v_a^{0.6}$) in $W/(\mathrm{m^2\ K})$, air velocity v_a in $m/$s, emissivity ε, and diameter of sphere D in m. All the temperatures in Eq. (6) are in Kelvin.

$$\mathrm{T_{mrt}} = \sqrt[4]{\mathrm{T_g^4} + \frac{\mathrm{h_{cg}}}{\varepsilon \times D^{0.4}} \times (\mathrm{T_g} - \mathrm{T_a})} \quad (6)$$

We used the more contemporary Eq. (6) to correct our globe data for air speeds, but we also filter out data with high wind speeds. We discuss higher air speed data to broadly consider the impact of air speed on globe thermometer determination of MRT.

Bedford & Warner referred to their error calculation method as using 'average error'. We attempted to replicate this by taking the absolute value of the difference between the two MRTs (one from globe thermometers and the other from our simulations), which are then grouped into different subsets in a table by the MRT and air temperature separation.

3.5. Black globe analysis of sensitivity to surface emissivity

Correcting for convection from varying air movement around the globe was the principle challenge to overcome in the Bedford & Warner work [1], where they assumed emissivity was an assigned constant. Emissivity of the matte black globes as defined by Vernon in 1932 [4] historically assumed black body conditions with spectral distributions obeying Plank's law of blackbody radiation. This blackbody emissivity was estimated for the black paint by Bedford & Warner to be 0.95 [1], and was adopted in many subsequent studies [15]. To test the effect of black globe paint preparation on the radiant heat transfer between a black globe and its surroundings, we conducted FTIR analysis on two copper samples from the standard 6-in. spherical globes. This allows investigation of both the real emissivity, and the non-blackbody spectral variations by breaking down the results across wavelength or wavenumber.

On one sample, one coat of matte black paint used on the globes was applied and allowed to dry. On the second sample, two coats of the same paint were applied, and allowed to dry in between each. Visual microscopy was first used to locate regions on each sample to determine areas of visibly homogeneous areas of coverage. Using a Nicolet iN10 MX to do FTIR analysis, we scanned each sample in reflection mode to calculate the reflectivity of each material at each wavenumber, λ, from 675 to 4000 $\mathrm{cm^{-1}}$ (2.5 to 15 μm) in 3.86 $\mathrm{cm^{-1}}$ increments. Transmissivity of the material at each wavenumber was confirmed to be 0. Therefore, reflection and absorption can be equated as in Eq. (7) where α is absorptivity and ρ is reflectivity.

$$\alpha(\lambda) = 1 - \rho(\lambda) \quad (7)$$

Invoking Kirchoff's law to obtain the emissivity $\varepsilon(\lambda) = \alpha(\lambda)$, the emissivity of each painted copper sample is obtained at each wavelength. This raw emissivity spectrum is then multiplied by the spectral radiance at each wavelength in $Wm^{-2}sr^{-1}\mu m^{-1}$ of a true black body emitter at 300 K. The resulting spectral radiance curve is then integrated to obtain the true radiative power of the black globe in $Wm^{-2}sr^{-1}$. The steradians, *sr*, represent the view factor of the globe with its surroundings, which assuming Lambertian emission is π. To obtain the hemispherical emissivity of the globes, this value is divided by the radiation received by an ideal black body emitter at the same temperature.

Once the hemispherical emissivity is obtained for each sample, ε_2 and ε_1, for the double and single layered paint samples, respectively, the error introduced by any emissivity difference is quantified. In the absence of convection, i.e. $v_{air} = 0$, at equilibrium, there is no net radiative flux, or $Q_{rad} = 0$. When this is true, as shown in Eq. (6), $T_{MRT} = T_g$. Therefore, the radiant exitance between each globe and its surroundings must also be equivalent, shown in Eqs. (8) and (9).

$$\varepsilon_{MRT} T_{MRT}^4 = \varepsilon_2 T_{globe,2}^4 \tag{8}$$

$$\varepsilon_{MRT} T_{MRT}^4 = \varepsilon_1 T_{globe,1}^4 \tag{9}$$

It is noteworthy that as shown in both equations, T_{MRT} is only equal to T_{globe} when their emissivities are the same, a correction not currently used in the literature. Since the left hand side of each equation is the same, we can similarly equate Eqs. (8) and (9) to compare the relative difference of each globe temperature, shown in Eq. (10).

$$\frac{T_{globe,2}}{T_{globe,1}} = \sqrt[4]{\frac{\varepsilon_1}{\varepsilon_2}} \tag{10}$$

This relationship can then be used to determine the relative error of each globe's reading in the same environment when their hemispherical emissivities are different, and holds true to the globe temperature readings when there is no air movement.

3.6. Computation of spatial MRT

Bedford & Warner would have observed spatial variation from their thermopile "pointing in turn" around the space, but the data was only used to generate an average radiation input. We measured surface temperatures with infrared thermometers in different directions to compile a model of the variation in all surrounding surface temperatures. We calculated how those surfaces would define the MRT not just at the point from which the surfaces were measured, but for any point in the space.

