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Direct simulation of conjugate heat transfer of jet in channel crossflow

Zhao Wu *, Dominique Laurence, Hector Iacovides, Imran Afgan

Modelling and Simulation Centre, School of Mechanical, Aerospace and Civil Engineering, The University of Manchester, Oxford Road, Manchester M13 9PL, UK

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A B S T R A C T

We present a DNS study of a hot, low momentum laminar water jet discharged into a cold turbulent channel stream through a circular orifice in one of the steel channel walls. The channel wall has a finite thickness and its outer side is cooled under Robin type thermal boundary conditions for a realistic external environment, leading to a conjugate heat transfer system. Nusselt number and r.m.s temperature fluctuations on the wall are compared with our earlier DNS results for the simpler iso-thermal and adiabatic conditions at the channel inner surface. Temperature fluctuations inside the channel wall are resolved to provide data for a conjugate heat transfer (CHT) thermal fatigue test case related to the ageing of pipe walls and welds studies, as found, for example, in power plant piping T-junctions. The crossflow Reynolds number is $\mathrm{Re} = 3333$, jet-to-crossflow velocity ratio is $R = 1/6$ and fluid-to-solid conductivity ratio is $1/64$.

The near-wall mean flow structures, a horseshoe vortex ahead and on the sides of the jet orifice, a shallow recirculation behind the discharge and a counter-rotating vortex pair drawing in a blanket of cooler cross-flow, lead to a complex convective and turbulent wall heat transfer pattern around the orifice. The main findings are:

(i) Wall maps of Nusselt number and r.m.s temperature, $\theta_{\mathrm{r.m.s}}$, for conjugate heat transfer are only qualitatively similar to the iso-thermal and adiabatic wall cases.
(ii) Inside the solid $\theta_{\mathrm{r.m.s}}$ and its dissipation, analysed from RANS modelling perspective, show that predicted thermal spot length scales are discontinuous on the interface, at variance with the 2-point spectrum-derived scales.
(iii) At the high wavenumber range, the spanwise temperature spectra decrease according to exponential-decay spectral models for the fluid turbulence in the Kolmogorov range, but with large exponential coefficients increasing with depth inside the solid.

1. Introduction

Jets in crossflow (JICF) are of great industrial interest with applications in turbine blades film cooling, de-icing of aeroplane wings, power plant piping systems and pollutant into water or atmosphere. Many studies on this type of problem have been motivated and reported, either experimental [1–9] or numerical [10–14].

However, few studies [11,15,16] are focused on the jet in crossflow problems with low jet-to-crossflow velocity ratios, R, which occur e.g. in T-junction pipes of a nuclear power plant emergency cooling systems. In a jet in crossflow with low jet-to-crossflow velocity ratios, there are three dominant time-averaged vortex structures (Fig. 1): a horseshoe vortex at the front edge of jet-exit, a counter-rotating vortex pair below the non-uniform velocity jet and a recirculation in the wake region [17].

Temperature differences between two piping flow streams will result in temperature fluctuations in the piping wall and may lead to thermal striping: high cycle thermal stress induced wall weakening, and possibly failure [18], particularly for the low momentum jet in crossflow where the secondary injection remains close to the T-junction welds. Prediction of thermal fatigue in a nuclear power plant piping system is a complex material science ageing problem but it is already challenging from the more limited thermal loading aspect studied herein. Perhaps the French Civaux pressurised water nuclear reactor (PWR) plant in 1998 [19] and the Japanese Tsuruga-2 and Tomari-2 PWR plants in 1999 and 2003 [20] are the most notable among this type of safety incidents.

To predict thermal fatigue, one needs to identify the temperature fluctuation magnitudes and frequencies inside the solid piping wall. It requires the coupling of heat transfer between fluid and structure, called conjugate heat transfer (CHT) analysis. The numerical simulations of conjugate heat transfer of a jet in

* Corresponding author.
E-mail addresses: zhao.wu@manchester.ac.uk, zzwz02@163.com (Z. Wu).

