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Research Paper

3D and transient numerical modelling of door opening and closing processes and its influence on thermal performance of cold rooms

Rui Carneiro, P.D. Gaspar*, P.D. Silva

University of Beira Interior, Electromechanical Engineering Department, Calçada do Lameiro, 6200-001 Covilhã, Portugal

HIGHLIGHTS

- A 3D CFD modelling of opening/closing cycle of cold room's doors is developed.
- The CFD simulation uses the tracer gas concentration decay experimental technique.
- Air infiltration rate through sliding door is 20% lower than through a hinged one.
- Air temperature inside cold room with sliding door is 17% lower than with hinged one.
- The developed model extends the analytical results for door opening/closing periods.

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ABSTRACT

This paper presents the comparison of three-dimensional and transient CFD modelling of the opening and closing processes of hinged and sliding doors and its influence on the thermal performance of cold rooms. A species transport model is used to model a tracer gas. The air infiltration through the door opening is determined by the tracer gas concentration decay technique. The prediction of air temperature and velocity fields in the cold room as function of external air temperature allows quantifying the increase of the air infiltration rate and consequently of the average air temperature inside the cold room. When the hinged door is used, the formation of vortices during the opening movement promotes a larger and faster thermal interaction between the two contiguous air masses. The air infiltration during the sliding door opening/closing is 20% lower than for a hinged door. Consequently, the average air temperature inside the cold room is 17% lower. The air infiltration rate was numerically predicted and compared with analytical models' results. The numerical model predicts closely the air infiltration rate for each door type. Moreover, the transient CFD modelling extends the results of the analytical models allowing the analysis of the influence of door opening and closing processes on the air temperature and velocity fields.

1. Introduction

The door opening and closing cycles for storing or removing food products from cold rooms imply the infiltration of hot and humid air. This condition may have several consequences on production efficiency, product quality, hygiene, food safety and maintenance [1]: (1) increase of the thermal load (it can reach up to 50% of the total heat load), which reduces the refrigeration system's ability to maintain the desired temperature; (2) higher coil frost formation rates that reduce the refrigeration capacity due to the insulating effect [2–4]; (3) temperature fluctuations that may impair food quality, food safety and induce weight loss [2,5]. Therefore, its analysis and quantification are very important once it can lead to the use of best practice measures and complementary solutions to reduce the frequency with which the refrigeration system is triggered, and consequently to a reduction of energy consumption while ensuring products quality [4,6].

Evans et al. [7] conducted a study to characterize the energy consumption of cold stores. Energy audits were performed in cold stores of several European countries to identify possible energy savings measures and practices. Infiltration/protection of doors represented about 8.3% of problems identified in refrigeration rooms with a volume higher than 100 m^3. An average energy saving from 6% to 17% was estimated with the implementation of simple maintenance practices and/or improvement on the cold room doors. Thus, the knowledge of the influence of the warm air infiltration into cold rooms is relevant since it allows setting up strategies, such as loading and unloading maps, collaborators training and awareness to the adoption of solutions/protection devices such

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* Corresponding author.
E-mail address: dinis@ubi.pt (P.D. Gaspar).

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Nomenclature

General

A	area [m^2]
b	wall thickness [m]
C	tracer gas concentration [%]
Ca	specific heat at constant pressure [kJ kg^{-1} K^{-1}]
g	gravity acceleration [9.81 m s^{-2}]
H	height [m]
i	infiltration [m^3]
I	infiltration rate [m^3 s^{-1}]
J_i	diffusion flux [kg s^{-1} m^{-2}]
k	thermal conductivity [W m^{-1} K^{-1}]; turbulent kinetic energy [m^2 s^{-2}]
$K_{f,L}$	Fritzsche & Lilienblum correction factor
L	length [m]
m	mass [kg]
n	generic quantity
p	pressure [Pa]
$\vec{r}$	position vector [m]
R	gas-law constant [J kmol^{-1} K^{-1}]
S	source term
t	time [s]
T	temperature [K or °C]
$\underline{u_i}$	velocity magnitude – component in i direction [m s^{-1}]
$\vec{v}$	velocity vector
v	velocity (average) [m s^{-1}]; specific volume [m^3 kg^{-1}]
V	volume [m^3]
W_a	molecular weight of gas [kg kmol^{-1}]
x; y; z	spatial coordinate system [m]
x_i	spatial coordinate – component in i direction [m]
Y_i	mass fraction of species i [kg$_i$ kg$_m$$^{-1}$]