Our infrared thermometer has both an IR sensitive thermopile detector chip (MLX81101, Melexis) similar to a Moll thermopile and an Application Specific Signal Processor (MLX90302, Melexis) built in for low noise amplification for direct digital output. A strength of our sensor is that it processes the object surface temperature digitally. The limitation is that these digital calculations are hidden inside the on-board circuitry and may be both empirically and analytically derived. The ambient temperature or device temperature is used in the derivation, but is proprietary to the Melexis sensor. Bedford & Warner only measured the radiation from surroundings via Moll thermopile with periodic measurements, producing intermittent point-specific MRT measurement. Our method allowed data to be recorded continuously and further interpreted through a simulation algorithm whose outputs are spatial MRTs at a resolution of 0.02 °C.

To calculate the spatial MRT variation and compare the points of globe thermometer measurements the laboratory is simplified into a rectilinear form with coherent surface temperatures. The spatial information was obtained from floor plans of the laboratory and converted into a collection of rectangles. The laboratory space was abstracted into a box consisting of a total of eight different rectangles. This includes the ceiling, walls, and the floor, which had two separate zones of radiant heating as shown in Fig. 2. The different surfaces are given homogeneous temperatures by averaging the surface temperatures that were measured. With a known geometry and the temperature information for all surfaces, the MRTs can be calculated as a 3-dimensional matrix in the space.

To evaluate the MRT at any given point in the space through the simulation algorithm, each of the rectangles was assumed to be of homogeneous temperature and split into two triangles enabling triangular solid angle calculations. The MRT can be calculated by the combination of resulting view factors using Eq. (4).

4. Results and discussion

4.1. Replication of MRT measurements

Revisiting the methodology from Bedford & Warner which compares a new method to evaluate MRT to the prevailing method, we summarized our results in Table 1. To keep the results consistent with the Bedford & Warner findings, the temperature units were converted to Fahrenheit to follow the 1934 publication.

Bedford & Warner categorized their results into different subsets with $MRT - T_a$ values. As T_g was often considered the equivalent of MRT, many studies on radiant systems identified $T_g - T_a$ to be within ± 2 °C [34,35]. This is consistent with what we found in this experiment using continuous measurement and focused on reproducing this separation of T_g and T_a (or in the case of the Bedford & Warner original study, MRT and T_a) to get more data points within the ±2 °C range.

Examining Table 1, the discrepancies between the reference and sensors were significant. While the original Bedford & Warner study had errors averaged at 1.36 °C, our revisit exhibits an averaged error of 1.02 °C. The amount of observations were, however, relatively inconsistent. All the measurements were fully automated in our experiment with a prolonged period of continuous measurements. Taking 8-minute averages, this was 1198 observations, which was much higher than the original 221 from Bedford & Warner.

4.2. Influence from air velocity

Air velocity demonstrates a significant influence on the MRTs calculated from the globe thermometers based on Eqs. (5) and (6). The convective losses as calculated for the correction of a globe by both Bedford & Warner in 1934 [1] and improved by de Dear in 1987 [15] are compared in Fig. 3 for the standard 6-inch globe. It is worth noting here that one of the most important contributions of the Bedford & Warner paper was the development of a robust correction for convection from air movement, which is what allowed for direct measurement of MRT from a black globe and subsequently became a universal method.

Comparing the Bedford & Warner convective heat exchange term from Eq. (5) ($H_C = 0.169\sqrt{v}(t_g - t_a)$) to what we used from Eq. (1) ($H_C = 2.5v^{0.6}$, converted to IP units), we obtained Fig. 3. The convective term we used in this study would probably reflect the convective heat transfer better comparing to what Bedford & Warner used since the influence of air velocity on the MRT estimation is less pronounced. This overestimation of convective heat loss by the Bedford & Warner model could lead to overestimation of MRT.

Currently, both ISO and ASHRAE adopted the calculation in Eq. (6) [3,36], effectively endorsing the globe thermometer as a reliable instrument for MRT measurement [37]. Recent studies, however, have noticed possible overestimation of MRT using Eq. (6) [38]. Our comparison of the past and present methods helps situate the relative improvement and sensitivity of these methods.

Both corrections demonstrate a direct sensitivity to the air velocity. These plots emphasize the fluid dynamic relationship between the globe temeprature and air velocity, but the other important factor is the difference of globe temperature and the air temperature. As the air temperature equilibrates with the globe temperature the actual convective loss clearly reduces to zero. However, two degrees of separation with moderate air velocities of 100 fpm (0.5 m/s) can influence the sensitivity of the globe temperature readings by more than 3 Btu/h/ ft^2 (10 W/m^2), resulting in the globe thermometer measurement only acccounting for 90% of the reading, with the other 10% corrected by convection. Clearly, as air speeds increase, causing the globe temperature separation to

