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Hybrid LES/DNS of turbulent forced and aided mixed convection to a liquid metal flowing in a vertical concentric annulus

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ABSTRACT

In the present study fully-developed turbulent forced and mixed convection heat transfer to a liquid metal flowing upwards in a concentric annulus is numerically investigated by means of Large Eddy Simulation (LES). The inner-to-outer radius ratio is 0.5. The Reynolds number based on bulk velocity and hydraulic diameter is 8900, while the Prandtl number is set to a value of 0.026. A uniform and equal heat flux is applied on both walls. Three different buoyancy strengths are considered, corresponding to onset of turbulence reduction, maximum impairment and recovery condition on the inner wall while recovery and enhancement develop on the outer wall. Due to the difference between thermal and hydrodynamic turbulent scales in liquid metals it is shown that with the same grid resolution a LES is performed for the flow field and at the same time a "thermal" Direct Numerical Simulation (DNS) for the temperature field. From a detailed analysis of the two-point correlation functions of velocity and temperature fluctuations it emerges that a streamwise extent of 25δ and 40δ (being δ the half gap width) is necessary for forced and mixed convection, respectively, while a quarter of circumference is enough in azimuthal direction for this radius ratio, Reynolds and Prandtl number. Comparison of the forced convection flow field with available DNS simulations shows very good agreement. Nusselt numbers evaluated from the few available literature correlations for liquid metals flowing in an annulus give unsatisfactory results, mainly on the inner wall. The mixed convection results are thoroughly analyzed and discussed in terms of friction factor, Nusselt number, first and second order statistics, budgets of turbulent kinetic energy and budgets of temperature variance. The obtained data are also useful for validating Reynolds-Averaged turbulence models. Moreover, simulations with two coarser grids at the condition of maximum turbulence reduction are also compared with the reference results of the fine LES. It results that when turbulence is impaired the grid resolution in circumferential direction can be strongly coarsened.

1. Introduction

Liquid metals have excellent heat transfer characteristics mainly due to their very high thermal conductivity. Their corresponding Prandtl number is low, from 10^{-3} up to $5 \cdot 10^{-2}$. The thermal viscous sublayer of liquid metals is much thicker than the corresponding hydrodynamic one, implying a significant molecular contribution to heat transfer also for Reynolds numbers, at which the turbulent energy exchange prevails for medium-to-high Prandtl number fluids, like gases, common liquids or oils. This paper is the companion of a previous study of the same author [1], where turbulent aided mixed convection has been analyzed at the same Reynolds and Prandtl number but for only one single buoyancy strength and with two coarse grids. In the present work the results found in Ref. [1] are extended by considering three buoyancy strengths, corresponding on the inner wall to the conditions of onset of turbulence reduction, maximum reduction and turbulence recovery. On the outer wall the same boundary conditions result in turbulence recovery and its enhancement. A hybrid LES/DNS approach is used, i.e. with same grid resolution a LES is done for the velocity field and a DNS for the temperature field. This is possible, being for low-Prandtl number fluids the smallest turbulent temperature scales much larger than the corresponding smallest velocity scales. This technique can be used to obtain sufficiently accurate results for liquid metal flows with a much coarser grid resolution than required for a full DNS and for higher Reynolds numbers. Simulations are carried out for an annulus with an inner-to-outer radius ratio of 0.5 at a Reynolds number of $Re = 8900$, a Prandtl number of $Pr = 0.026$ and with a constant and uniform heat flux applied on both walls. A much finer grid

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Nomenclature

Roman letters

Bo	Buoyancy number Eq. (5) (–)
C_D	Darcy-Weisbach friction factor (–)
C_f	Fanning friction factor (–)
c_p	specific heat capacity at constant pressure (J/kg K)
d_h	hydraulic diameter $d_h = 4\delta$ (m)
g	acceleration of gravity in negative axial direction (m/s^2)
Gr_q	Grashof number $Gr_q = \frac{g\beta q_w d_h^4}{\nu^2 \lambda}$ (–)
k	turbulent kinetic energy (–)
L_x	streamwise domain extent (m)
N_x, N_r, N_θ	number of control volumes in axial, radial and circumferential direction (–)
Nu	Nusselt number $Nu = \frac{q_w d_h}{(T_w - T_b)}$ (–)
p	pressure $\frac{P - g x_i \delta_{i1}}{\rho u_b^2}$ (–)
Pr	Prandtl number (–)
q_w	wall heat flux (W/m^2)
r^*	inner-to-outer radius ratio R_i/R_o (–)
R	radius (m)
Re	Reynolds number $Re = u_b d_h/\nu$ (–)
$R_{\Theta'\Theta'}$	two-point correlation coefficient of temperature fluctuations (–)
$R_{u'u'}$	two-point correlation coefficient of streamwise velocity fluctuations (–)
t	time (–)
T_b	bulk temperature (K)
T_τ	friction temperature $T_\tau = q_w/(\rho c_p u_\tau)$ (K)
T_w	wall temperature (K)
u, v, w	velocity components in x, r and θ direction (–)
u_τ	friction velocity $u_\tau = \sqrt{\tau_w/\rho}$ (m)
u_i, u_j	i-th and j-th velocity component in cartesian coordinates (–)
x, r, θ	axial, radial and circumferential coordinate (–)
y	distance from inner or outer wall (m)

