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Big Ass Fans

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Simulated Impact of Energy Codes

Thermal Comfort in Heated-and-Ventilated-Only Warehouses

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Building energy codes and standards contain minimum requirements that provide a path to energy efficient buildings and building systems. ASHRAE/IES Standard 90.1 and the International Energy Conservation Code (IECC) are the main national building code models in the United States. Both Standard 90.1 and the IECC are updated on three-year cycles with the goal of reducing building energy consumption.

Decreased energy consumption in each update is achieved through a variety of energy conservation measures including: increased insulation levels, reduced lighting power density and reduced solar heat gain from fenestration. These measures not only save energy, they also have potential to improve thermal comfort of occupants in non-air-conditioned spaces.

So let’s examine the predicted thermal comfort level using a prototype warehouse and compare using Standard 90.1-2004, 2010 and 2016 energy efficiency levels.

The Fanger and Adaptive comfort models will be used to determine occupant thermal satisfaction. The OSHA Heat Index will also be used to evaluate frequency of high-risk hours for occupants and impacts on productivity will be examined.

Using EnergyPlus, a warehouse building model that prescriptively complied with Standard 90.1-2004, -2010, and -2016 for each of the seventeen climate zones (for a total of 51 prototypes) were simulated and the results were compiled for analysis.1-3 The simulations included the Fanger4 and Adaptive Comfort5 models to determine occupant thermal comfort levels and predict worker productivity impact. The NOAA Heat Index was also used to determine the frequency of high-risk hours for the warehouse occupants.6 An additional 17 models were simulated to evaluate elevated air speed impact on worker productivity.

Methods and Procedures

The modeled warehouse (Figure 1) is approximately the same as the warehouse used by PNNL in the
development of the *Advanced Energy Design Guide for Small Warehouses and Self-Storage Buildings*. It is 50,000 ft$^2$ (4645 m$^2$), has a floor-to-ceiling height of 28 ft (8.5 m) and has three thermal zones. The office zone is 2,550 ft$^2$ (237 m$^2$). The fine-storage zone of the warehouse is 12,450 ft$^2$ (1157 m$^2$). The bulk zone of the warehouse is 34,500 ft$^2$ (3205 m$^2$).

The warehouse occupant count was assumed to be zero in the PNNL models. Based on the internal load assumption of three operating forklifts, it was determined the number of occupants in the bulk warehouse area should be increased. Various sources were evaluated and significantly different occupant densities were noted.

Based on widely varying occupant densities, a conservative value of 5,000 ft$^2$ (465 m$^2$) per occupant was used to determine the number of occupants in the fine and bulk storage zones. Occupants are present from 6 a.m. until 6 p.m., with the building fully occupied from 8 a.m. to 12 p.m. and 1 p.m. to 5 p.m. The heat gain for the warehouse occupants was calculated to be 730 Btu/h per person based on an average metabolic rate of 2.0 met, heat generation of 5.4 W/ft$^2$ (58.15 W/m$^2$) of skin and 20 ft$^2$ (1.84 m$^2$) of skin.

The remaining internal loads were unchanged from the PNNL models. These loads include 0.75 W/ft$^2$ (8.1 W/m$^2$) of plug loads in the office, 2.7 kW of heat gain for each of the three forklifts in bulk storage; lighting power densities were determined by Standard 90.1. Schedules applied to the internal loads were similar to the occupancy schedule, with the exception of the forklifts which included charging during unoccupied hours.

Minimum ventilation rates were set for each of the three zones based on the version of ASHRAE Standard 62.1 referenced in Standard 90.1; and a well-mixed space was assumed. The PNNL models also include 80,000 cfm (2265 m$^3$/min.) of comfort ventilation (exhaust fans and dampers) in bulk storage. 80,000 cfm (2265 m$^3$/min.) equates to a ventilation rate of approximately five air changes per hour. With no data source or remarks listed for this assumption, the mechanical ventilation was reduced to 1.5 air changes per hour (24,150 cfm (684 m$^3$/min.), which was more typical of minimum code construction.

Infiltration rates and schedules were unchanged from the PNNL models with general infiltration based on a combination of 0.038 cfm/ft$^2$ (0.193 L/s·m$^2$) of wall area, 500 cfm (14 m$^3$/min.) of leakage from each of the relief dampers, 32 cfm (0.91 m$^3$/min.) per closed dock door, and 783 cfm (22 m$^3$/min.) per open dock door with a truck in place. Three dock doors are assumed to be open with a truck in place during the occupied hours for the entire year per the PNNL Technical Support Document for the Warehouse Advanced Energy Design Guide.

Single-zone, rooftop units were assigned to the office and fine storage zones, while unit heaters were used in bulk storage. Thermostats were set to 75°F (24°C) for occupied cooling and 70°F (21°C) for occupied heating with a 10°F (5.6°C) reset during unoccupied hours in the office and fine storage zones. The heating setpoint was a constant 55°F (13°C) in the bulk storage during heating and an on-point of 85°F (29°C) was set for the comfort ventilation fans.

The building envelope’s thermal properties were determined by the requirements set forth in Standard 90.1-2016. Construction types consistent with a metal building were selected. Windows were provided only in the office area and seven dock doors were located in bulk storage. An internal mass of 19 million pounds (8 618 255 kg) was input in the bulk area to represent the goods stored on the racking as described in the PNNL Technical Support Document.