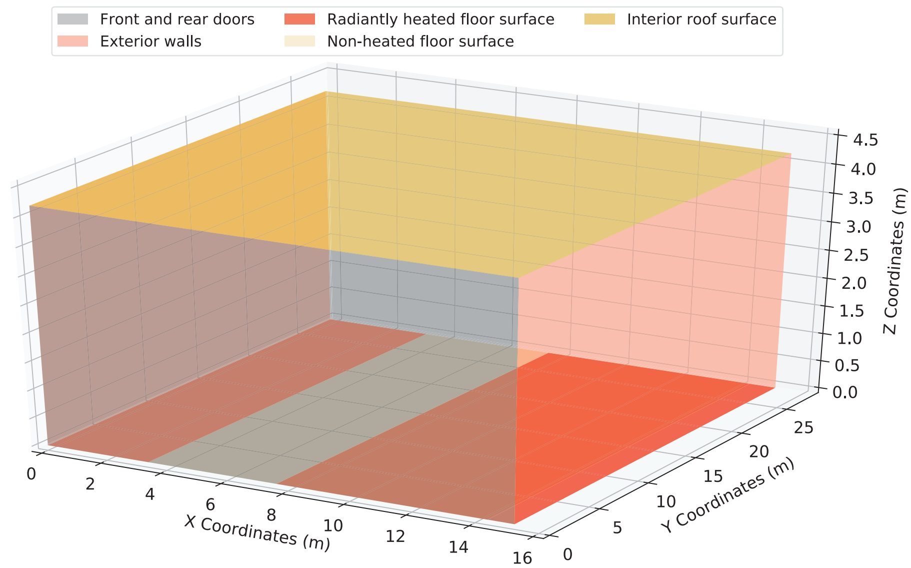

Fig. 2. Abstract representation of the laboratory space in 3D with its surfaces at different temperatures.

Table 1
Comparison of differences in value between MRTs from globe and infrared sensor between the Bedford & Warner study and this work.

Mean black body temperature (thermopile value) minus air temperature (°F)	Number of observations (Bedford & Warner)	Average error made in estimating MRT (°F) (Bedford & Warner)	Number of observations (This study)	Average error made in estimating MRT (°F) (This study)
-6.0 to -4.1	4	1.23	94	2.32
-4.0 to -2.1	13	1.06	248	0.91
-2.0 to -0.1	19	0.59	311	1.01
0 to 1.9	76	0.94	393	0.57
2.0 to 3.9	57	1.48	68	0.92
4.0 to 5.9	30	1.16	41	0.95
6.0 to 7.9	11	1.50	21	1.93
8.0 to 9.9	5	1.20	13	3.24
10.0 or over	6	3.08	9	4.22

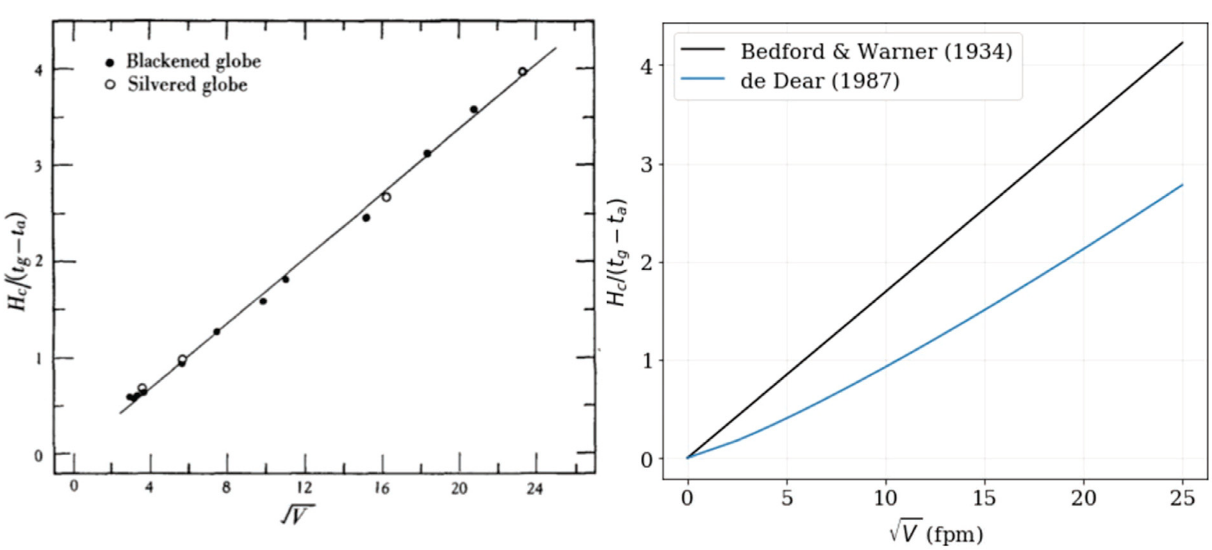

Fig. 3. At left is the original plot from the Bedford & Warner paper [1] confirming the correlation for the non-emissive (silver) and emissive globes (black) for convective losses. At right is the comparison of the convection loss calculation method by Bedford & Warner and de Dear[15] with convection loss in $Btu/hr/ft^2$ normalized by temperature difference in °F from globe t_g to air t_a and with square root of velocity in fpm (feet per minute).

