Experimental Thermal and Fluid Science 74 (2016) 308–323

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

journal homepage: www.elsevier.com/locate/etfs

Numerical and experimental study of airflow patterns and global exchanges through an air curtain subjected to external lateral flow

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ARTICLE INFO

Article history:
Received 23 September 2015
Accepted 25 November 2015
Available online 17 December 2015

Keywords:
Air curtain
Perturbed jet
Cabinet
Turbulence
CFD
PIV

ABSTRACT

The objective of this study is to experimentally and numerically investigate the aerodynamic behavior and the effectiveness of an air curtain confining cavity and subjected to external lateral stream. Experiments were carried out on a scale down model (1:5) representing a generic configuration of a display case, using LDV and PIV techniques to investigate the air flow characteristics. Two complementary modelling approaches were performed. The first is based on computational fluid dynamics (CFD) which enables to better understand the local air flow characteristics, while the second deals on the global fluxes exchanged between the air curtain, the ambient and the cavity. The good agreement obtained between CFD and experimental results allows to validate the numerical model and also to build the global model. Comparisons of experimental and numerical data obtained with and without external perturbation make it possible to quantify the effect of the perturbation on the air curtain characteristics such as airflow patterns, velocity profiles, maximum velocity decay, half-width jet growth and its stability as well as those related to the global fluxes exchanged between the air curtain and its surroundings. To evaluate the sealing performance of the air curtain with and without external perturbation, dimensionless parameters related to air tightness, thermal entrainment and thermal confinement efficiency were identified and analyzed. It was showed that for higher values of external lateral velocity, the performance of the air curtain was reduced consequently.

1. Introduction

In many industrial applications, air curtains formed by plane air jets are used to provide a dynamic barrier for reducing and controlling the heat and mass transfer between two adjoining areas with different level of temperature, humidity and pollution. Air curtains are used to create refrigerated spaces [1,2], open minienvironment for sensitive high quality products [3] or to reduce the spreading of fire smokes in underground tunnels [4,5]. One of the relevant applications is the vertical open Refrigerated Display Cabinet (RDC) widely used in supermarkets. Within this scope, air curtain plays a key role in keeping food at prescribed regular temperatures, while allowing an energy-saved control and an open access for customers. In a typical RDC, the air jet flows from nozzle inlet located at the top front to a nozzle exit located at the bottom front of the case, acts as a barrier between the warm ambient air and the chilled compartment. Due to their design, RDC are very sensitive to ambient conditions and they are considered as the weakest link of the cold chain. This could be partially explained by the fact air curtains are easily disturbed by the outside ambient air, which in addition results in higher temperature rise and more power consumption [6–8]. These disadvantages are difficult to overcome since the European testing standard, EN441 is established for steady ambient conditions where the surrounding velocity is below 0.15 m/s.

As the air curtains play a very important role in the cold preservation of display cabinets, various researches have been made in this field, including experimental studies [6,9,10], computational fluid dynamics (CFD) simulations [11–16] and global modelling approaches [17–19].

Many authors [11–16] have shown computational fluid dynamics (CFD) to be a valuable tool to rapidly provide design options to improve airflow within display cabinets. In their studies, The authors use the CFD models to optimize RDC design or to minimize energy losses through air curtain by testing the influence of the main factors which include the dimensions of the nozzle inlet, the nozzle exit, the length of air curtains, the initial velocity, turbulent intensity and temperature of air curtains and the temperature and velocity of the ambient environment.

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http://dx.doi.org/10.1016/j.expthermflusci.2015.11.028
0894-1777/

Nomenclature

C	dimensionless mass fraction (–)
C_p	specific heat of air (J kg^{-1} K^{-1})
D_H	hydraulic diameter of inlet (m)
e	nozzle inlet width (m)
H	height of the cavity (m)
I	turbulence intensity ($I_i = \frac{\sqrt{\overline{u_i^2}}}{U_i}$) (%)
k	kinetic energy of turbulence (m^2 s^{-2})
K_y	jet-spreading rate (–)
L	nozzle inlet length (m)
$\dot{m}_0$	mass flow rate of the jet (kg s^{-1})
Nu	Nusselt number, Nu = hd/λ
p	static pressure (Pa)
Pr	Prandtl number, $Pr = \frac{Cp\mu}{\lambda}$ (–)
Re	Reynolds number, $Re = \rho U\, e/\mu$ (–)
T	temperature (K)
$\overline{u_i u_j}$	Reynolds stresses component (m^2 s^{-2})
U_i, u_i	mean and fluctuating velocity component in x_i direction (m s^{-1})
U_{rms}	normalized streamwise RMS velocity = $\sqrt{\overline{u'^2}}\Big/U_m$ (–)
V_c	volume of the cavity (m^3)
x_0	virtual origin of the normalized velocity half width (m)
$y_{1/2}$	jet half-width, calculated at the y-location at which $U(x) = 1/2$ Um(x)
x, y, z	streamwise (x), transverse (y) and lateral (z) directions in Cartesian Coordinates (m)

