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Experimental Study of Heat Transfer Mechanisms and Energy Consumption in a Heated Truck Weigh Station during Winter

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Abstract – This study presents the findings of an extensive experimental campaign conducted at a weigh station located in Quebec City (Canada) during the winter 2023-2024. The primary objective was to understand the thermal dynamics and energy consumption profile of the weigh station when the unit heaters beneath the weighing platforms were activated. Our investigation revealed that non-uniform temperature distributions within the pit, where the scales and associated equipment are located, resulted from the inactive state of one of the unit heaters during the initial 36 days of the experimental campaign and additionally due to their arrangement. Furthermore, distinct energy consumption profiles were observed during operational periods when all seven-unit heaters were in use compared to periods with only six unit heaters operating. The utilization of all unit heaters improved the control of the heating system, which is based on two thermocouple temperature readings, leading to a range of energy consumption more adapted to outdoor temperature fluctuations. Overall, increasing the heating capacity of the weighing station by 10 kW raised the average pit temperature. This allowed the pit temperature to stay within the adequate working temperature for the weighing equipment within the pit while reducing the average energy consumption of the weighing station. In addition, this study presents a dataset for validating steady-state Computational Fluid Dynamics (CFD) models of weighing stations, contributing to future optimization of design and operational strategies.

Keywords: Heat transfer monitoring; Energy consumption; Temperature distribution; CFD validation

1. Introduction

The trucking sector plays a crucial role in the transportation supply chain. Trucks account for over 28% of goods transportation in Canada [1]. However, overloaded trucks pose significant safety risks and cause damage to the roads. Regulations governing truck loading are consequently necessary and enforced through weigh stations nationwide. It has been shown that weigh stations help reduce the percentage of heavy vehicles with excess loading and stabilizes truck equivalency factors for pavement design [2]. Currently, there are 32 operational weighing stations in the province of Québec, managed by the Société de l'assurance automobile du Québec (SAAQ) [3]. When an operation is carried out, trucks in the station's vicinity are rerouted toward the station and are required to move onto a platform to be weighed. In regions with cold climates like Québec, snow and ice accumulation on weighing platform surfaces and freezing of the sensing equipment can distort readings. Heating systems are employed to melt the snow accumulated on the platforms of the weighing station and maintain equipment at an acceptable temperature. Air unit heaters, placed beneath weighing platforms, are commonly used for this purpose, but they often result in high energy consumption and non-uniform temperature distribution. Whereas current research on weigh stations is focused on topics such as weigh-in-motion systems [4-5] and improving accuracy [6], the challenge of reducing their energy consumption in cold climates is still largely unexplored in open literature. Utilizing a validated Computational Fluid Dynamics (CFD) model of weighing stations, supported by experimental data, facilitates the precise identification of sources of energy inefficiencies and the design of better stations. However, the size, complexity, and the fact that stations are subjected to changing outdoor conditions, make in situ experimental studies quite challenging. To the authors' knowledge, there is currently no available experimental thermal datasets on operating weigh stations in open literature, nor energy consumption profiles available. This limits our understanding of the system's performance, complicates model validation, and, in the end, prevents the design of better systems. In this paper, we present the results of a comprehensive experimental campaign that was conducted in a weighing station in the winter 2023-2024. This study offers an overview of the experimental procedure and presents essential datasets that aid in understanding the thermal behavior and energy consumption of the system. Additionally, it supports the validation of the weighing station's CFD model by providing one of many validation cases.

