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Research Paper

Development of an unsteady analytical model for predicting infiltration flow rate through the doorway of refrigerated rooms

Shen Tian [a,b,c,d], Yuping Gao [a,b,d], Shuangquan Shao [a,b,*], Hongbo Xu [a,b], Changqing Tian [a,b]

[a] CAS Key Laboratory of Cryogenics, Technical Institute of Physics and Chemistry, Beijing 100190, China
[b] Beijing Key Laboratory of Thermal Science and Technology, Technical Institute of Physics and Chemistry, Chinese Academy of Sciences, Beijing 100190, China
[c] Tianjin Key Laboratory of Refrigeration Technology, Tianjin University of Commerce, Tianjin 300134, China
[d] University of Chinese Academy of Sciences, Beijing 100049, PR China

HIGHLIGHTS

- An unsteady analytical model for predicting the infiltration flow rate is developed.
- The proposed model is validated by two independent experiments.
- The prediction errors of infiltration air volume are distributed between ±10%.
- The feasibility of applying the model to practical applications is analyzed.

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ABSTRACT

Infiltration through the doorway, which accounts for a very large part of total cooling load, has been highlighted in the previous studies on energy consumption of cold stores. Usually, the prediction of the infiltration flow rate is based on steady models and CFD simulations. However, the steady models are not very accurate for predictions of dynamic flow rates and the CFD transient simulations are time consuming. In this paper, the infiltration flow inside the door is described by the time-dependent differential equations of motion and continuity. An unsteady analytical model is developed by using these equations based on two independent infiltration procedures. Meanwhile, an equation to calculate the effective length of the infiltration is introduced to the proposed model to help improving prediction accuracy. The transient variables in this model are velocity, density and time. And these equations yield an ODE system, which can be numerically solved by using the Matlab software to get the dynamic infiltration flow rates. This model is validated by two independent experiments: infiltration with small and large door opening sizes respectively. The prediction errors are between ±10% for infiltration air volume and ±12% for infiltration flow rate. The performance of this model is also compared with the steady models. It is concluded that the proposed model has a better accuracy than the steady models in the strong transient occasions (with large door opening sizes). And this model is simpler than the CFD simulations on the calculations of the dynamic infiltration flow rates.

1. Introduction

Cold stores are one of the main infrastructures in the cold chain systems. In recent years, with the promotion of global cold chain commodity market, the number of cold stores has become tremendous. It is reported that there are 60–70 million m^3 cold stores in Europe [1], 118 million m^3 in the US [2] and 160 million m^3 in China [3]. Along with the huge number of cold stores, a large amount of energy is consumed by refrigeration equipment for all year round working. It is reported that the mean specific energy consumption (SEC) is 56.1, 73.5 and 61.2 $kWh\,m^{-3}\,year^{-1}$ for chilled, frozen and mixed cold stores respectively according to a recent survey [1]. Thus it is estimated that, in China, the energy consumption of cold stores in a year is approximately equal to the energy that consumed in one day by the whole society. With the further development of the cold chain system and the increased expectation for fresh and safety products from consumers, the number of cold stores may continuously increase as well as the total energy consumption.

* Corresponding author at: Beijing Key Laboratory of Thermal Science and Technology, Technical Institute of Physics and Chemistry, Chinese Academy of Sciences, Beijing 100190, China.

E-mail address: shaoshq@mail.ipc.ac.cn (S. Shao).

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Nomenclature

A	area (m^2)
C	specific heat capacity (kJ kg^{-1} °C^{-1})
d	moisture content (g kg^{-1})
g	gravity acceleration (m s^{-2})
H	height (m)
L	length (m)
M	mass (kg)
q	cooling load (kW)
Q	infiltration flow rate (m^3 s^{-1})
r	latent heat of vaporization (kJ kg^{-1})
R	diameter (m)
t	time (s)
v	velocity (m s^{-1})
V	volume (m^3)
Greek symbols	
ΔP	pressure difference (Pa)
ρ	density (kg m^{-3})
λ	coefficient of friction resistance
ζ	coefficient of local resistance
γ	sensible heat of solidification (kJ kg^{-1})
Subscripts	
c	refrigerated room
d	door
e	equivalent
f	friction
g	gravity
i	indoor
o	outdoor
el	effective length
tl	total length
lat	latent
max	maximum
sen	sensible
tot	total