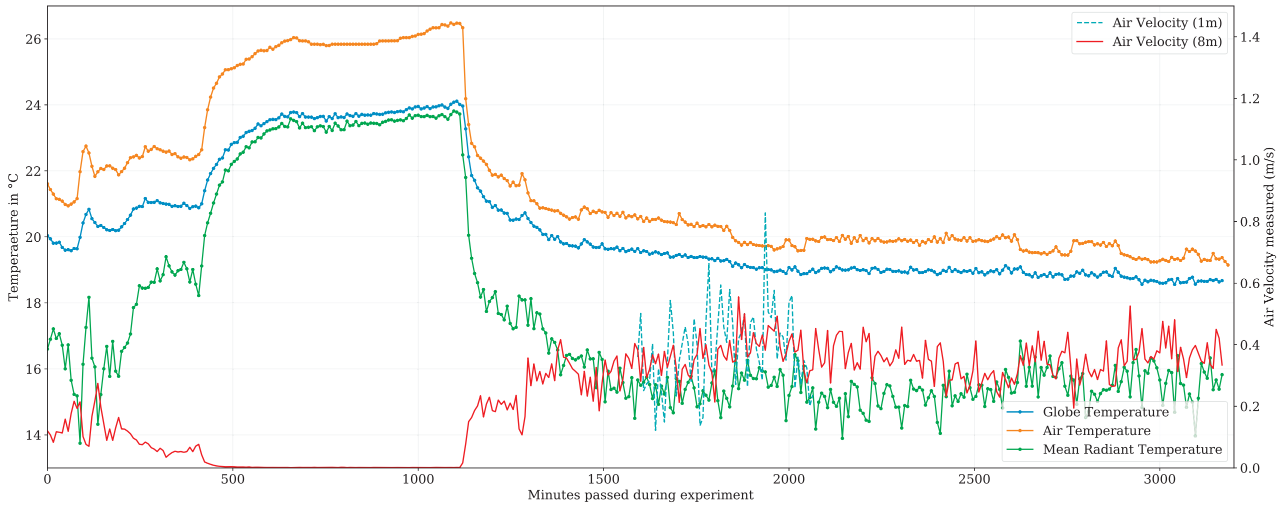

Fig. 4. Temporal rate of change of globe temperature and resulting MRT from GT2 after accounting for air velocities.

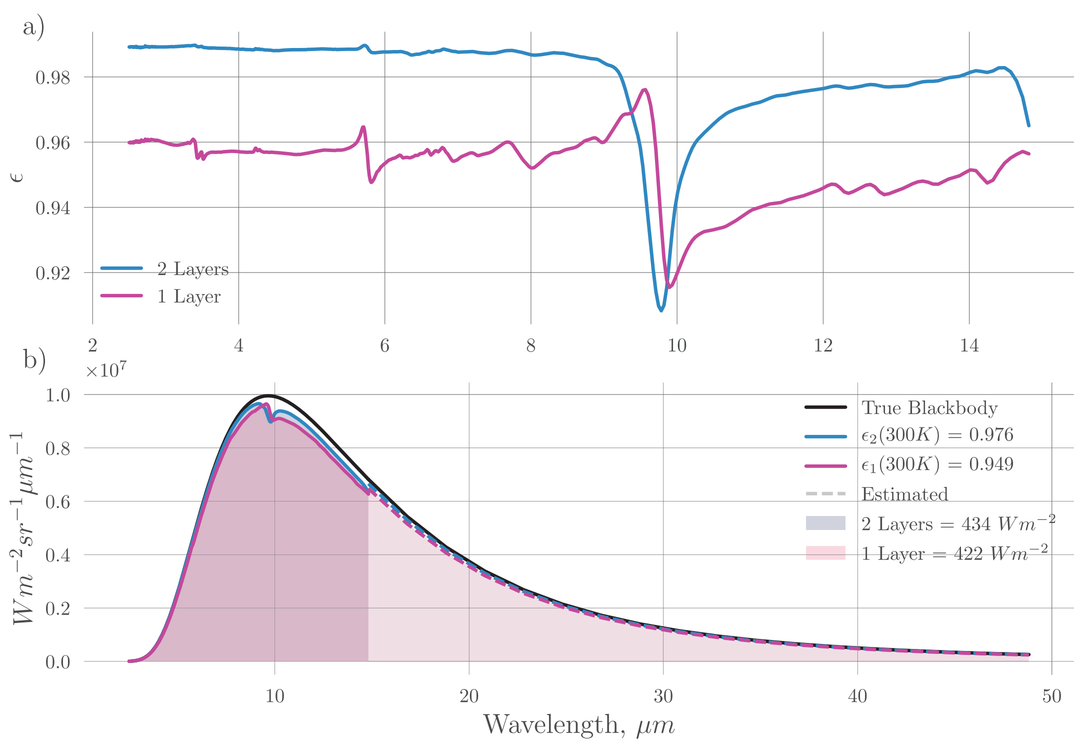

Fig. 5. Emissivity (top) and spectral radiance (bottom) of black globes with one and two coats of matte black paint, thin and thick, respectively.

be lower, the correction causes the reading to become highly dependend on the air speed. Therefore for this reason, it can often be challenging to use globe thermometers outdoors. For globe temperature separation at five degrees, the sensitivity to even small air movements of 20 fpm (0.1 m/s) are significant. This resulted in our decision to remove these influences in the replication data in Table 1. In this experiment, we finalized results in Table 1 by filtering out measurements with large air velocities above 0.1 m/s and averaged our measurements, i.e. both globe temperature and air velocities in 8-minute intervals. Bedford & Warner did not present the full set of air velocities used in their paper, but they do mention a similar settling time on the order of 15 min for the black globe, which substantiates our decision to take 8 min averages.