2. Description of weighing stations

The studied weighing station comprises a series of six platforms of varying lengths (from 4 to 5 m long) over which trucks pass, positioned above a pit measuring 26.1 m in length, 3.7 m in width, and 1.7 m in height. Fig. 1 offers a visual presentation of the weighing station, where the pit houses the scales and associated equipment, such as the air unit heaters. The platforms, constructed from steel, have a thin asphalt layer on top of them, while the pit itself is made from concrete and insulated by a 0.1-m-thick rigid insulation layer on all sides. Seven unit heaters with different heating powers are positioned within the pit. These unit heaters are equipped with internal fans and adjustable diffusers. Notably, except for the unit heaters situated in platforms 1 and 2, all other unit heaters share the same orientation, with the flow directed towards the northern wall of the pit. Fig. 2 illustrates the flow direction from the heater's outlet. The unit heaters operate using a rule-driven algorithm; if the temperature in the pit exceeds 3°C, the heating system stops, and it is turned on when the temperature drops below 3°C within the pit. The control pit temperature is determined by averaging readings from the two thermocouples located at both ends of the pit. At the beginning of this experimental campaign, the unit heater situated under the platform 6 (in yellow in Fig. 2) was out of service. That heater became operational on January 26, 2024. It is worth mentioning that there are 0.02-m-wide junctions throughout the weighing station, both between consecutive platforms and between the platforms and the upper surface of the pit, as visible in Fig. 1b. Air exchanges between the pit and the ambient environment can occur through these gaps. In this paper, we analyzed data from December 21, 2023, to March 5, 2024, covering 36 days when the platform 6 heater was unavailable and 40 days when it was operational.

(a) (b)

Figure 1. Photos of the weighing station (a) Seen inside the pit (b) Seen from above

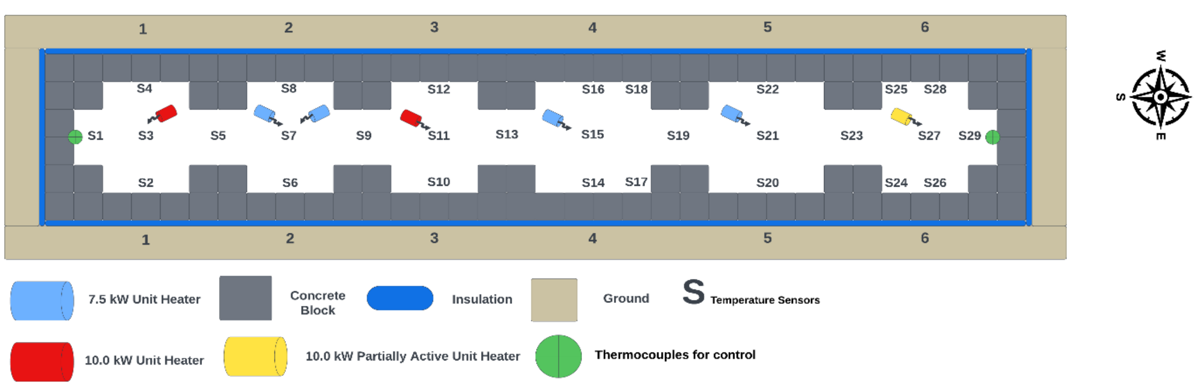


Figure 2. Floor plan of the pit

3. Methodology

Figure 3 illustrates the sequential steps of the experimental campaign, beginning with the initial design phase, progressing through data processing and the presentation of essential datasets. Due to the length of the weighing station (26.1 m) and the non-symmetric distribution of unit heaters within the pit, the temperature sensors used for this measurement campaign had to be strategically placed in the pit. The positions of the 87 temperature sensors are indicated in Fig. 2. As shown in the figure, 29 vertical stands are used (visible in Fig. 1a and labeled "S" in Fig. 2) to monitor the temperature at three different heights: LOW (0.40 m above the floor), MID (0.80 m), and TOP (1.2 m) levels. The temperature sensors are NTC thermistors with a resistance tolerance of ±3%, operating within a temperature range from -55°C to 125°C. Data registration occurs every 60 seconds, a frequency chosen due to its effectiveness in minimizing noise levels for the 8-channel data acquisition system used in this experimental study. The initial data collection started on December 21, 2023. At the time of writing this paper, data registration is still ongoing. It is worth mentioning that alongside the data registration process, ambient data were simultaneously collected from a nearby weather station. The registration process was briefly paused on January 9, 2024, February 12, 2024, and March 5, 2024, to apply some modifications to the monitoring setup and it was promptly restarted to ensure continuous acquisition of data.