Greek symbols

ε	turbulent dissipation rate. (m^2 s^{-3})
δ_{ij}	Kronecker symbol
μ	laminar dynamic viscosity (Pa s)
λ	thermal conductivity (W m^{-1} K^{-1})
μ_t	turbulent viscosity (Pa s)
ν	kinematic viscosity (m^2 s^{-1})
ρ	density (kg m^{-3})

Subscript

$\perp$	normal
0	relative to inlet boundary condition
a	ambient
c	cavity
cl	centerline
lf	lateral flow
m	maximum
i, j, k	relative to coordinate system
x, y, z	relative to coordinate system

Acronyms

ELS	external lateral stream
LDV	Laser Doppler Velocimetry
PIV	Particle Image Velocimetry
RDC	Refrigerated Display Cabinet
RMS	Root Mean Square

Smale et al. [14] bring out a review on the importance of the complementary role of CFD approach and its ability to handle the complex configurations of refrigerating facilities including RDC. The authors stress the importance of the validation of CFD models which necessitates rigorous comparisons with experimental data.

D'Agaro et al. [7] perform 2D and 3D CFD simulations to investigate the effects of the cabinet length, of the air curtain and of longitudinal ambient air movement on air flow pattern and temperature distribution in a frozen food vertical display cabinet. The authors pointed out the importance of the 3D effects. The computed refrigerating power shows that even low room air velocity of 0.2 m/s, due to its interaction with the end-wall vortices, has a significant impact on cabinet performance. A similar result was found by Gaspar et al. [6] who conducted an experimental work to study the heat transfer rate and thermal entrainment factor of air curtains in a RDC for different ambient air conditions. In this study, the high values of thermal entrainment observed at the sidewall locations can be attributed to sidewall effects, as the air curtain is unable to restrict the free entry of external air at the extremities of the RDC. The results of Gaspar et al. [6] also show that the increase of ambient air velocity magnitude from 0.2 to 0.4 m/s, even parallel to the plane of the equipment's frontal opening, promotes thermal interaction between the conservation zone and ambient air masses by disturbance of aerothermodynamics barrier provided by air curtain. The total heat transfer rate increases 53% due to increase of air infiltration load across the air curtain.

Navaz et al. [17] carried out a parametric study with CFD computations and DPIV to identify and to quantify parameters that have significant effects on the amount of entrained (warm) air in an RDC and its minimization. The authors found that the turbulence intensity, the shape of the mean velocity profile at the nozzle inlet, and the Reynolds number are mainly responsible for the amount of entrained air in a display case. The results indicate that lowering the Reynolds number of the air curtain reduces the entrainment rate. However, sufficiently high momentum should still exist to enforce the integrity of the air curtain structure.

Ge et al. [16] performed a simulation model for the multi-deck medium temperature display cabinets through the integration of CFD air dynamic and detailed cooling coil sub-models. This model can therefore be used to explore and analyze the optimal designs of the geometrical structures of cabinets, curtains and coils and further of control strategies and operating states for the cabinets.

However, it's worth to notice that the validation of the majority of CFD models reported in the literature (Cortella et al. [12], D'Agaro et al. [7], Cortella [11], Ge et al. [16]) are obtained by comparisons with test results limited to temperature and humidity (no velocity measurements were performed). Even when velocity measurements have been performed, they are limited to some velocity profiles [1] which is not enough to validate complex 3D airflow patterns [2]. Thus, there is a need to use of more advanced non-intrusive techniques like PIV and LDV in order to obtain high enough resolution to characterize air flow patterns and velocity profiles and turbulence levels. The obtaining of such results allows a better understanding of airflow characteristics and also improves the quality of CFD validation.

Havet et al. [20] and Rouaud et al. [21] used Laser tomography and tracer gas experiments to investigate the influence of external perturbations such as sharp pressure changes created by an opening-door on a minienvironment protected by an curtain device. The corresponding results clearly indicate that the minienvironment and the particularly the air curtain are strongly sensitive to perturbations. The resulting violent back-and-forth motion of the jet induces eddies responsible for entrainment of external pollution inside the working area. Moureh et al. [22] develop a CFD model to predict the influence of air conditioning system on a vertical cabinet. Nevertheless, the main drawback of these works is that only qualitative results were achieved.

Two important physical parameters appear in the bibliography analysis and have been studied in general by all others, and are named thermal entrainment reflecting the energy loss, and the air curtain tightness which is responsible for the temperature or pollution infiltration to the confined cavity. According to Howell