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Nomenclature

C_1, C_2	constants
c_p	specific heat
E	spectrum
G	α_f/α_s ratio of thermal diffusivities
h	convective heat transfer coefficient
H	half of channel height and radius of jet-exit
k	turbulent kinetic energy
Nu	Nusselt number
Pr	Prandtl number
r.m.s	root-mean-square
R	$\langle u_j\rangle/\langle u_c\rangle$ jet-to-crossflow velocity ratio
Re	Reynolds number
t	time
T	temperature
u, v, w	velocity components in x, y and z directions
x	streamwise distance
y	wall-normal distance
z	spanwise distance

Greek symbols

α	$\lambda/\rho c_p$ thermal diffusivity
β_1, β_2	constants
Γ	fluid-solid interface
ε	dissipation rate
η	Kolmogorov length scale
θ	$(T-T_c)/(T_j-T_c)$ dimensionless temperature
κ	wavenumber
λ	thermal conductivity
ν	kinematic viscosity
ρ	density
Ω	volume domain

Subscripts

$(\cdot)_c$	crossflow
$(\cdot)_f$	fluid
$(\cdot)_j$	jet
$(\cdot)_n$	wall-normal direction
$(\cdot)_s$	solid
$(\cdot)_t$	turbulence modelling value
$(\cdot)_{wall}$	on the wall

Superscript

$(\cdot)^n$	time-step n
$(\cdot)'$	fluctuating component

Other

$\langle\cdot\rangle$	time-averaged

Abbrev.

CHT	conjugate heat transfer
DNS	direct numerical simulation
JICF	jet in crossflow
LES	large-eddy simulation
PWR	pressurised water reactor
RANS	Reynolds-averaged Navier–Stokes

crossflow at present are mostly based on Reynolds-averaged or large-eddy methods, and their reliability needs further validation. Experimental data on the conjugate heat transfer is rare as walls in lab rigs are usually adiabatic, since the transparent Plexiglas is often the material used, which allows optical access for flow and turbulence characteristics measurements. Thus, the present study objective is to generate a reliable and comprehensive DNS database for jets in channel crossflow at a low jet-to-crossflow velocity ratio, corresponding to a real industrial situation, but for which no experimental data is available. Both time-averaged and instantaneous profiles are examined, to understand the physics of jet in crossflow at low jet-to-crossflow velocity ratios and the conjugate heat transfer problem. The data can also help test and improve the engineering RANS and LES turbulence models, which so far mostly relied on simple channel flow DNS, such as reference [21]. Our earlier DNS results for adiabatic and the iso-thermal thermal boundary conditions applied to the fluid domain [22] are included here for comparison to evaluate the relevance of these simpler test case conditions. In this series study, we described the flow physics of the jet in crossflow in [17], used proper orthogonal decomposition and dynamic mode decomposition to study the coherent structures in [23] and evaluated the RANS models in these simple cases in [24]. The database is accessible free online (http://dx.doi.org/10.17632/7nx4prgjzz.3) [25].

Section 2 provides the numerical details of conjugate heat transfer extension, followed by the results and discussions in Section 3 and conclusions in Section 4.

2. Numerical details of conjugate heat transfer

The DNS simulations are performed with the computational fluid dynamics code Incompact3d; a highly accurate and widely benchmarked open-source DNS code [26,27]. More than 40 papers have been published, based on simulations arising from the use of this code (cf. http://www.incompact3d.com/). Recently Flageul et al. [28] equipped Incompact3d with the ability to solve conjugate heat transfer in periodic channel flows. These developments were validated against analytical solutions and rarer DNS data of channel flow with conjugate heat transfer. The authors in present paper extended their code for a 3-D jet in channel crossflow configuration.

2.1. Numerical methods

The present DNS of the jet in crossflow employed the same numerical scheme as that in [17] in the fluid domain, a sixth-order central compact finite scheme applied to the velocity components stored on a collocated grid and a spectral method for solving the pressure Poisson equation on a staggered grid. The second-order Adams-Bashforth scheme is used for the time-advancement.

The numerical method in the solid domain and the fluid-solid coupling are described in [28] and are available as an open-source module with minimal changes to the code. This section summarises numerical methods used in the solid domain and fluid-solid coupling, as well as those modifications made to Flageul's code. Hereafter, the subscript "*s*" denotes the solid, while "*f*" denotes the fluid.

Thermal conduction in the solid is governed by the following differential equation:

$$\partial_t T_s = \alpha_s(\nabla_x^2 T_s + \nabla_y^2 T_s + \nabla_z^2 T_s) \quad (1)$$

where T_s and $\alpha_s = \lambda_s/(\rho_s c_{p,s})$ are the solid temperature and thermal diffusivity, with λ_s, ρ_s and $c_{p,s}$ the solid thermal conductivity, density and specific heat capacity respectively. For simplicity "x" and "z" denote the main channel streamwise and spanwise wall parallel axes, and "y" the wall normal one.