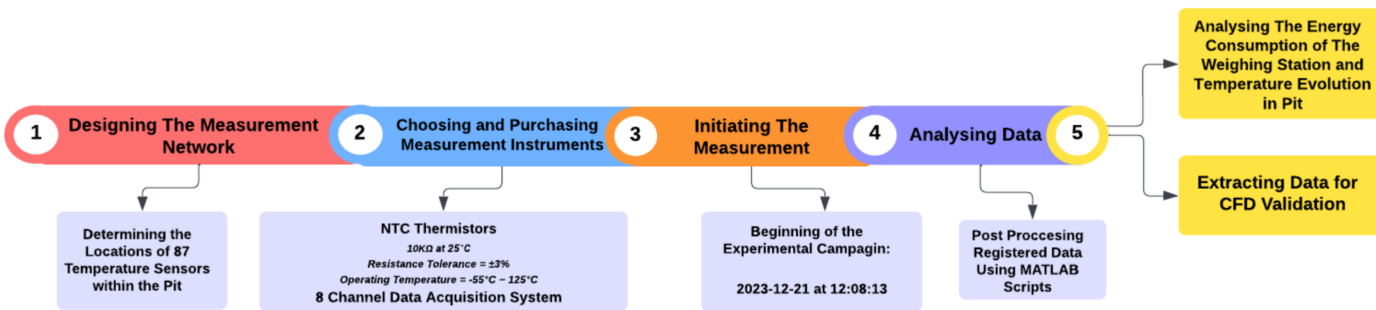


Figure 3. Measurement campaign chart

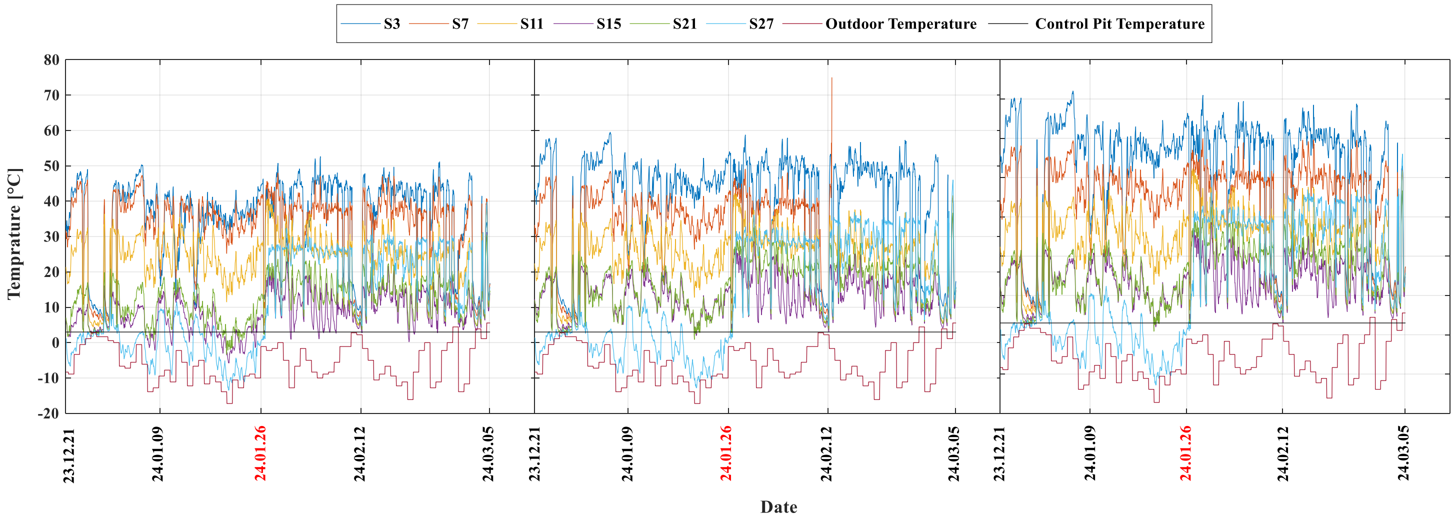
The first step of the data treatment stage of this data analysis involved identifying malfunctioning sensors. Considering that sensors are exposed to harsh outdoor conditions, it was expected that some of them could be disconnected or shorted. After a careful analysis of the results, we found that 5 sensors were not functioning properly, and they were excluded from the analysis. At the next step, the recorded data were modified from a 1-minute frequency to a chosen frequency by computing the average values to facilitate the present analysis. After profiling the sensors using the average values, the subsequent stage involved post-processing the data for analyzing the temperature evolution in the pit and the energy consumption of the weighing station when the heating systems start operating. For tracking temperature evolution, a 30-minute frequency was employed. However, for a more detailed understanding of the heating system's status (whether it is ON or OFF), a 2-minute frequency was used in this study. The analysis of energy consumption at the weighing station during the winter 2023-2024 was facilitated by discerning the status of the heaters and the duration of their operation.

