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A model for predicting air permeation between temperature-fluctuated refrigerated room and ambience through magnetic seal

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ABSTRACT

The air permeation caused by the pressure difference at both sides of the magnetic seal accounts for a significant part of energy loss in a refrigerated room. The purpose of this study is to model the air permeation rate. Based on momentum equations of air flow along the permeation paths, the air permeation rate is deduced as a function of the average height of permeation paths and the flow factor. The average height is obtained by a resultant force of magnetic attraction and pressure difference under the assumption of parabolic asperity profile in the permeation paths; and the flow factor is calculated by semi-empirical correlations based on the average height of the permeation paths. An experiment is designed to validate the model, and the results show that the predicted air permeation rate can describe 98% of the experimental data within a deviation of ± 15% and the mean deviation is 5.6%.

Un modèle pour prédire la perméation d'air entre une chambre froide à température fluctuante et l'air ambiant à travers un joint magnétique

Mots-clés: Perméation de l'air; Chambre froide; Joint magnétique; Différence de pression; Modèle

1. Introduction

Refrigerated rooms, such as refrigerators, freezers, cold storages and freezer cars, are widely used for food, biological product and medicine preservations (Liu et al., 2015; Zhou et al., 2013). The magnetic seal is a commonly used sealing structure of the refrigerated room, which contacts with the cabinet of the refrigerated room by the magnetic force.

Air may permeate through the magnetic seal between the refrigerated room and the ambience. The air temperature and pressure periodically fluctuate in the refrigerated room with the control of on/off mode (Lu et al., 2004; Hermes and Melo, 2008), leading to the inhalation of hot air and the exhalation of cold air through the magnetic seal. The air permeation process periodically occurs, like the "breathing" of a person, and its effect is called as "breathing effect".

Air permeation through the magnetic seal caused by the "breathing effect" is one of the main sources of the energy loss in the refrigerated room. The power consumption used to offset this part of the energy loss accounts for approximately 20% of the total power consumption of a refrigerated room (Kim et al., 2011; Afonso and Castro, 2010; Yan et al., 2016). Air permeation can also cause the frosting on evaporator walls (Stein et al., 2002; Knabben et al., 2011; Hermes et al., 2014; Laguerre et al., 2010), leading to the deterioration of heat transfer performance (Seker et al., 2004a, 2004b). Besides, the removal of the frost will decrease the preservation quality (Bansal et al., 2010). Thus, it is important to reduce the air permeation through the magnetic seal.

Increasing magnetic attraction force of the seal is a way to reduce the air permeation, while it may cause inconvenience for users. The increased magnetic attraction force will reduce the air permeation rate and the air pressure in the refrigerated room will decrease significantly when the refrigerated room supplies cooling

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Nomenclature

C	fitted coefficient for calculating φ
D	fitted coefficient for calculating φ
E	composite Young's modulus, Pa
F_c	total contact force of soft and hard surfaces, N
F_i	contact force of each pair of asperities, N
F_{mt}	magnetic attraction force, N
G_d	weight of the door, N
Δh_{ave}	average height of permeation paths, m
K	parameter describing roughness
l_1	width of magnetic seal, m
l_2	length of magnetic seal, m
m	air permeation rate along real rough permeation paths, kg s^{-1}
m_{ideal}	air permeation rate along ideal smooth permeation paths, kg s^{-1}
m_p	air permeation rate per length, kg s^{-1} m^{-1}
N	number of contact asperities
P	air pressure, Pa
ΔP	pressure difference, Pa
r	horizontal distance between the peaks of contact asperities, m
R	curvature radius of asperity, m
R_s	specific gas constant of air, J kg^{-1} K^{-1}
S	area, m^2
S_c	contact area of soft and hard surfaces, m^2
t	time, s
T	air temperature, K
u	air velocity in x direction, m s^{-1}
v	air velocity in y direction, m s^{-1}
V	air volume flow rate, m^3 s^{-1}
w	air velocity in z direction, m s^{-1}
Greek	
σ	composite surface roughness, m
μ	dynamic viscosity of air, N s m^{-2}
ρ	density, kg m^{-3}
φ	flow factor
δ_i	deformation of each pair of asperities, m
β	vertical distance between the peaks of contact asperities, m
γ	directional property of surface
ε	Poisson ratio of material
η	density of asperity peaks on soft or hard surface, m^{-2}
Φ	height distribution of asperities
Subscript	
a	ambient
h	hard surface
in	inside the refrigeration room
s	soft surface

