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DNS of turbulent mixed convection over a vertical backward-facing step for lead-bismuth eutectic

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ABSTRACT

Studies of turbulent mixed convection over a vertical backward-facing step for liquid metals are indispensable to research the buoyancy effects in flow separation and reattachment scenarios that occurs in innovative nuclear and solar power facilities. Direct numerical simulations of turbulent buoyancy-aided flow at two moderate Richardson numbers ($Ri = 0.1$, 0.2) and buoyancy-opposed flow at $Ri = -0.04$ for lead–bismuth eutectic (LBE, Prandtl number $Pr = 0.025$) are performed. The forced convection and air mixed convection ($Pr = 0.7$, $Ri = 0.1$) are also simulated for comparison. In all the cases Reynolds number is 4805 and the expansion ratio is 1.5. Mean statistics like velocity components, temperature and heat fluxes are given. Second-order quantities such as Reynolds stresses, temperature fluctuations, and turbulent heat fluxes are also discussed. The results show that buoyancy has substantially altered the flow field for LBE flow compared to air flow at moderate *Ri*. For buoyancy-aided LBE flow, the recirculation zone is reduced in size and the reattachment length is shortened. With *Ri* increasing, the second vortex gradually prevails over the main vortex and finally pushes it detach from the wall, leading to positive skin-friction coefficient. Buoyancy weakens the turbulent quantities such as Reynolds stresses, temperature fluctuations and turbulent heat fluxes. Both skin-friction coefficient and Nusselt number increase due to the reduced reversed flow resulting from buoyancy acceleration near the wall. However, it is opposite for the case of buoyancy-opposed flow. The skin-friction coefficient and Nusselt number decrease due to the increased reversed flow though the turbulence is enhanced in buoyancy-opposed flow. These high-resolved data could promote the understanding of this scenario and improve turbulent modelling for flow separation and reattachment of low Prandtl fluids.

1. Introduction

Flow separation and reattachment induced by a sudden expansion in the flow passage often appear in a wide variety of engineering applications where heating or cooling is required. They will significantly affect the characteristics of flow and heat transfer near the expansion, further having a negative impact on the lifetime and performance of facilities. Thus, accurate and reliable prediction of such flow field and heat transfer is necessary. Backward-facing step, represented by its simple geometry while covering complex flow separation and reattachment, is often chosen as the benchmark case [1] for modelling validation.

Low Prandtl number fluids ($Pr \ll 1$), such as liquid metals, featured with large thermal conductivity, have an advantage in heat transfer and could withstand severe temperature operating condition due to its high boiling point [2]. However, low Prandtl number results in a large separation between the thermal and viscous boundary layer scale, making the Reynolds analogy invalid [3]. Thus, modelling of turbulent transport of momentum and energy of liquid metal flow over a backward-facing step is challenging. Besides, low *Pr* fluids flow are more susceptible to the buoyancy, making the situation more complex [4]. Hence turbulent mixed convection for liquid metals over a backward-facing step is the main study object of present work.

Compared to the convectional fluids, studies of turbulent mixed convection for liquid metals are much less. This could be attributed to the measurement difficulties for liquid metal experiments [5]. The most reliable two experiments were conducted by Buhr et al. [6] for mercury ($Pr = 0.025$) and Jackson et al. [7] for sodium ($Pr = 0.005$) in vertical pipe flow. According to the review of mixed convection in vertical tubes for medium-to-high Prandtl number fluids by Jackson et al. [8], heat transfer is impaired first and recovered at strong buoyancy for turbulent buoyancy-aided flow, while it is enhanced for buoyancy-opposed flow. Experimental data shows that sodium behaves like the laminar one while mercury

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Nomenclature

C_f	skin friction coefficient, $\frac{\tau_w}{0.5\rho u_b^2}$
ER	expansion ratio, $H/(H\text{-}h)$
g	gravitational acceleration
Gr	Grashof number, $\frac{g\beta\Delta T h^3}{\nu^2}$
H	channel height
h	step height
$\langle k\rangle$	turbulent kinetic energy, $\frac{1}{2}\langle u_i'u_i'\rangle$
L	length of the computational domain
Nu	Nusselt number, $\frac{\dot{q}\cdot h}{(\langle T_w\rangle-\langle T_{in}\rangle)\cdot\lambda}$
Pr	molecular Prandtl number
p	pressure divided by density
$\dot{q}$	heat flux density
Re_h	bulk Reynolds number, $\frac{u_b h}{\nu}$
Re_τ	friction Reynolds number, $\frac{u_\tau h}{\upsilon}$
St	Stanton number, $\frac{Nu}{Re\cdot Pr}$
Ri	Richardson number, $\frac{Gr}{Re^2}$
T	dimensionless temperature, $\frac{T^*-T^*_{in}}{\Delta T}$
ΔT	characteristic temperature increase, $\frac{\dot{q}h}{\lambda}$
T_{in}	inlet temperature
T_τ	friction temperature, $\frac{\dot{q}}{\rho C_p u_\tau}$
T_w	wall temperature
t'	fluctuating dimensionless temperature
u, v, w	velocity components
U_b	bulk velocity
U_c	convection velocity
u_τ	friction velocity, $\sqrt{\frac{\tau_w}{\rho}}$
x	streamwise coordinate
X_r	reattachment length
X_n	location of the maximum heat transfer
y	wall-normal coordinate
z	spanwise coordinate