4. Results

4.1. Analysis

4.1.1. Temperature evolution in the pit

Figure 4 illustrates the 30-minute averaged temperature values reported by sensors positioned at the LOW, MID, and TOP levels of six selected stands along the pit centerline, spanning from December 21, 2023, to March 5, 2024. Additionally, it depicts the daily averaged outdoor temperature recorded by the nearby weather station and the 3°C threshold to control pit temperature. By analyzing the temperature profile of sensors affixed to S27, positioned beneath platform 6 and precisely in front of the unit heater, we can observe the operation of the unit heater beneath this platform since January 26, 2024. Prior to this date, the unit heater was not operating, and the S27 sensors mostly mirrored the outdoor temperature pattern. Before January 26, 2024, except for December 25, 26, and 27—during which the weighing station was closed, and no operations were conducted—the rest of the unit heaters were operational, and they functioned continuously. The uninterrupted operation



(a) (b) (c)

Figure 4. Sensors profiles at the (a) LOW, (b) MID, and (c) TOP levels

of the unit heaters was due to the low temperature readings reported by the thermocouple positioned on the northern wall of the pit, directly facing the unit heater at the last platform, which was out of service for that period. This prolonged operation of the unit heaters resulted in a nearly steady-state temperature profile of the sensors, which was only affected by the change in outdoor temperature due to heat losses through the gaps. The steady-state temperature profiles will be further discussed in Section 4.2.

The studied weighing station can be segmented into two distinct sections: the first section, encompassing platforms 1 to 3, and the second section, comprising platforms 4 to 6. Upon examining Fig. 4, it becomes evident that before January 26, 2024, significant differences existed in temperature readings, with reported values decreasing as one move from S3 to S27 for sensors positioned at all three levels. This variation can be attributed to the non-operational status of the unit heater situated beneath platform 6. After solving the technical issue and ensuring the functionality of all unit heaters, the temperature difference persisted, but to a lesser extent, and sensors situated at the center of platforms 1, 2, and 3 consistently recorded higher temperatures. This disparity can be ascribed to the total heating power of 35 kW provided by unit heaters in the first section (platforms 1 to 3), in contrast to the 25 kW supplied by those in second section (platforms 4 to 6). Furthermore, one of the unit heaters under the second platform and the unit heater under the first platform push air toward the pit south wall, contributing to this non-uniform temperature profile within the pit.