capacity under the on mode. A large pressure difference between the ambience and the refrigerated room will occur and cause a large cohesion force at the door, leading to the difficulty in opening the door (Bansal et al., 2011). In order to reduce the air permeation as well as guarantee to open the door easily, all factors influencing the air permeation should be analyzed, and their relationships should be quantitatively described.

Among all the factors on the air permeation, the pressure difference and the permeation paths are the most important ones. The pressure difference is the driving force for air permeation, while the permeation paths determine the resistance of air permeation. The pressure difference can also influence the permeation paths by changing the tightening force of the seal in the refrigerated room. Thus, the coupling effects of pressure difference and permeation paths should be investigated in order to develop a model for predicting the air permeation rate.

The air permeation through the magnetic seal is the process of fluid permeation through contact interfaces. The existing researches on the model of fluid permeation rate can be categorized into two types, including the gas permeation through contact interfaces and the oil permeation through contact interfaces.

Gas permeation through contact interfaces has been modeled in the existing researches. The theoretical models are established based on the contact theory of rough surfaces and the permeability theory (Persson and Yang, 2008; Bottiglione et al., 2009; Persson, 2001; Lorenz and Persson, 2009). The permeation paths can be regarded as the porous media, and the permeation models based on the penetration theory of porous media are established (Zhang, 2008; Zheng et al., 2013; Jolly and Marchand, 2009). The semi-empirical models are developed by relating the leakage with the face loading and the other relevant parameters (Polycarpou and Etsion, 1998; Cai et al., 2015, 2017). The simplification of permeation paths such as considering the permeation paths as a capillary structure (Marchand et al., 2005) or a row of elongated square micro channels (Ke et al., 2015, 2017) is also an effective method to calculate the gas leakage. In order to validate the models, the gas tracing technology is applied in the measurement of the air leakage in the refrigerated room (Afonso, 2015).

Oil permeation through contact interfaces has also been modeled, e.g. the models developed by introducing the flow factor parameter based on the average Reynolds equation (Letalleur et al., 2002; Sahlin et al., 2007; Patir and Cheng, 1978,1979). The permeation rate of lube oil is also measured by experiments to validate the models (Marie and Lasseux, 2007).

The pressure difference in the existing gas and oil permeation models is independent with the permeation paths. However, for the refrigerated room, the pressure difference will not only drive the air to permeate but also influence the tightening force of seal, leading to the variation of permeation paths. Moreover, the effects of pressure difference on the permeation paths are different in the inhaling and exhaling process of "breathing effect". Thus, the existing models cannot be directly applied to predict the air permeation rate in the refrigerated room.

The purpose of the present study is to propose a model for calculating the air permeation rate in a refrigerated room. Moreover, an experiment is performed to validate the model.

2. Modeling object

The schematic diagram of a refrigerated room is shown in Fig. 1. The refrigerated room is composed by a cabinet and a door, as shown in Fig. 1(a). The air flows into or out of the refrigerated room through the magnetic seal when the temperature and pressure of air in the refrigerated room fluctuate, as shown in Fig. 1(b). The contact interfaces, including the hard surface (surface of cabinet) and the soft surface (surface of magnetic seal), form the paths for air permeation, as shown in Fig. 1(c) and (d).

The air permeation caused by the "breathing effect" is schematically shown in Fig. 2. The operation of the refrigerated room is controlled by an on/off mode. When it is at on-mode, the evaporator cools the air inside the refrigerated room and makes the air temperature and pressure to decrease, resulting in the inhalation of hot air, as shown in Fig. 2(a). When it is at off-mode, the evaporator stops cooling the inside air and the air temperature and pressure increase, leading to the exhalation of cold air, as shown in Fig. 2(b).