Greek symbols

δ	Function Delta de Dirac
δ_{ij}	Kronecker tensor
Δ	increment; range; difference
ϕ	dependent variable (generic)
θ	door opening degree [°]
λ	stopping criterion of iterative process
μ	dynamic viscosity [kg m^{-1} s^{-1}]
ρ	density [kg m^{-3}]

Lower rates

1	initial time
2	final time
avg	average
ext	air outside the cold room
i	initial
i, j, k	component of cartesian directions x, y and z
in	air inside the cold room
ref	reference
rel	relative
tracer	tracer gas
var	variation of a quantity
vc	element; control volume
total	reference to the air total infiltration rate
ϕ	generic dependent variable

Higher rates

$\rightarrow$	vector

as strip PVC curtains, air curtains, flexible fast-opening doors and vestibules to improve energy efficiency [2–4].

Several analytical, experimental and/or numerical methods can be used to estimate the air infiltration rate into cold rooms. Foster et al. [8] carried out experimental measurements of a tracer gas concentration to calculate the air infiltration rate through cold room entrances with different sizes and with different air temperatures within the chilled space. The experimental results were compared with numerical predictions and with the results provided by analytical models. The results showed that analytical models developed by Gosney & Olama [9] and Fritzsche & Lilienblum [10] are those that best predict the air infiltration rate and even with better accuracy than the computational model. However, when a transient analysis is performed, the analytical models provide inaccurate predictions of the air infiltration rate because the door opening and closing movements are not considered. Gonçalves et al. [11] experimentally measured the air infiltration rate into a cold room using a tracer gas technique. The experimental results were compared with numerical model predictions and with the results provided by analytical models. It was concluded that analytical models are not suitable for determining the air infiltration rate in a transient analysis. The predictions obtained with the numerical models are in agreement with experimental results, and then the solution was validated since numerical models give a closest prediction of the air infiltration rate into the cold room as well the air temperature and velocity fields, either inside or outside of the chilled space.

The tracer gas technique, such as found in both studies discussed above, is one of the experimental methods that can be used to determine the air infiltration rate [12,13]. Within the tracer gas technique, the tracer gas concentration decay technique is suitable for this purpose. This method consists in introducing a predetermined quantity of tracer gas, C_{initial}, inside the cold room volume, V [m^3]. This gas will be mixed with indoor air to ensure a uniform concentration, equal to the preset. The air infiltration rate, I [m^3 s^{-1}], can be determined after a time period, T [s], by the knowing of the tracer gas concentration, C_{final}, using Eq. (1) [2,11–13].

$$I = \frac{V}{T} \ln \left(\frac{C_{\text{initial}}}{C_{\text{final}}} \right) \tag{1}$$

Several studies have considered the development of analytical models to quantify the air infiltration over the time. Table 1 includes empirical mathematical expressions to determine the air infiltration, I [m^3 s^{-1}]. All equations have a common set of variables. The density is an example, once the infiltration rate is directly related to the difference of density between the air of the interior, ρ_i, and external, ρ_o, environments. In addition, the opening area, A [m^2], the height of the door, H [m], and the accel-

Table 1
Analytical air infiltration models by natural convection through the door opening [9].

Authors/Year	Equations
Brown and Solvason [15]	$I = 0.343A(gH)^{0.5}\left[\frac{\rho_{in}-\rho_{ext}}{\rho_{avg}}\right]^{0.5}\left[1 - 0.498\left(\frac{b}{H}\right)\right]$
Tamm [14]	$I = 0.333A(gH)^{0.5}\left[\frac{\rho_{in}-\rho_{ext}}{\rho_{in}}\right]^{0.5}\left(\frac{2}{1+(\rho_{ext}/\rho_{in})^{0.333}}\right)^{1.5}$
Fritzsche and Lilienblum [10]	$K_{f,L} = 0.48 + 0.004(T_{ext} - T_{in})$
	$I = 0.333K_{f,L}A(gH)^{0.5}\left[\frac{\rho_{in}-\rho_{ext}}{\rho_{in}}\right]^{0.5}\left(\frac{2}{1+(\rho_{ext}/\rho_{in})^{0.333}}\right)^{1.5}$
Gosney and Olama [9]	$I = 0.221A(gH)^{0.5}\left[\frac{\rho_{in}-\rho_{ext}}{\rho_{in}}\right]^{0.5}\left(\frac{2}{1+(\rho_{in}/\rho_{ext})^{0.333}}\right)^{1.5}$
Pham and Oliver [16]	$I = 0.226A(gH)^{0.5}\left[\frac{\rho_{in}-\rho_{ext}}{\rho_{in}}\right]^{0.5}\left(\frac{2}{1+(\rho_{ext}/\rho_{in})^{0.333}}\right)^{1.5}$