Upon further investigation into the evolution of the temperature profile within the pit, it becomes apparent that, despite the average outdoor temperature remaining consistently similar during periods with and without the operation of the unit heater beneath platform 6, with only a 1.43°C difference, there were notable disparities in the maximum and minimum average temperature values within the pit for these two specific intervals. Fig. 5 illustrates the daily volume average temperature within the pit, alongside the daily average outdoor temperature registered by the nearby weather station. Preceding and following January 26, 2024, the maximum average temperature values were 22.88°C and 31.50°C, respectively. Similarly, the minimum average temperature values before and after January 26, 2024, were 5.69°C and 9.06°C, respectively. These findings underscore variations in temperature dynamics within the pit, which contribute to enhancing the melting rate of accumulated snow on the platforms and maintaining equipment at a higher temperature.

4.1.2. Energy Consumption

Given that the weighing station was constrained by having one unit heater not functioning for the initial 36 days of this experimental campaign, comparing the energy consumption profile of the weighing station during these two periods would result in a better understanding of the weighing station's energy performance. Fig. 6a illustrates the energy consumption of the weighing station versus the average outdoor temperature, while Fig. 6b represents the energy consumption of the weighing station versus the average pit temperature. To enhance data representation, temperature values are averaged for every 6-hour interval, and the reported energy consumption corresponds to the amount of energy consumed during these intervals.

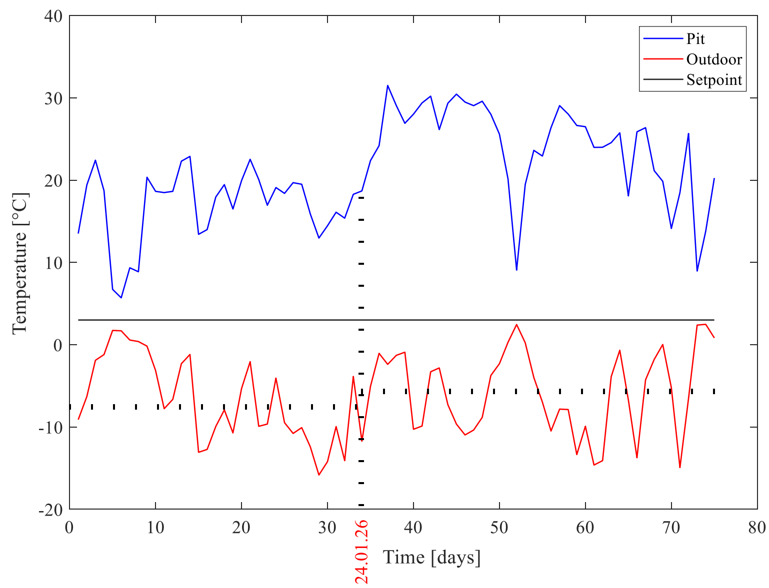
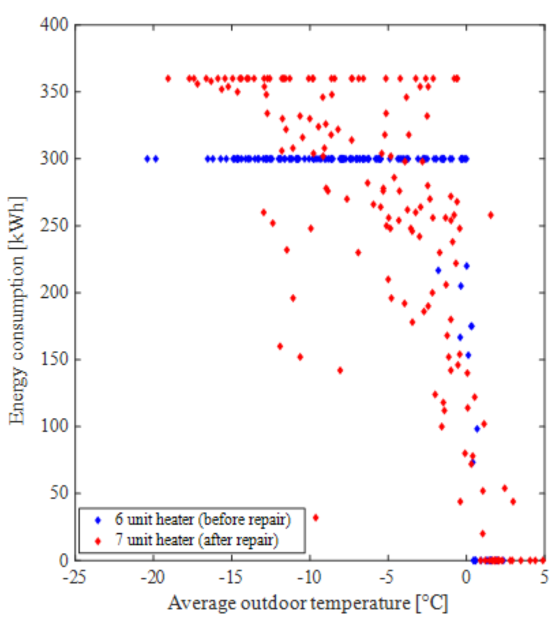
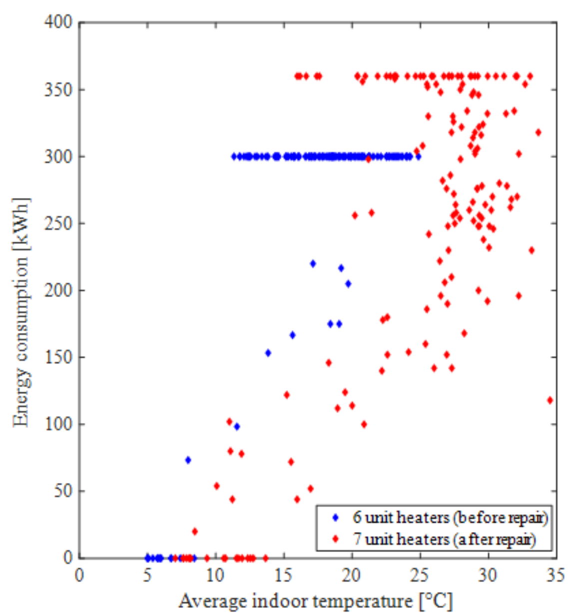