In Fig. 4, we plot a set of data with higher air speeds from the temperature of the globe thermometer and calculated MRT from a set of replication measurements. The air velocities during the cooling experiments were minimal reading nearly 0 m/s during the experiment, which was typical for the steady state measurements used for the replication data. In Fig. 4 the MRT predictably agrees with globe temperature readings with no air movement. The rest of the measurements, however, show the clear and significant separation between the globe temperature and the calculated MRTs corrected using the de Dear Eq. (6). For air velocities that are above 0.1 m/s but still below 0.2 m/s, the drop from globe temperature to the resulting MRT is still significant at 1.13 °C. Clearly the lack of an accompanying air velocity sensor can easily lead to error in MRT measurements, even for small air movements. We also plotted a small portion of the air velocity measurement with a 1 minute average, instead of 8 minute average in Fig. 4 to show how noisy the data becomes. Using smaller time intervals would therefore be undesirable since noisy air velocity readings could camouflage potential MRT changes.

Using air velocity as a filtering criteria may also be problematic because the moments of drastic convective heat loss that are removed could be significant. This applies in our experiments in particular for the interventions of opening the exterior doors, which allowed wind of more than 1 m/s to enter. Also the buoyancy-driven natural convection caused by the very warm floor below the cold air after the doors were closed can also generate high air velocities. This brings us to an interesting question of whether the globe thermometers have a preferable range of air velocities. Existing standards [3,37] do not provide a range of air velocities it should work within. Existing guidelines of globe thermometer usage recommends only steady state measurement after the globe. It should be in thermal equilibrium with the surrounding environment. But under many air movement conditions, and as shown in our data in Fig. 3, there is significant potential for the air speed signal to have a much larger impact on the resulting MRT than on the globe temperature reading. This is particularly relevant with low air speeds below 0.5 m/s that contemporary hot point anemometers are less sensitive to. Transient convective heat transfer between globe thermometers and the surrounding air could still significantly affect the calculated MRTs in ways not considered in standard methods. In addition, in all the scenarios of transient door opening and closing the air temperature may also differ hence the air temperature sensor placement becomes important. The actual change of air velocities also does not affect the black globes linearly over time, and so simple averaging out the fluctuation with longer time periods will not accurately reflect the effect of opening/closing.

Since Bedford & Warner did not elaborate on the actual air velocities of their experiment, we were unable to more accurately account for the actual errors in the calculation of MRT caused by overestimating the convective heat loss as indicated in Fig. 3. Since according to our own experimental observations, the larger separation between the globe and air temperature is often more obvious when the air velocity is present, i.e. when the MRT needs to be corrected with the convective heat loss. Observing our data it is clear that with high difference between globe and air temperature, the MRT output from a globe thermometer becomes heavily dependent on the correction from the air speed sensor. ISO 7726 standard approached this issue by suggesting a large inaccuracy interval of ± 5 °C arising from a globe thermometer assembly's sensor inaccuracies, and demonstrates the need for a globe thermometer to have an accuracy within ± 0.2 °C. There has yet to be a standard that clearly describes this intricacy in the measurement.

Fig. 4 also shows the variability in the hot point anemometer readings we measured both as 8 minute averages and as a small section of the full data from the sensor. Hot point anemometers are another important new tool to allow for quick measurement of air movement. This was what de Dear used to measure air speed for the development of the new model [15], and also what we used for our experiment. The response time of these sensors is much faster than the globe thermometer. Therefore, although this is a more advanced technology for measurement, it in fact creates a problem when combined with the globe thermometer. The real effect over the settling time of a globe thermometer as defined by the air speed measured hundreds of times over the course of its settling time does not easily lend itself to correcting for the convective losses from the globe thermometer. This would require a complex fluid dynamic model integrating the varying speeds measured over the course of the settling time.

The original Bedford & Warner results may in fact be less affected by this problem. The analogue silvered kata thermometer system used to determine air speeds for convective losses had both a similar geometry as the black globe thermometer as well as a similar settling time. The device therefore outputs the real convective losses under a physical condition analogue to that experienced by the globe thermometer. As such, the contemporary methods used by de Dear [15] and by this replication may in fact be more problematic in how they correct convection with globes.

The caveat to this error is that the silvered kata thermometer, although similar to the black globe in geometry, only approximated a limited emissivity. Likewise, the globe does not represent an ideal blackbody emissivity condition. These sources of error are not considered by either Bedford & Warner or in contemporary black globe MRT calculations.

4.3. Emissivity and non-blackbody sensitivities

We investigated the sensitivity of MRT results from globe thermometers through FTIR analysis of both emissivity and blackbody spectra from typical black globe paint. Fig. 5(a) illustrates the variation of emissivity from one to two coats of matte black paint. Matte black paint is commonly specified in black globe thermometer measurements, but such a minute difference of coat number is not specified, and in practice to obtain visibly full coverage several coats is often required. Emissivity and spectral radiance charts were created that show a significant difference that could affect globe thermometer readings.

Fig. 5 demonstrates the different spectral properties of two finishing options. The two coating options are clearly not an exhaustive list of possibilities, but rather illustrate the dependence of radiative exchange between the globe and its surroundings based on very simple changes in surface finish. The copper with double coating exhibited a hemispherical emissivity, ϵ_{hemi} of 0.976, while a single coating exhibited ϵ_{hemi} of 0.949. As demonstrated in Eq. (10), the emissivity difference would introduce an error of $\sqrt[4]{0.949/0.976} = 0.993$. This means, the temperature readings of each globe in K would differ by up to 0.7%, or 2.1 °C at 300K. This is quite a significant error based entirely on radiant heat transfer physics, especially considering the finishing options tested are representative of variations common in the contemporary and historical preparation of black globe thermometers.