**Comfort Analysis, Productivity and Heat Index**

Comfort calculations for the occupant in the bulk storage area were based on the following assumptions: The metabolic rate for the warehouse tasks were assumed to be 75% of the time spent lifting and packing and 25%
Clothing insulation was based on a dynamic clothing insulation model. Two different comfort models were included in the building simulations. The first model, Fanger’s Comfort Model, is used to determine the occupants’ predicted mean vote (PMV) and the predicted percent dissatisfied (PPD). PMV values of greater than 0.5 indicate discomfort due to warm thermal sensation and PMV values of less than –0.5 indicate discomfort due to cool thermal sensation.

The second model, the Adaptive Comfort Model, is used to determine if space conditions meet the 80% acceptability level based on a seven-day mean, outdoor-air temperature and the calculated indoor operative temperature. The impact of thermal comfort on productivity was determined based on the Fanger Comfort Model PMV and Equation 1 established by Srinavin and Mohamed.

**Equation 1: Productivity Loss Based on Thermal Discomfort**

\[ \text{Pl} = 99.91 - 0.796 \times \text{PMV} - 1.843 \times \text{PMV}^2 \]

**Variables**

- **Pl** = Productivity level (%)
- **PMV** = Predicted Mean Vote

Financial impacts of productivity loss were based on the occupancy level for each hour and an hourly wage of $15.12.

Indoor air temperature and relative humidity were also used to determine the number of hours in each heat stress category of NOAA’s Heat Index Chart. The Heat Index Chart is used by employers to avoid employee heat stress/heat stroke (Figure 2).

**Comfort Analysis and Productivity**

The Fanger Comfort Model was applied to the representative worker in the bulk storage part of the warehouse and PMV values were calculated for each hour of the year. The comfort zone is between 0.5 and –0.5 on the Thermal Sensation Scale. Bulk storage has 3,636 occupied hours per year. The number of occupied hours where occupants were predicted to be uncomfortable due to heat (PMV > 0.5) for each building simulation are presented in Figure 3.

While the number of hours where occupants were uncomfortably warm decreased slightly with the 2010 and 2016 versions of Standard 90.1, nearly all climate zones maintained a significant percentage of hours outside of the comfort zone per the Fanger Comfort Model noted in Figure 4.
As an alternate to the Fanger Comfort Model, the Adaptive Comfort Model Based on European Standard EN15251 was also used.\textsuperscript{15} While occupants’ activity levels are higher than the 1.3 met limit for the Adaptive Comfort Model, the adaptive method was applied since the occupants can adjust clothing levels, the dock doors can be opened and closed, and there is no active cooling system in bulk storage. Figure 5 presents the number of occupied hours where the occupants were predicted to be uncomfortable by the Adaptive Model method.

The Adaptive Model shows reduced uncomfortable hours compared to the Fanger model, but still shows a significant number of hours outside the comfort zone.

**Financial Impact**

The impact on productivity loss of adding 160 fpm (1.8 mph [2.9 kph]) of elevated air speed was evaluated for all climate zones for the Standard 90.1-2016 buildings and is presented in Table 1. 160 fpm (48.77 m/min.) is a typical, average air speed used in cooling comfort applications with circulator fans and is the upper limit of air speed when occupants do not have control of the fan in ANSI/ASHRAE Standard 55.\textsuperscript{16} The number of uncomfortable hours, and the financial impact on productivity, decreased significantly with the addition of 160 fpm (48.77 m/min.) of elevated air speed.

**Heat Index**

Heat index combines relative humidity and temperature to create “apparent” temperature, which provides an estimate of how warm indoor air will feel to an occupant. High Heat Index values indicate an increased likelihood of workers experiencing heat-related illness. Figure 6 presents the number of hours in each Heat Index Category the warehouse workers would experience for each version of Standard 90.1.

The hours in the Extremely Hot category are essentially eliminated for Climate Zones 1A and 1B with 2010 and 2016 revisions to Standard 90.1. The hours in the
Very Hot and Hot categories are generally reduced and moved closer to outdoor air conditions. The general shift to lower categories will provide decreased risk of heat stress to warehouse workers and potentially provide financial benefit to employers.

OSHA recommends a work-rest schedule be developed for times when the Heat Index is above 90°F (32°C), Category II – Hot. Table 2 presents an example work-rest schedule used to mitigate the likelihood of heat related illness/injury.

Based on the number of rest minutes per hour for a moderate work schedule, the cost of Category II, III, and IV Heat Index break time was estimated. Table 3 summarizes annual cost for each location and version of 90.1.

While the cost of breaks decreases dramatically in the 2010 and 2016 versions of Standard 90.1, in climate zones 1A through 3A, the annual lost wages are still significantly high and could be used to financially justify the addition of some ECM to decrease worker heat stress.

### Summary and Discussion

The impact of hot and humid conditions on the occupants of heated- and- ventilated-only warehouses in climate zones 1 through 4 is significant and costly. While the 2010 and 2016 versions of Standard 90.1 have increased worker comfort and productivity levels, six climate zones still showed more than forty percent of the occupied hours outside of the comfort zone for the “Typical Meteorological Year.” The lost productivity and wages from the high PMV conditions represent a large opportunity for financial justification of incorporating additional thermal comfort measures into the design of warehouses.

If thermal comfort continues to be ignored by energy codes, and in initial designs of buildings, building occupants will seek thermal comfort by adding additional equipment to the building.
The example comfort measure of elevated air speed resulted in significant reductions in uncomfortable hours and productivity losses in Climate Zones 1A, 2A, 3A, 3B, 3C, 4A, 4B, 5A, and 5B. Air speeds of 250 fpm (76 m/min.) are relatively practical to achieve in warehouse environments. The increased air speed would provide increased occupant comfort and improve worker productivity.

References