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Measuring the transient airflow rates of the infiltration through the doorway of the cold store by using a local air velocity linear fitting method

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HIGHLIGHTS

- The infiltration is responsible for more than half of the total cooling load.
- A direct method is developed for measuring the transient infiltration airflow rates.
- The method is validated by the experiments of tracer gas decay technique.
- The measurement errors of infiltration airflow rates are distributed between ±10%.
- The practical application of the proposed method is discussed.

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ABSTRACT

The measurement of the infiltration airflow rates can support the calculation of the infiltration cooling load for the better understanding and optimizing the energy consumption of cold stores. However, the large temperature difference and the intense transient features make it difficult and complex to measure the airflow rates accurately. In this paper, a simple and practical method to measure the transient infiltration airflow rates is developed by using the local air velocity linear fitting. The proposed method is validated by the measurement results of the tracer gas decay method. It is concluded that the proposed method shows a good performance on the transient infiltration airflow rates measurement. The measurement errors are between ±10%. To enhance the application of this method, the layout of the measuring points of the air velocities are analyzed. The results show that, along the vertical layout direction, air velocity measuring points around the neutral level (where the cold and the warm air separate, about the middle height of the door) are not preferred when using this method. What's more, the calculation of the infiltration cooling load by using this measuring method is also discussed.

1. Introduction

Cold stores are main infrastructures and vital nodes of the cold chain system. With the rapid expansion of the cold chain market all around the world, tremendous cold stores are being used for the storage of the perishable products. It is reported that, the gross refrigerated storage capacity totaled 118 million cubic meters in the U.S. [1], 60–70 million in Europe [2] and about 133 million in China. Such a great number of cold stores consume a considerable amount of energy for working all year round. Meanwhile the cost of energy consumption has a robust correlation with the total cost. Therefore, a better understanding and optimization of the energy use of cold stores is intensely needed by the cold store owners and users.

It is believed that the refrigeration system is responsible for 60–70% of the electrical energy consumption of cold stores [3]. This part of energy is mainly used to remove the cooling load. For a better understanding of the energy use, a detailed analysis of the impact factors of the cooling load is needed. Similarly, thermal behavior or cooling load is also much concerned by researchers for the study of energy consumption of other buildings, such as commercial buildings [4], educational buildings [5] and research buildings [6]. Among these studies, the intermittent occupancy, which have significant impact on overall energy use, were

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Nomenclature

A	area (m^2)
C	specific heat capacity (kJ kg^{-1} °C^{-1})
d	moisture content (g kg^{-1})
E	effectiveness
G	airflow rate (m^3 s^{-1})
H	height (m)
Q	cooling load (kW)
r	latent heat of vaporization (kJ kg^{-1})
t	time (s)
u	velocity (m s^{-1})
V	volume (m^3)
W	width (m)

Greek symbols

ρ	mass density (kg m^{-3})
r	latent heat of vaporization (kJ kg^{-1})
λ	sensible heat of solidification (kJ kg^{-1})

Subscripts

tot	total
sen	sensible cooling load
in	indoor
out	outdoor
lat	latent cooling load
max	maximum
P	protection of doors
a	door with protection
b	door without protection

highlighted for the accurate prediction of the energy consumption of buildings [4–7]. The infiltration airflow through the opening of doors is an intermittent occupancy, especially in the cold store, which is a special kind of building with large temperature difference between indoor and outdoor. It can lead to a strong and transient air exchange through the door of cold stores. It is reported in some early researches that the infiltration through the doorway can be responsible for more than half of the total cooling load of cold stores [8]. Therefore, estimating the infiltration cooling load is a key point to the study of the energy use assessment and the energy saving strategies of cold stores.

In a specific case with the fixed condition of the temperature difference and door opening size, the infiltration cooling load is directly and mainly affected by airflow rates [9]. Thus, a premise to estimate the infiltration cooling load is the accurate measurement or determination of the airflow rates. However, measuring the infiltration airflow rates of cold stores has some challenges:

(1) The infiltration has a single-sided flow pattern (air flows in and out in the same side or surface) which establishes an intense and complex air exchange process around the doorway plane [10].
(2) The infiltration airflow rate varies along with the temperature difference between indoor and outdoor environment. Transient features are observed during the door is open [9].

On the top of the challenges, the accurate measurement of these intense and transient infiltration airflow rates is difficult.

An available method to measure the transient infiltration airflow rates is the tracer gas technique or the indirect method [11]. The concentration decay method, which is one of the tracer gas techniques, seems to be easy to implement and accurate enough. The use of CO_2 as a tracer gas was employed in some early researches to measure the airflow rates [12–14]. In the study of the infiltration in cold stores, Foster et al. conducted experiments by using the CO_2 decay method [15,16]. The mean infiltration flow rates under different infiltration conditions were obtained. Tian et al. also utilized this method to measuring the transient infiltration airflow rates in a specific cold store [17]. A detailed transient feature of the infiltration airflow rates was observed. However, this method relies on the data that collected from local tracer gas sensors. The sufficient air mixing process to get a homogeneous indoor air for the measurement is needed. And the tracer gas decay method can only yield the average flow rate of a period of time. Thus multi-period measurements or a lot of repeated measurements are needed for the measurement of the transient airflow rates.

Another method to measure the transient infiltration airflow rates is the direct method, which is supported by the local air velocity measurement [11]. The conventional model that describes the air flows inside and outside a building is the Bernoulli equation [18–20]. This so-called 'orifice equation' may fail on the description of the airflow rate through large openings for the assumptions that the velocity distributions are constants in the opening [21,22]. To avoid this drawback, a practical formula for the large openings is proposed and suggested by the ASHRAE (2009) handbook [23].

$$G = E \cdot A \cdot \bar{u} \tag{1}$$

The air velocity u in Eq. (1) is easy to be measured. Thanks to the velocity measurement, the high frequency data can be collected simultaneously at numerous points for the description of the velocity distributions. Comparing to the indirect method, the multi-period measurements by the tracer gas method are not needed, which makes the direct method time-reduced and more practical. However, the direct method is commonly recommended on the steady flow occasions. There is an opening effectiveness E in Eq. (1). Different values for E are given depending on the conditions of airflow incidence angle to the opening. Thus, this method may fail on the calculation of the transient airflow rates for the unsteadiness of the opening effectiveness E [24]. What's more, research on the direct method to measuring the transient airflow rates is barely found. Therefore, a further study on this kind of direct method may be necessary.

Currently, there is not mentioned on the direct method to measure the transient air infiltration. According to the characteristics of the air infiltration of cold stores [17,25], it is attempted to develop a simple and direct method to measure the transient air infiltration flowrate of opening for cold stores and similar buildings with large indoor and outdoor air temperature differences. Air velocities, which are measured by the omni-directional hot-wire anemometers (HWA sensors) per second at different positions, are linear fitted to calculate the mean air velocity through the door at each second. The transient airflow rates then can be obtained by utilization of a simple equation. The measurement results from the multi-period tracer gas decay technique, which is a reference method, are used to validate the proposed direct method. For the practical applications, the layout of the air velocity sensors and the calculation of the infiltration cooling load are also discussed.

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