Hemispherical emissivity though, was recognized as a variable to control in original MRT work. Using FTIR we point out that the hemispherical emissivity is potentially a source of error from surface properties. Emission does not always follow a perfect blackbody curve. Fig. 5b also reports the results from the FTIR of the effect that the spectral emissivity has on the radiative power (emission at each wavelength or wavenumber). The results for globes painted with one and two layers show a significant change in spectral emissivity with a significant anomaly around 10 μm. By integrating the true spectral radiance curve and multiplying by π, the radiant exitance at the surface of the standard globe would change from 422 to 434 W m^{-2} from an additional coat of black paint. Of course this is particular to two rather arbitrary applications of paint, a difference on the order of 12 W m^{-2} over the entire globe's surface area is significant enough to cause the 0.7% measurement error. Over the 0.079 m^2 of actual globe surface area, this equates to a 0.95W difference of radiant exitance between the two globes.

Further, as the temperature of the globes shift, the hemispherical emissivity value changes as a function of temperature, incurring further error. This can be confirmed from the FTIR data, which shows the black paint is not a true gray body emitter. Such an error is particularly problematic when comparing globe readings in the same environment but different locations, as was performed

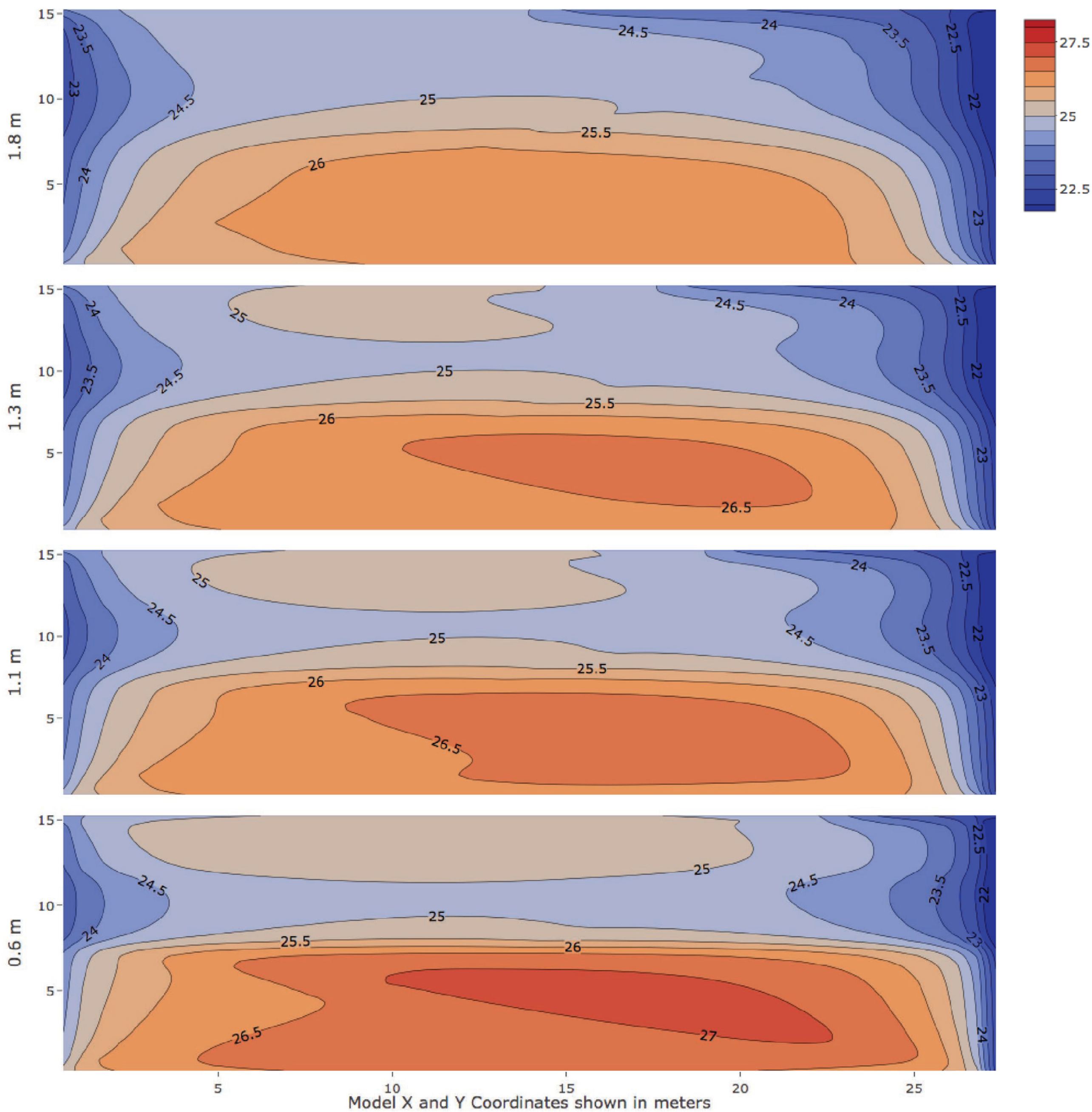

Fig. 6. Mean Radiant Temperature simulated at different heights for the experimental space during the radiant heating experiment at the 145th 8-min interval.

in this study. It is clear that black globe surface preparation itself has strong effects on measured values, and incongruity between multiple black globe readings could easily be attributed to error in radiant exchanges in addition to the convective losses previously described. This investigation was particularly successful at demonstrating overlooked corrections that must be made for the radiant heat transfer to improve the globe's fidelity to the true MRT, both across multiple globe measurements, and for surfaces with emissivities different from that of the globe.

