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Measurement and evaluation of indoor thermal environment in a naturally ventilated industrial building with high temperature heat sources

Yi Wang*, Jie Gao, Xiao Xing, Yuanlu Liu, Xiaojing Meng

School of Environmental and Municipal Engineering, Xi'an University of Architecture and Technology, PR China

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ABSTRACT

In this study, indoor thermal environment and workers' perceptions were investigated at four different locations in a naturally ventilated industrial building with high temperature heat sources in summer and winter. The results demonstrated that the differences between the mean radiant temperature and air temperature were between 0.8 °C and 5.3 °C in summer and between 1.6 °C and 11.0 °C in winter, and the average air velocity generally ranged from 0.3 m/s to 1.5 m/s. Moreover, the average wet bulb globe temperature (WBGT) was between 27.3 °C and 29.0 °C in summer and between 5.7 °C and 8.9 °C in winter, which coincided with the workers' perceptions of the thermal environment. The WBGT thus may be one of the potential indices to evaluate the indoor thermal environment in summer and winter. A prediction model for the indoor WBGT using the thermal environmental parameters was developed strictly based on the law of analogy for heat and mass transfer. The predictions agreed quite well with the measured data for WBGT of between 24 °C and 30 °C in summer and 2 °C–10 °C in winter, and the absolute differences between the predicted and measured WBGT were between 0 °C and 1.1 °C with an average of 0.3 °C in summer and between 0 °C and 1.2 °C with an average of 0.5 °C in winter. Therefore, the proposed indoor WBGT prediction model was valid and can be used to determine the acceptable thermal environmental parameters during the design stage for naturally ventilated industrial buildings with high temperature heat sources.

1. Introduction

The indoor thermal environment is normally unacceptable in naturally ventilated industrial buildings with high temperature heat sources, such as iron and steel plants and metallurgy plants [1–4]. As a result, workers who are directly exposed to the unacceptable thermal environment may have increased health symptoms and decreased productivity [5–8].

Evaluation indices of indoor thermal environment are essential for determining the acceptable thermal environmental parameters during the design stage of naturally ventilated industrial buildings. Some researchers had proposed several indices to evaluate the indoor hot environment in summer, such as predicted four hour sweat rate (P4SR) [9], heat stress index (HSI) [10], predicted heat strain (PHS) [11] and wetbulb globe temperature (WBGT) [12]. Because WBGT can be conveniently measured by instruments, it has been adopted by many international environmental standards and regulations as the evaluation index for indoor hot environments [13–15]. In winter, the indoor thermal environment may also be unacceptable due to insufficient heat insulation for the building envelope [1,4]. As the effect of radiation from the high temperature heat sources is taken into account, WBGT may be one of the potential indices to evaluate the indoor thermal environment in winter [16,17].

According to ISO 7243 [13], indoor WBGT is determined by the weighted average of natural wet bulb temperature and globe temperature. As the WBGT is not directly related to indoor thermal environmental parameters, namely indoor air temperature, mean radiant temperature, air velocity and relative humidity [18], it may be not possible to use the indoor WBGT to determine acceptable thermal environmental parameters during the design stage of naturally ventilated industrial buildings [19]. To solve this problem,

* Corresponding author. School of Environmental and Municipal Engineering, Xi'an University of Architecture and Technology, No. 13 Yanta RD., Xi'an 710055, Shaanxi, PR China.

E-mail address: wangyi6920@126.com (Y. Wang).

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several indoor WBGT prediction models using the thermal environmental parameters have been developed, such as Denedde and Bernard's model [20,21] and Brake's model [22]. Nevertheless, only Denedde and Bernard's model has been validated through field measured data in summer conditions [20,21]. In Denedde and Bernard's model, the effect of the wick surface temperature and environment temperature on the mass transfer at the wick surface was neglected, which is not in accordance with the law of analogy for heat and mass transfer [23]. Moreover, there are very few studies regarding workers' thermal perception on their environment in naturally ventilated industrial buildings.

The purpose of this study is to investigate the thermal environment and workers' perceptions in naturally ventilated industrial buildings with high temperature heat sources in summer and winter. A indoor WBGT prediction model is developed strictly based on the law of analogy for heat and mass transfer, which will contribute to the rational design of naturally ventilated industrial buildings with regard to natural ventilation and heat protection and insulation.