Figure 5. Daily volume average temperature inside the pit



(a)



(b)

Figure 6. Energy consumption during 6-h periods versus (a) average outdoor temperature, and (b) average pit temperature

Figure 6.a illustrates that when the weighing station was limited to 6 operational unit heaters, their operation remained continuous for most days across a wide range of outdoor temperatures, from -20°C to nearly 0°C. This continuous operation of the unit heaters resulted in the energy consumption profile of the system before January 26, 2024, resembling a step function. During these periods, the heating system showed less dynamic behavior in response to the outdoor temperature

changes. When the outdoor temperature dropped below -3°C, the unit heaters were unable to maintain their operation status relatively, and their full heating capacity was reported for each 6-hour interval. Since January 26, 2024, with all seven-unit heaters operational, the heating system has been capable of adjusting its operation based on readings obtained from thermocouples. This adjustment has resulted in a more diverse range of energy consumption in response to varying outdoor temperatures, effectively preventing excessive energy consumption. With the unit heaters now automatically adapting their operational status, the average outdoor temperature threshold for unit heaters to operate continuously has shifted to approximately -12°C, which is about 9 degrees lower than when one unit heater was out of service.
Additionally, Fig. 6.b illustrates that at identical energy consumption levels, the average temperature within the pit was higher when seven unit heaters were operational compared to periods when six unit heaters were in operation. For instance, the maximum average pit temperature reported for the days prior to January 26, 2024, was 24.85°C. However, this temperature value was achieved with a significantly lower energy consumption level during the subsequent 40 days when all heaters were in operation. As depicted in the figure, for the operational periods following January 26, 2024, the average pit temperature exhibited greater sensitivity to the energy consumption variation, resulting in preventing the unit heaters from operating uninterrupted as much as possible.

Figure 7 illustrates the daily energy consumption of the studied weighing station over the 76 days of the experimental campaign. As depicted in the figure, the average energy consumption for the initial 36 days, with 6-unit heaters, was 1049.5 kWh/day. However, this number decreased to 972.48 kWh/day for the subsequent 40 days. It is worth mentioning that the difference in the average outdoor temperature between both periods was negligible, allowing a direct comparison of energy consumption without considering the outdoor temperature effect. Increasing the number of operational unit heaters by one unit enhanced the heating capacity of the weighing station by 10 kW; however, the energy consumption was reduced despite this increase, attributable to the unit heaters operating for shorter periods of time and their operation being better controlled by the thermocouples' temperature readings.

