A COMPUTATIONAL STUDY OF TURBULENT BUOYANT FLOWS USING RANS MODELLING, PANS APPROACH AND LES

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by

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This thesis is dedicated to

my late mother Radhika Devi
and
my late uncle Rameshwar Kunwar

CERTIFICATE

This is to certify that the thesis entitled "**A COMPUTATIONAL STUDY OF TURBULENT BUOYANT FLOWS USING RANS MODELLING, PANS APPROACH AND LES**" being submitted by **Mr. Rajesh Kumar** is the report of bonafide research work carried by him under my supervision. This thesis has been prepared in conformity with the rules and regulations of **INDIAN INSTITUTE OF TECHNOLOGY DELHI**. I further certify that the thesis has attained a standard required for the award of **Doctor of Philosophy** degree of the Institute. The research reported and the results presented in the thesis have not been submitted, in part or full to any other institute or university for the award of any other degree or diploma.

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(Rajesh Kumar)

ABSTRACT

Buoyancy effects due to density differences commonly exist in turbulent fluid flows occurring in nature and in engineering applications. A turbulent flow comprises a wide spectrum of time and length scales of motion. Buoyancy plays a significant role in the physics of turbulence. It affects the production and dissipation of turbulence kinetic energy of the flow. Therefore the accuracy of computational simulation of thermal plume fundamentally depends on how well the effects of buoyancy on turbulence are modelled. Primarily three approaches are used to model a turbulent flow, namely, Reynolds-averaged Navier-Stokes (RANS) equations, large eddy simulation (LES) and direct numerical simulation (DNS). Variable resolution method is a recent addition to the turbulence models. The Partially-averaged Navier-Stokes (PANS) approach is a variable resolution method that lies between LES and RANS in terms of computational cost. This method is designed to improve accuracy by resolving more scales of motion than RANS but lesser than LES. This thesis presents steady RANS methodology, unsteady RANS methodology, PANS approach and LES to study turbulent buoyant flows. The present thesis also attempts to elucidate physical features of important mean and turbulent quantities in simplified flow configurations involving buoyancy effects in turbulent flows.

The vertical buoyant jet configuration, which is an example of a free-shear turbulent flow affected by buoyancy, has been studied in the present thesis using RANS, URANS and PANS modelling. A thermal plume is relevant to various industrial applications. An investigation of thermal plume is also important because it can be considered as a test case for modelling of fire which can help designers and safety engineers to develop preventive measures and fire safety systems. A thermal plume is essentially buoyancy-driven flow, therefore it is necessary to incorporate the effects of buoyancy on turbulence in a turbulence model. The effects of buoyancy are included by the addition of a source term. In all the models considered

in the present thesis, the effect of buoyancy is taken into account by the addition of source term in the transport equation of turbulence kinetic energy and turbulent dissipation rate. The source term has been modelled using the simple gradient diffusion hypothesis (SGDH) and the generalized gradient diffusion hypothesis (GGDH). The SGDH tends to under-estimate the spread rate of vertical thermal plumes and over-estimate the spread rate of horizontal, stably-stratified flows. In the present thesis, the models based on the buoyancy modifications via GGDH hypothesis have been proved to be more accurate in capturing the mean flow properties, spread rate and turbulent properties. The present PANS model is shown to enhance the computing capability significantly in predicting buoyancy-driven flows compared with those of RANS and URANS models. Finally, various important unsteady flow structures of turbulent thermal plume have been visualized from the instantaneous flow statistics obtained using the PANS simulations. Qualitative and quantitative comparisons with reported experimental results are also performed, demonstrating the ability of the above-mentioned techniques to accurately simulate buoyancy and stratification effects in turbulent flows.

Four existing LES sub-grid scale (SGS) models for buoyant turbulent flows are assessed in the thesis by comparing the results with experimental data reported in the literature for thermal-driven square cavity. Understanding the flow physics of this configuration is of interest for various industrial applications, such as, cooling of electronic equipment, solar collectors, air ventilation of buildings, cooling of nuclear reactors, etc. Furthermore, computational study of a cavity flow is considered as a benchmark case to develop new turbulence closure models and new computational algorithms. In addition to serving as an excellent test case for SGS models, this problem demonstrates interesting phenomena related to the interaction between buoyancy and wall-bounded turbulence. Particularly, the effect of buoyancy on the vertical wall boundary layer is studied. Improvements are made to the one *equation eddy viscosity SGS model by taking into account the contribution of the buoyant force in the SGS production.*

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NOMENCLATURE

B	production of turbulence due to buoyancy, kg/(ms^3)
g	acceleration due to gravity, m/s^2
h	enthalpy, J/Kg
k	turbulent kinetic energy, m^2/s^2
p	total pressure, N/m^2
p_d	component of total pressure, $p_d = p - \rho g.X$, N/m^2
P	production of turbulence due to shear, kg/(ms^3)
r	radius, m
S	strain rate, s^{-1}
S_{ij}	strain rate tensor, s^{-1}
T	temperature,K
u_i	velocity component in the ith direction,m/s
W	mean velocity in the axial direction,m/s
z	axial distance,m

Greek symbols

δ_{ij}	Kronecker delta, dimensionless
ε	turbulent dissipation rate,m^2/s^3
ω	specific dissipation rate, s^{-1}
μ	molecular viscosity, kg/(ms)
μ_t	turbulent viscosity, kg/(ms)
ρ	density, kg/m^3
τ_{ij}	shear stress tensor, N/m^2
σ_t	turbulent Prandtl number,dimensionless

Subscripts

0	quantities at the source
∞	properties of the ambient

i	vector direction
c	quantities at the centerline

Superscripts

$\overline{\varphi}$	time-averaged quantity
φ'	fluctuation (Reynolds statistics)
$\tilde{\varphi}$	Favre-averaged quantity
φ''	fluctuation (Favre statistics)

Abbreviation

LES= large eddy simulation

RANS=Reynolds-averaged Navier Stokes

SGS=sub-grid stress

SGDH=simple gradient diffusion hypothesis

GGDH=generalized gradient diffusion hypothesis