Greek letters

α	molecular thermal diffusivity (m^2/s)
α_t	turbulent thermal diffusivity (m^2/s)
β	thermal expansion coefficient (K^{-1})
$\Delta x, \Delta y, \Delta\theta$	grid spacing in axial, radial and circumferential direction (m)
Δ	mean grid size (m)
δ	half gap width $\delta = (r_o - r_i)/2$ (m)
δ_{ij}	Kronecker delta (–)
ε	dissipation rate of k (–)
η	Kolmogorov length scale $\eta = (\nu^3/\varepsilon)^{1/4}$ (m)
η_T	Corrsin length scale $\eta_T = \eta Pr^{-3/4}$ (m)
λ	molecular thermal conductivity (W/mK)
ν	kinematic viscosity (m^2/s)
ν_t	turbulent kinematic viscosity (m^2/s)
ν_{sgs}	subgrid kinematic viscosity (m^2/s)
ρ	density (kg/m^3)
τ_w	wall shear stress (N/m^2)
Θ	non-dimensional temperature $\Theta = \frac{T - T_b}{q_w d_h/\lambda}$ (–)

Operators

$\overline{(\cdot)}$	averaged over x, θ and t
$(\cdot)^+$	normalized by ν, u_τ and T_τ
$(\cdot)'$	fluctuating component

Abbreviations and acronyms

DNS	Direct Numerical Simulation
LES	Large Eddy Simulation
RANS	Reynolds-Averaged Navier-Stokes
RMS	Root Mean Square
LES0	reference Large Eddy Simulation
LES_VC	very coarse Large Eddy Simulation
LES_C	coarse Large Eddy Simulation

Subscripts

0	forced convection
b	bulk
sgs	subgrid-scale-stress
i	inner wall
mx	mixed convection
o	outer wall
rms	root mean square

resolution than that used in Ref. [1] is here adopted. A sensitivity analysis on the domain extension in streamwise and circumferential directions is done for both forced and mixed convection. The modifications caused by mixed convection with respect to forced convection on friction factors, Nusselt numbers, first and second order statistics, budgets of turbulent kinetic energy and budgets of temperature variance are thoroughly analyzed and discussed. The results obtained with the grids adopted for the simulations in Ref. [1] are now also compared with the reference results of the present fine grid. For an overview of the literature on mixed convection in general and to liquid metals in particular as well as for application fields of liquid metals as heat transfer fluids, the interested reader is referred to Ref. [1] and references therein.

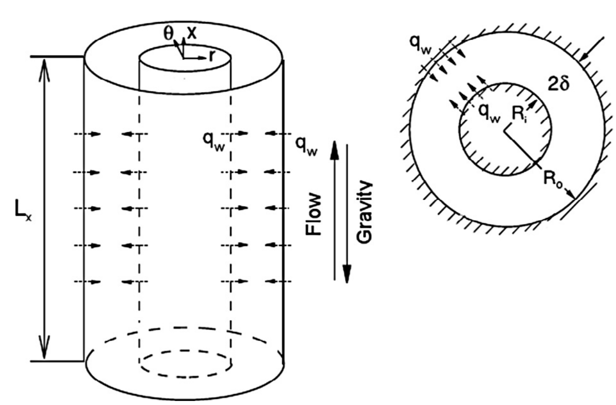

Fig. 1. Schematic of computational domain.

2. Governing equations and numerical method

For the domain sketched in Fig. 1, the non-dimensional continuity, momentum and energy equations, (1)–(3), are solved in cartesian coordinates for an incompressible Newtonian fluid with constant thermophysical properties, no viscous dissipation and with the Boussinesq approximation for buoyancy. All variables are non-dimensionalized by the hydraulic diameter, d_h, and the bulk velocity, u_b. It should be remarked that the velocity and pressure are filtered variables and therefore a subgrid-scale viscosity, ν_{sgs}, appears in the momentum equation. Vice versa, no heat flux model is used for the temperature, which is therefore not a filtered quantity. The validity of this approach is discussed and confirmed in Section 3. The last term on the right-hand side of Eq. (2) arises from considering a periodic flow in streamwise direction, while