4.4. Spatial and temporal change of MRTs

Using the indirect infrared measurements of the surface temperatures, we were able to produce the MRTs in a 3D space as illustrated in Fig. 6. From the resulting 3-dimensional MRTs, spatial variations at a given height (0.6 m) can be as much as 5 °C horizontally, and 2 °C vertically. This spatial variation of MRT is a very under-investigated field. Although a few researchers have already shown a contoured map of MRTs simulated from surface temperatures of the surrounding environment [39], the MRTs of any given space are still often considered singular [40]. This also relates to the original Bedford & Warner study which also heavily relied on spatial variation of MRTs. A total of 221 observations were reported across different separation of mean black body temperatures and air temperatures. The actual investigations were conducted in 'factories' and acknowledged the possible variations between the 'conditions' of the 'observation locations', implying the globe thermometer(s) could have been placed at different locations inside said 'factories'. Our simulation results as shown in Fig. 6 illustrates a much more apparent spatial distribution of MRT within a large factory-like space, which we were able to verify with our experimental results. These MRT gradients as shown in Fig. 6 can-

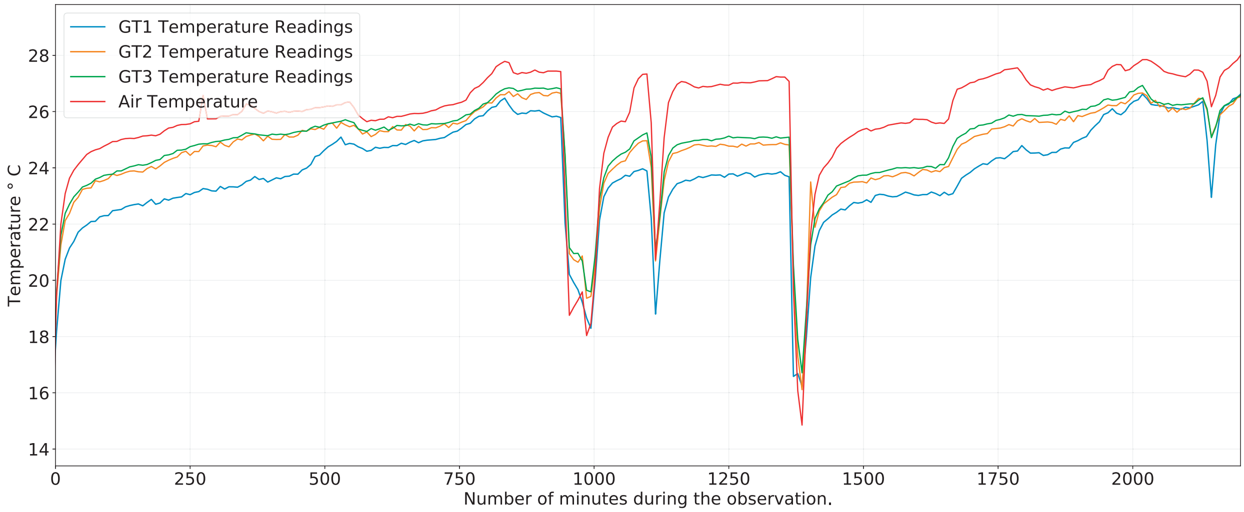

Fig. 7. Temperature deviation between the three globe thermometers observed during heating scenario with minimum airflow during the measurement.

not be fully established by a few globe thermometers and can be computationally expensive to compute. Developing better apparatus and methodology that can provide the spatial MRT distribution independent of convection could be very helpful. Producing a contour map of the MRTs at given heights, for example, could be a very helpful tool to communicate the potential MRT variation [39]. Such a contour map not only helps to visualize the spatial variation of MRT, but also fulfills our need of plausible apparatus to measure spatially resolved MRTs.

Globe thermometers are capable of capturing point-specific MRTs, but deploying enough globe thermometers at locations that would characteristically show the MRT variations could be very challenging. Even when the globe thermometers are properly positioned to reflect the MRT variations, they are still subject to location-specific convection and emissivity as discussed above.

This is better shown in our effort to understand the temporal variation of measured MRTs in the laboratory space. We have plotted the air temperature and globe thermometer readings in Fig. 7. Between the globe temperatures measured from three locations, GT3 was higher than GT2 by 1.23 °C and GT2 to GT1 by 0.35 °C. Accounting for the air temperatures and air velocities, we found the MRT at GT3 to be 1.21 °C higher than at GT2, and GT2 0.15 °C higher than at GT1. The MRT at GT3 was simulated from surface temperature measurements to be 1.51 °C higher than that of GT2 and GT2 0.49 °C higher than GT1. This was consistent with our measurement from the globe thermometers.