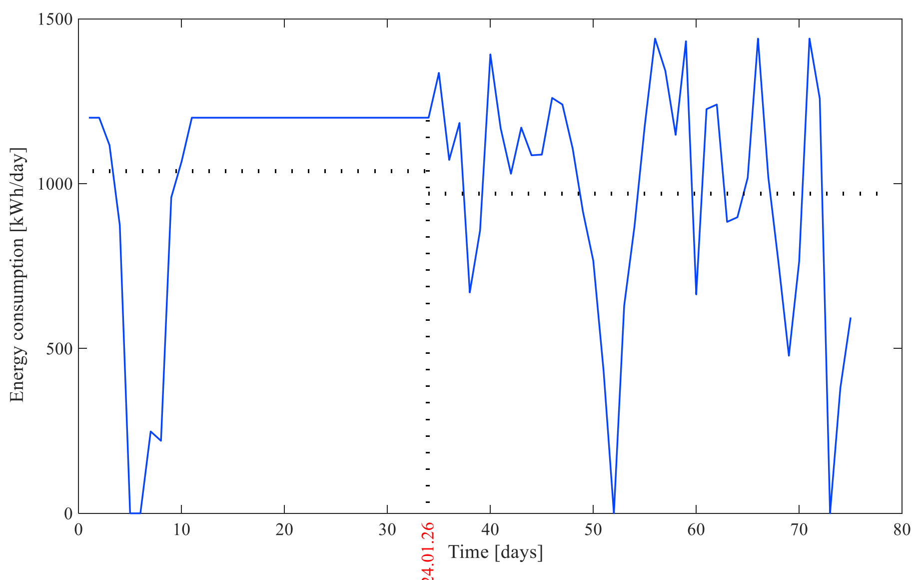


Figure 7. Daily energy consumption of weighing station during the 76 days of experimental campaign

4.2. Extraction of data for CFD Validation

In addition to being used for developing a better understanding of the heat transfer and energy consumption patterns of the weighing stations, the measurements were also used to validate a CFD model that was developed in parallel (not described here). This subsection explains how data were extracted from the dataset for that purpose and presents an example of the resulting temperature profiles used for validation.

Given that the first version of the weighing station's CFD model that we developed runs in steady state to limit the computational time, extracting information suitable for model validation requires identifying instances when the system achieved thermal stability while the ambient conditions remained relatively constant. When thermally constant conditions within and outside the pit are present, the measurements at the different sensor locations during that time interval can be compared with the results of the CFD model. The continuous experimental campaigns enabled the identification of several instances during which nearly steady-state conditions were reached, but only one is presented here for the sake of concision.

It has been previously discussed that before January 26, 2024, the unit heater situated in front of the thermocouple attached to the northern end of the pit was not operational. This technical issue resulted in the continuous operation of the remaining unit heaters. Consequently, this created several thermally steady-state intervals within the pit, coinciding with relatively constant ambient conditions. In essence, most validation cases correspond to those moments preceding January 26, 2024. The case selected for this paper was arbitrarily chosen from that specific interval. The duration of the validation case is defined by the period during which the ambient conditions remained relatively constant.

For instance, on January 11, 2024, the outdoor temperature remained nearly constant at -8°C from 6 PM to 8 PM. During this time, there was negligible snow precipitation with a total accumulation of 0.0005 m. The average wind velocity was 0.04 m/s, and the average humidity, 89%. By analyzing the sensor profiles during this two-hour interval, it was found that maximum standard deviation for temperature values was 0.67°C for the TOP level, 0.70°C for the MID level, and 0.58°C for the LOW level sensors. In other words, the temperature profile was nearly constant during that two-hour interval.