2. Methodology

2.1. The naturally ventilated industrial building

The measurements were performed in a typical steel and iron plant located in Xi'an, China. The building was built of bricks and concrete in the early 2000s and was 276 m long and 18 m high. The building had two bands of windows at the south wall, with each approximately 1.8 m high. The upper windows were used for lighting, and the lower windows had steel shutters that can be opened manually if needed. The roof windows mounted at the ceiling were open during the operation. The schematic diagram of the plant appears in Fig. 1. There is no heat protection and insulation in the building currently.

The air flow in the plant is mainly achieved by natural ventilation through windows and controlled by the buoyancy flow caused by the heat sources. Fresh air with low velocity is supplied by natural ventilation through the windows and spread out above the floor and is then mixed with the updraft air caused by the heat sources. The mixed air from the lower part is transported to the upper part and forms the updraft that is finally exhausted outdoor through the roof windows.

The heat sources in this plant mainly include a furnace, hot steel beams, a cooling bed, and packaged steels (see Fig. 2). The raw steel is put into the furnace to be melted and formed into hot steel beams. Then, the hot steel beams are rolled and transferred to the cooling bed after being cut to the required lengths at the middle section. Finally, the hot steel beams are cooled down and transferred to the packaging zone. The steel surface temperatures were 1100 °C at the beginning of melting and approximately 140 °C for packaging. In this study, four locations close to the heat sources were selected in the plant where workers were directly exposed to the thermal environment with strong heat radiation (see Fig. 2). According to the reference [24], the emissivity values were approximately 0.9 for the building envelope surface and 0.4–0.6 for the high temperature heat source surfaces (140 ~ 1100 °C).

2.2. Measurement parameters and instruments

The measurements were separately performed in summer from July 12 to 15 and in winter from December 5 to 8 in 2014. The measured parameters include indoor air temperature, globe temperature, air velocity, relative humidity and natural wet bulb temperature, which were collected using calibrated instruments, as shown in Table 1. The measurement instruments were placed close to the workers, at a height of 1.1 m above the floor. Moreover, the outdoor air temperature was obtained from the meteorological bureau of Shaanxi province.

Measurements at each location were made successively from 10:00 to 17:00. Due to the limited availability of instruments, the instruments were only put in one location during the measurement day. After measurement was completed in one location, the instruments were moved to the next location.

2.3. Questionnaire survey

The questionnaire included basic anthropological information of respondents, such as age, gender, height and weight as well as information on working years. The questionnaire also included a personal assessment of the thermal environment using subjective judgment scales based on ISO 10551 [25]. The assessment was in terms of their personal perception, comfort, thermal preference, personal acceptability and personal tolerance, as shown in Table 3.

During the survey period, 64 workers who had stayed at the study field for at least 30 min prior to the survey were invited to complete the questionnaire. Simultaneously, physical measurements were made. All of the workers were males, and they were of ages from 21 to 63 years old. All of the persons participating in the survey were volunteers. Worker's clothing and activity at four different locations in the plant were almost the same in summer and winter.

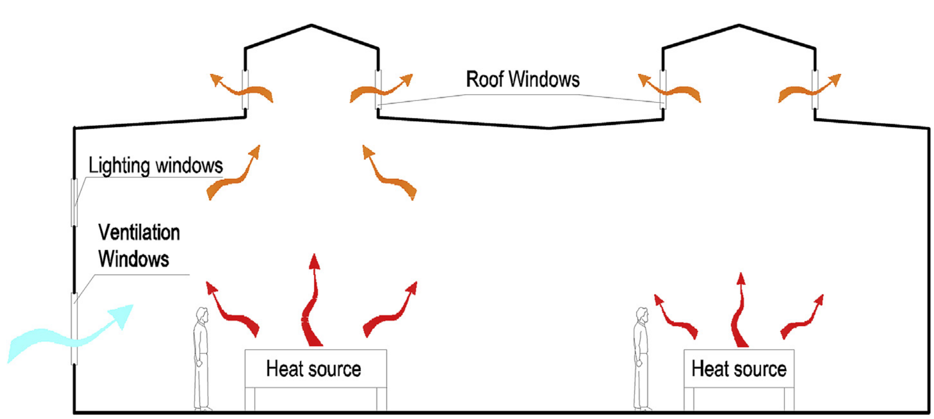

Fig. 1. The schematic diagram of the plant with natural ventilation.