As can be observed from Fig. 7, the temporal variation of MRTs measured with globe thermometers follows the change of air temperature closely, despite being corrected for convection with the air velocities recorded. This could be due to the transient nature of the air being introduced into the workshop as an attempt to enlarge the gap between MRT and air temperature to replicate the Bedford & Warner experiment. Since the globe thermometers are exposed to cold air at high velocities, the readings from it were yet to be considered reliable until equilibrated. During the period of measurement when the globes were clearly equilibrated, the globe thermometers maintained consistent spatial separation as seen within simulations. This is to be expected since the radiant environment remains relatively unchanged since the concrete radiant heating slabs had thermal masses that were very likely to be cooled down by short bursts of convection with cold air.

More transient states during and immediately after the door-opening also raise interesting questions regarding globe thermometer's capability of capturing transient states. As can be observed from Fig. 7, air temperature rapidly climbed back up alongside globe temperatures after the door-opening sessions concluded despite a relatively low air speed ($v <$ 0.2 m/s). This rapid heat exchange could be viewed as a buoyancy-driven natural convection where the huge air volume is heated up rapidly despite no apparent convection. Non-uniformity of a radiant environment may already be attenuated due to the convection of air inside the globe thermometer according to existing literature [41]. Our observation of a strong dependency of globe temperature on air temperature despite lower air speed points to a similar dampening effect on MRTs when natural convection is present.

It is also worth questioning whether there are additional experiments that we could run to investigate a smaller subset of MRT and T_a separation. As was previously pointed out by Walikewitz et al. [22], separation between MRT and T_a clearly exists, but the extent of the actual variation in both the indoor and the outdoor environment is unclear. Introducing a more extensive set of environmental conditions (lowering the radiant floor temperature for a typical swing-season day where the air temperature is relatively low, for example) could potentially be a good option to further investigate the interrelationship - or the lack thereof - between the air temperatures and MRTs.

Admittedly, we have a few apparent sources of errors: we constructed the globe thermometers in-situ and did the calibration ourselves. Also, the infrared thermometers have an inherent limitation of 0.5 °C accuracy. We have endeavored to eliminate these errors by doing cross-calibration between the globe thermometers and calibrating the infrared thermometer with objects of known temperature to fully utilize the 0.02 °C precision of the infrared thermometers. Comparing this study and the original Bedford & Warner experiments, both also have spectral limitations. The infrared sensors used in this experiment have an optical filter from 5.5 to 14 µm. The Moll thermopile the original experiments utilized, on the other hand, could have a significant absorption fall-off, in particular in the 10 to 15 µm range [42]. This does not appear to have been fully investigated during the Bedford & Warner investigation, but could also have influences on the errors in the original studies. Moreover, the Moll thermopile from the Bedford & Warner study should have had a fixed field of view. The original study used rotational methods to obtain a full aggregated radiation flux with it. This motion-based sensing technique could also have added source of errors since it was carried out manually. In comparison, our new method, despite its inherent accuracy for not covering the entire spectrum, approaches this problem by having a fully-automated data collection routine such that the systematic errors can be better understood and therefore minimized.

5. Conclusions

Through revisiting the work of Bedford & Warner [1] we have confirmed both the original study of globe thermometer MRT error while also elucidating significant shortcomings of the technique with respect to convection, emissivity, and spatial variation. We replicated the MRT measurements using globe thermometers and found a similar range of error on the order of 1 °F for small separation between air temperature and globe temperature. At higher separation of air and globe temperature the errors are higher as the globe becomes more sensitive to convective losses.

We calculated and plotted a comparison of the original convective correction technique compared to the current method used in standards today, and showed a significant difference that may have caused overestimates of the effect in the original work. We also demonstrated how modern hot point anemometers are not matched to the time-constant of the globe thermometer, and how the original technique using a similar silvered kata thermometer globe could be better. Most digital sensors can have their noise balanced out by using a moving average, but air movement is neither slow nor linear. Therefore deriving convection corrections for globes based on these devices requires serious consideration for the temporal variation in these readings, and what the real effect on the globe is over its settling time. This could be why our errors were higher for higher separation between air and globe temperature readings. Air temperature and speed can both have errors in their own measurement that may have a much larger impact on the actual globe temperature measurement.

We also experimentally determined the emissivity using FTIR analysis for an arbitrary change in surface treatment from one to two layers of black paint, which changed the emissivity from 0.949 to 0.979. More nuanced is the fact that the paint does not have an ideal graybody emission curve, so the emissivity is calculated based on a curve of emissivity that varied with spectrum and is not independent of the measured temperature. The variation of MRT measured by the globe temperature could therefore cause error due to non-graybody emissivity. Similarly, we demonstrated that differences in the preparation of black globes regarding the amount of paint applied can change the emissivity by nearly 0.03, which could systematically skew the heat flux on the black globe by an amount changing the MRT 2.1 C.

We used a combination of simulation and experimental results to demonstrate the MRT variation through space. Our results showed the variation could be as significant as 5 °C at a given height. Assisted by a simplified geometry-based simulation, we were able to construct a 3-dimensional matrix of the MRT in space. This distribution was further verified with globe thermometer measurements. The spatial variation of MRT eluded to in the original study was illustrated and validated. The previous analysis of convection and emissivity also demonstrated how spatial variations of readings may have caused errors to be exacerbated by these effects. We believe the spatial resolution of MRT could be better understood by developing tools that visualize 2D contour maps of MRT. More importantly, we believe it is important to encourage development of a more air-independent tool or methodology to measure for the surface temperatures of a space that is free of convective heat loss disturbances so that a room with known geometry can have its MRT spatially resolved.

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