Greek symbols

α	molecular heat diffusivity
β	thermal expansion coefficient
C_p	specific heat capacity
λ	thermal conductivity
ν	kinematic viscosity
ρ	density
τ	instantaneous time
τ_w	wall shear stress, $\left|\mu\frac{d\langle u\rangle}{dy}\right|_w$

Miscellaneous

$\langle\cdot\rangle$	averaging operator in time and spanwise direction
$(\cdot)_w$	quantity on the heated wall
$(\cdot)'$	fluctuation of a quantity
$(\cdot)^+$	normalized by u_τ
RMS	root mean square
$(\cdot)^*$	dimensional quantities

behaves like the convectional fluids. The high ratio of molecular-to-turbulent thermal diffusivity of sodium should account for its behavior at the investigated Reynolds numbers [7]. Recently, Zhao et al. [9] detailedly studied the characteristics of LBE mixed convection in a pipe by compared with air flows using direct numerical simulation (DNS). For liquid metals, the magnitude, the onset and the extent of the heat transfer impairment strongly depend on the Péclet number [10,11]. Besides, contrarily to the pipe flow where liquid metals with $Pr \sim 0.025$ behave similar to air or water, big differences exist in the annulus flow [11,12]. Thus, turbulent mixed convection studies for more complex geometry for liquid metals are much more needed.

Investigations of mixed convection over backward-facing step have been extensively conducted for air laminar flow. Review of the effect of several global parameters like Reynolds number (Re), step height (h), expansion ratio (ER), Pr, etc. was conducted by Abu-Mulaweh [13]. Hong et al. [4] was the only one studying the effect of Pr in laminar buoyancy-aided flow. They found that low Pr fluids were susceptible to buoyancy effect. In recent years, turbulent heat transfer over a backward-facing step for liquid sodium has attracted much more interests. A backward-facing step experiment platform for sodium is under construction [14]. Numerically, Zhao et al. [15] studied Pr effects on force convections over a backward-facing step flow using DNS. Niemann and Fröhlich [16] investigated a turbulent mixed convection of liquid sodium over a vertical backward-facing step using DNS. Buoyancy force acting on the fluid at the heated wall substantially altered the flow field and the recirculation zone is largely reduced in size. Turbulence is weakened due to the altered flow field. Subsequently, they did a similar work with higher Re_h, ER and Richardson number (Ri) [17]. Buoyancy impact on the budgets of turbulent kinetic energy were studied detailedly. Their works contribute to the physical understanding of buoyancy effects on turbulent heat transfer for liquid sodium in backward-facing step. Based on their DNS data, Schumm et al. [18–20] conducted Reynolds-averaged Navier-Stokes simulations (RANS) to study the influence of different turbulence and heat transfer models on the correct prediction of the forced and buoyancy-aided flow. Low Re turbulent model combined with Kays turbulent Prandtl number correlation [21] seems to better agree with DNS results.

Though several studies on buoyancy-aided flow over a backward-facing step have been conducted, more characteristics of turbulence and heat transfer are still needed for research under the conditions of different fluids, different gravity direction, and so on. In present work, lead-bismuth eutectic (LBE, $Pr = 0.025$) force and mixed convections with different gravity direction over a vertical backward-facing step are studied by DNS with a fourth-order spatial discretization precision. Effects of buoyancy on the flow and heat transfer are comprehensively investigated. First- and second-order statistics of velocity and temperature are discussed in detail. To better analyze the Pr effect on turbulent heat transfer, an air mixed convection case ($Pr = 0.7$, $Ri = 0.1$) is also simulated for comparison. Our study can promote further understandings of turbulent mixed convection for low Prandtl number fluids. Besides, the generated data by DNS allow the validation and improvement of the turbulent heat flux closure models for RANS.

2. Configuration and numerical method

2.1. Geometry description

The configuration investigated in present work is a vertically oriented backward-facing step with step height h as depicted in Fig. 1. The origin of coordinates o locates in the step separating point. The streamwise extent is $22h$, with $2h$ length in front of the expansion and $20h$ length downstream. The whole expansion wall is heated by uniform heat flux. The channel height H behind the step is $3h$, so $ER = H/(H\text{-}h)$ is 1.5. An extra segment of $10h$ downstream with adiabatic wall for the buoyancy-opposed case is added to stabilize the calculation and reduce the influence of the outlet boundary condition, which is not shown here for brevity.