Within cold store facilities, refrigeration system is responsible for 60–70% of the total electrical energy consumption [4]. The electricity used by the refrigeration system is directly dependent on the cooling load. Meanwhile, the cooling load is an important parameter for calculating the cooling capacity during the design phase of the refrigeration system. Thus it is possible to better understand and optimize the energy use of cold stores by accurate prediction of the cooling load. The cooling load of a building is mainly influenced by the heat transfer through the envelope, solar heat gain through the window, infiltration and internal heat gains [5]. Among these elements, the influence of the infiltration seems to synchronously change with the outdoor environment in other buildings [6]. And this part of cooling load can be predicted by steady models. Nevertheless, in cold stores, with larger temperature difference between indoor and outdoor, the infiltration shows more intense features. It is reported that infiltration through the doorway of cold stores is responsible for more than half of the total cooling load [7]. Large amount of warm and moisture air is added into the refrigerated room due to the randomly open of the door, as a result that greatly increases the sensible and latent cooling load. Lafaye de Micheaux et al. [8] stated that the heat load introduced by the infiltration is directly related to the infiltration flow rate. Therefore, many researchers have carried out the experiments and simulation studies on the characteristics and the predictions of the infiltration airflow to study the energy impact from the infiltration.

Infiltration through the doorway is the buoyancy driven single-sided air flow caused by the temperature difference between indoor and outdoor [9–12]. The intensity of the infiltration is dependent on the characteristics of the door and the driving mechanism of the airflow [13,14]. Many studies on this type of airflow are mainly focused on the little temperature difference occasions. And few of the investigations on the large temperature difference occasions are the simulations in the research field of the refrigerated display cabinets [15,16]. In 1963, Brown et al. proposed a model to predict the infiltration flow rate through the doorway of cold stores [17]. Since then many researchers have carried out experimental, theoretical and simulation studies on the infiltration. Foster et al. [18] compared the prediction performance of a series of steady models against the experimental results of a refrigerated room. The comparisons showed that all the steady models overestimated the infiltration flow rate and the largest prediction error was over 20%. Foster et al. [18] also validated a transient CFD model with their experimental results. The conclusion is that the CFD model, although could provide a complete description of the flow field, was less accurate than the most accurate steady model on the prediction of infiltration flow rate. However, the authors also pointed out that the grid size of the transient CFD model was not small enough to accurately predict the infiltration. Recently, Lafaye de Micheaux et al. [8] experimentally investigated the infiltration of a refrigerated truck body and established a transient CFD model to predict the infiltration. Based on the experimental and numerical analysis, the authors concluded that the infiltration flow had strong dynamic features, which were corresponding with two distinct stages: the buoyancy-driven flow and the steady-state natural convection. Considering the experimental results and uncertainties, the transient CFD model showed good agreements on the simulation of dynamic infiltration flow rates. However, excluding the time that exploited to build the physical model and set up the parameters, it took at least 6 days for the model solution.

As above mentioned, steady models and CFD simulations can be used to predict the infiltration flow rate. But they also have some disadvantages that may limit their applications:

(1) The infiltration flow rates which predicted by the steady models are constants. However, with such a big temperature difference, the infiltration of the refrigerated room shows some strong dynamic features during the door open [8]. The predictions of the steady models are not precise enough.
(2) The transient CFD model shows a good accuracy in the prediction of dynamic infiltration flow rate. However, it consumes a large amount of computing resources for precise predictions, which may cause difficulties in the engineering applications.

Therefore, Lafaye de Micheaux et al. proposed an analytical model to predict the dynamic buoyancy driven flow in their study [8]. This model employed the ideal flow theory (not considering the potential energy of air) to analyze the infiltration of a refrigerated truck body. Two time-dependent equations of force balance and energy conservation were used to establish this model. It was validated by their experiments that this model can correctly reproduce the infiltration dynamics. However, they mainly studied the refrigerated truck bodies that having small inner volumes compared to the doorway surface area, also pointed that more work is