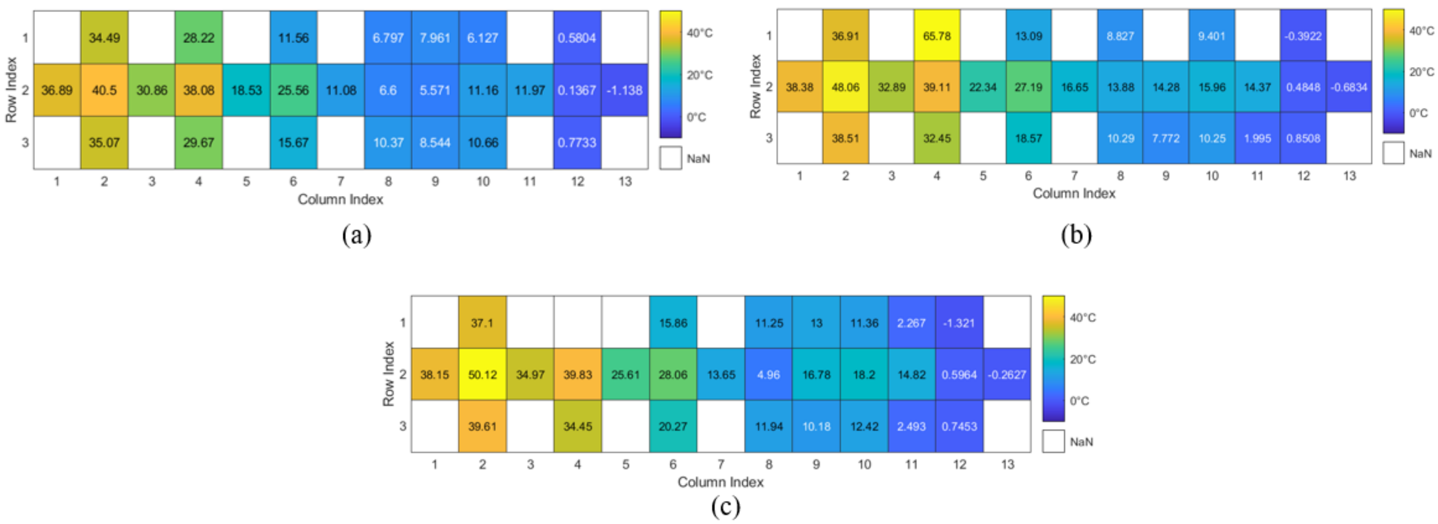


Figure 8. Steady-state temperature profile the (a) LOW, (b) MID, and (c) TOP levels (January 11, 2024, 6 PM to 8PM)

Figure 8 reports the measured temperature values within the pit. Note that due to sensor malfunction, there is no value reported for sensors 24 and 25 from the LOW level, sensor number 8 from the TOP level, and sensors 18 and 25 from the MID level. Fig. 8 is one of several datasets that could be used as a validation case for weighing station's steady-state CFD models. The validity of the converged CFD solution can be evaluated by directly comparing temperature values at the locations of the stands at three different heights.

5. Conclusion

In this study, we presented the results of a comprehensive experimental campaign that was conducted in a weighing station during the winter 2023-2024. Our findings reveal several crucial insights into the operation of weighing stations in cold climates like in Canada. First, we observed that the non-operational status of one of unit heaters and the arrangement of unit heaters within the pit resulted in a non-uniform temperature distribution within the pit.

Additionally, we observed disparities in energy consumption profiles between periods when all unit heaters were operational and when one was out of service. Having all seven unit heaters available resulted in enhanced automatic adjustment of their operation based on thermocouple temperature readings. This led to a wider range of energy consumption level in response to outdoor temperature variations and a higher sensitivity of the average pit indoor temperature to energy consumption changes. This improvement ultimately resulted in a lower average energy consumption during the period when the heating capacity of the weighing station was increased by 10 kW.

Moreover, our study provides valuable data for validating CFD models of weighing stations, enhancing our understanding of heat transfer dynamics, and aiding in the design of more efficient systems. By comparing experimental data with the results of the steady-state CFD model, we can refine modeling techniques and improve predictive capabilities for optimizing weighing station designs.

Different avenues for future research can be explored. We aim to utilize the validation case presented in this study to evaluate the validity of the weighing station's CFD model. Upon validating the model, our objective is to identify energy inefficiencies and determine the optimal configuration and control that can reduce the energy, consumption while keeping adequate temperature profiles within weighing stations in winter.

6. Acknowledgement

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