An Evaluation of Computational Fluid Dynamics for Modelling Buoyancy-Driven Displacement Ventilation

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To Mom and Dad who have always encouraged
me and supported my work

“Only after the last tree has been cut down,
Only after the last river has been poisoned,
Only after the last fish has been caught,
Only then will you find that money cannot be eaten”

Cree Indian Prophecy

Abstract

Environmental concerns and demands for energy efficiency have prompted building designers to reconsider natural ventilation rather than mechanical ventilation and air conditioning. Natural ventilation can be brought about either by wind pressure or by buoyancy forces generated by temperature differences. This research addresses buoyancy-driven flows in a displacement ventilation regime.

Buoyancy-driven displacement ventilation occurs when thermal plumes, which form above heat sources such as occupants and electrical equipment, cause warm, buoyant air to accumulate in the upper part of a space forming a stratified layer. This layer drives a flow out of openings at high level which then draws in fresher air through low level openings. The design of such ventilation strategies must ensure that the layer of stratified air is able to drive a sufficient airflow rate and that the lower level of the stratification remains above the occupants' breathing zone.

Computer models can be used to assist with the design of naturally ventilated buildings. One such tool which has seen increased use with the advent of faster, more affordable, desk-top computers, is *Computational Fluid Dynamics (CFD)*. CFD is a detailed airflow modelling technique which solves the governing equations of air motion to give predictions of, primarily, pressure, velocity and temperature at many locations throughout the geometry under consideration. However, literature to-date points to short-comings in the capabilities of CFD for modelling buoyancy-driven flows.

The aim of this research was to evaluate the accuracy with which CFD is able to model buoyancy-driven flows. This has been done by defining three simple benchmark cases for which both analytical results and salt bath modelling measurements exist. These fundamentally different modelling techniques enable two distinct mechanisms for evaluation. The benchmarks comprise rectangular spaces with point and line sources of buoyancy (heat input) on the floor and openings to the outside air in the top and bottom. The CFD simulations were carried out using the code CFX which comprises solution and modelling techniques (such as turbulence modelling) which are typical of many commercially available CFD programs.

The program gave favourable predictions for the level of the horizontal interface between the warm and cool air, the temperature change across the interface, and the air change rates and flow patterns. Some discrepancies existed in modelling the buoyant plumes produced above the heat sources when using the standard $k-\varepsilon$ turbulence model. These were reduced when employing the more recent $k-\varepsilon$ model based on renormalisation group theory.

The work has shown that careful control of the solution process is needed when modelling buoyancy-driven flows and that care is needed when specifying the conditions at the boundaries separating internal and external air. The work offers guidance to others wishing to use the benchmarks and suggests how these techniques could be used for modelling buoyancy-driven flow regimes in real buildings.

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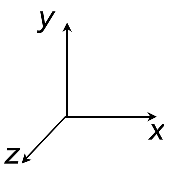
Contents

Nomenclature

(-)	dimensionless variable
A^*	effective opening area (m^2)
Ar	Archimedes number (-)
a_u	total area of upper openings (m^2)
a_l	total area of lower openings (m^2)
B	strength of buoyancy source (m^4/s^3)
C	empirical constant in point source plumes (-)
C_1, C_2, C_3, C_μ	turbulence model constants (-)
C_d	discharge coefficient (-)
C_P	specific heat capacity (J/KgK)
c	momentum theorem constant (-)
D	empirical constant in line source plumes (-)
D_ϕ	diffusivity (Γ_ϕ/ρ), (m^2/s)
d_f	length scale for false time-steps (m)
E, E_{He}	wall function constants (-)
G'	plume buoyancy (m/s^2)
G'_H	hypothetical value of G_T at $y = H$ (m/s^2)
g	acceleration due to gravity (m/s^2)
g'	reduced gravity or buoyancy (m/s^2)
g'_h	change in buoyancy across the interface, or stratification strength (m/s^2)
H	height of space (m)
He	total enthalpy (J/Kg)
He^+	normalised enthalpy (-)
He_{ref}	enthalpy reference value (J/Kg)
He_{res}	enthalpy residual (Watts)
He_W	enthalpy at wall (J/Kg)
h	height of interface (m)
he	static enthalpy (J/Kg)

