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Heat and moisture insulation by means of air curtains: Application to refrigerated chambers

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ABSTRACT

The present study is devoted to the determination of the efficiency of air curtain units (ACUs) applied to heat and moisture insulation of refrigerated chambers. A detailed study of the fluid dynamics and heat and mass transfer of the ACU in the refrigerated space and the external ambient is carried out by means of large eddy simulations (LES). The heat and moisture entrainment through the doorway and their transport inside the inner space are fully described. Three different configurations are studied: non-recirculating, recirculating and twin-jet air curtains. The condensation produced in the cool walls of the refrigerated space is evaluated considering the warm humid air from the ambient which penetrates inside the chamber through the doorway. The influence of both the discharge velocities and the discharge angles on the sealing capabilities of the three different tested ACU configurations is determined.

Isolation thermique et hydrique aux moyens de rideaux d'air: Application aux chambres frigorifiques

Mots clés : Rideau d'air ; Recirculation ; Double jets ; Efficacité d'énergie thermique ; Condensation ; Modèle de turbulence LES

1. Introduction

An air curtain unit (ACU) is a device which produces a plane impinging jet acting as an ambient separator. The application of ACUs in the refrigeration and HVAC fields implies the need for determining the efficiency of these devices to avoid both the heat and moisture entrainment in the protected spaces. The jet produced by the ACU and its sealing capability strongly depend on the difference of pressure and/or temperature between the inner (protected) and outer (ambient) spaces and the wind effect. The efficiency of ACUs has been studied by several authors since the 1960s.

The studies of Hetsroni and Hall (1964) and Hayes and Stoecker (1969) are the first attempts to characterise ACUs by means of simplified models. Later, Sirén (2003a, 2003b) introduced

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Nomenclature

C_w	turbulence model constant [-]
c_p	specific heat at constant pressure $[J\,kg^{-1}\,K^{-1}]$
D_v	diffusivity of water vapour in air $[m^2\,s^{-1}]$
E_{ff}	air curtain sealing efficiency [-]
$\dot{G}$	mass flux rate $[kg\,m^{-2}\,s^{-1}]$
g	gravity acceleration $[m\,s^{-2}]$
L_v	latent heat of vapourisation $[J\,kg^{-1}]$
Pr	Prandtl number, $Pr = \mu\,c_p/\lambda$ [-]
RH	relative humidity [-]
$\mathbf{S}$	rate of stress tensor $[s^{-1}]$
$\mathcal{S}$	traceless symmetric part of square of $\boldsymbol{\gamma}$ $[s^{-2}]$
Sc	Schmidt number, $Sc = \nu/D_v$ [-]
u	velocity vector with components (u,v,w) $[m\,s^{-1}]$
Y_v	mass fraction of water vapour [-]
x, y, z	Cartesian coordinates [m]

Greek symbols

α	thermal diffusivity, $\alpha = \lambda/\rho/c_p$ $[m^2\,s^{-1}]$
$\boldsymbol{\gamma}$	velocity gradient tensor $[s^{-1}]$
Δ	length scale of the filter [m]
Δl	characteristic length of the control volume [m]
Δt	time step [s]
$\boldsymbol{\delta}$	unit tensor [-]
θ	nozzle discharge angle [°]
λ	thermal conductivity $[W\,m^{-1}\,K^{-1}]$
μ	dynamic viscosity $[kg\,s^{-1}\,m^{-1}]$
ν	kinematic viscosity $[m^2\,s^{-1}]$
ν_e	kinematic eddy viscosity $[m^2\,s^{-1}]$
ρ	density $[kg\,m^{-3}]$
$\boldsymbol{\tau}$	Reynolds stress tensor $[m^2\,s^{-2}]$
$\bar{\phi}$	filtered variable ($\varphi = \mathbf{u}$, p, T, Y_v, . . .)

Subscripts

da	dry air
δ	liquid–gas interface
e	effective
g	gas phase
t	turbulent
v	water vapour
ω	liquid water

a semi-analytical method which allows a more accurate dimensioning of these devices. More recently, Giráldez et al. (2013) proposed an improved semi-analytical methodology that takes into account deviations in the jet trajectory that can produce additional losses.

More advanced strategies using CFD (computational fluid dynamics) techniques have been extensively applied. Foster et al. (2006) used a 2D CFD model to evaluate the effectiveness and optimum jet velocity for a plane jet air curtain. They studied the importance of the shape of the jet and the influence on the air curtain effectiveness of the jet velocity and door-open duration. However, the results of the 2D analysis were not satisfactory and the necessity of 3D simulations was pointed out. Subsequently, these authors (Foster et al., 2007) presented a 3D simulation where the influence of the stack pressures on the deflection of the lateral ends of the air curtain is analysed.

Different CFD studies have been carried out on open vertical display cabinets where air curtains separate the protected refrigerated space from the exterior. D'Agaro et al. (2005) showed that secondary vortices at the side walls provide the most important mechanism for air entrainment. Comparison with experimental results showed that 3D computations are required to properly describe the air flow, a 2D simulation being inadequate for such configurations. Cortella et al. (2001) implemented a 2D finite element code based on the stream function-vorticity formulation, and LES turbulence modelling for the analysis of air flow and temperature distributions (fully 3D LES modelling was used by the authors in the above mentioned paper (Giráldez et al., 2013)). Valkeapää and Sirén (2010) studied the thermal energy efficiency of ACUs, comparing both recirculating and non-recirculating installations. They apply the semi-analytical approach developed by Sirén (2003a) to study an upward blowing ACU. They found that the upper limit for the tightness of recirculating installations is about 80%.

Hammond et al. (2011) proposed a design guide for cabinet designers based on experimental work and CFD analysis using a 2D model. Navaz et al. (2005) focused the attention on three important parameters which condition the flow entrainment in ACUs: turbulence intensity, Reynolds number and velocity profile at the discharge, and their effect on the development of turbulence and mixing. Marinetti et al. (2014) simulate the 3D isothermal air flow inside cooling ducts of horizontal open type cabinet. They showed the capability of the model to predict the main features of the flow field.

None of the above mentioned papers consider the vapour transport from the humid air. Furthermore, all of them (except the papers already mentioned by Cortella et al., 2001, and the one by the authors (Giráldez et al., 2013)) use commercial CFD codes and standard two equation RANS modelling (in general k-ε models).

Turbulence modelling using RANS (Reynolds averaged Navier–Stokes) approach is based on the time average Navier–Stokes equations. As it is well known, time averaging generates new unknowns (the turbulent Reynolds stresses and heat fluxes), which have to be modelled. This is a formidable task because these terms are highly anisotropic and involve all the scales of the turbulent flow. A wide variety of models have been proposed, with the above mentioned two-equation models being the most popular. The accuracy of the simulations is very dependent on the turbulence model and the selection of the most appropriate one for a specific application is crucial. Jaramillo et al. (2009) analysed air curtain devices applied to refrigerated chambers. Their studies showed that numerical results are strongly dependent on the different turbulence models tested (algebraic Reynolds stress and linear and non-linear k-ε and k-ω RANS models).

In this sense, LES (large eddy simulation) is a much more powerful approach. The largest scales of the turbulent flow, which are anisotropic, unsteady and 3D, are solved in detail while only the smallest scales (the so called subgrid scales) are modelled. Even though LES is computationally more demanding than RANS, their simulation capabilities are much higher.