$\underline{J_{He}}$	enthalpy flux at wall (J/m^{2}s)
k	turbulent kinetic energy (m^2/s^2)
l	length scale (m)
M	volume flux in plume (m^3/s)
P, p	pressure (Pa)
Pe	Peclet number (-)
P_w	pressure difference due to wind (Pa)
P_s	pressure difference due to stack effect (Pa)
Q	heat flux (W/m^2)
q	mass flux (Kg/s)
q_v	airflow rate (ach^{-1})
Ra	Rayleigh number (-)
Re	Reynolds number (-)
r	radial distance (m)
S_ϕ	source term in ϕ equation (varies)
T	temperature (K)
t	time (s)
t_f	false time-step (s)
u_i	velocity tensor = (u, v, w) (m/s)
u^+	normalised velocity (-)
u^{par}	velocity parallel to wall (m/s)
V	velocity scale (m/s)
v_f	velocity scale for false time-steps (m/s)
v_{G}	Gaussian axial plume velocity (m/s)
v_{T}	'Top-hat' axial plume velocity (m/s)
W	heat input (Watts)
x_i	spatial coordinate tensor = (x, y, z) (m): 
y^+	normalised distance (-)

y_0^+, y_{He}^+	wall function constants (-)
α	plume entrainment (-)
β	coefficient of expansion (K^{-1})
β_o	turbulence model constant (-)
ΔHe_h	change in enthalpy across the interface (J/Kg)
ΔT_h	change in temperature across the interface (K)
δ_{ij}	kronecka delta $= \begin{cases} 1 \text{ if } i = j \\ 0 \text{ if } i \neq j \end{cases}$ (-)
ε	dissipation of turbulent kinetic energy (m^2/s^3)
ϕ	arbitrary variable (varies)
Γ_{eff}	effective diffusivity (Kg/ms)
Γ_{He_t}	eddy diffusivity for enthalpy (Kg/ms)
Γ_ϕ	diffusion coefficient for ϕ (Kg/ms)
η_o	turbulence model constant (-)
κ	wall function constant (-)
λ	thermal conductivity (W/mK)
μ, μ_{eff}	total (effective) dynamic viscosity (Kg/ms)
μ_l	laminar viscosity (Kg/ms)
μ_t	turbulent (or eddy) viscosity (Kg/ms)
θ	azimuth angle (radians)
ρ	density (Kg/m^3)
σ_{He}	turbulent Prandtl number for enthalpy (-)
σ_k	turbulent Prandtl number for k (-)
σ_ε	turbulent Prandtl number for ε (-)
σ_{ij}	shear stress tensor (Pa)
τ	wall shear stress (Pa)
υ	kinematic viscosity (μ/ρ), (m^2/s)
ξ	normalised interface height = h / H

subscripts

Bref	buoyancy reference
Eref	enthalpy reference
ext	external (ambient)
G	Gaussian value (see Appendix B)
int	internal
o	reference value
T	‘top-hat’ value (see Appendix B)
L	values expressed as a quantity per metre length

superscripts

$k-\varepsilon$	value pertaining to standard $k-\varepsilon$ turbulence model
RNG	value pertaining to RNG $k-\varepsilon$ turbulence model

Glossary and Abbreviations

ach^{-1}	air changes per hour
AIVC	Air Infiltration and Ventilation Centre
BRE	Building Research Establishment
CFD	Computational Fluid Dynamics
CFDS	Computational Fluid Dynamics Services
CIBSE	Chartered Institute of Building Services Engineers
Control Volume	Discrete volumes of space in the computational domain over which the transport equations are solved
ESRU	Energy Systems Research Unit
PLEA	Passive and Low Energy Architecture