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Large-eddy simulation of an impinging jet in a cross-flow on a heated wall-mounted cube

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ABSTRACT

A large-eddy simulation (LES) is performed in order to predict the mean velocity field, the turbulence characteristics and the heat transfer rate of an impinging jet in cross-flow configuration on a heated wall-mounted cube. The WALE model was used to model the subgrid-scale tensor. The results from the LES are compared with a Reynolds stress model (RSM) and against earlier measurements with identical set-up. A comparison between the results from the predictions and the measurements shows that in general the LES has better agreement with the measurements compared to the RSM and particularly in the stagnation region of the impinging jet.

1. Introduction

Impinging jets are used for many industrial applications where high heat and/or mass transfer rates are required (e.g., drying paper, textiles, tempering glass and cooling of electronic components). The current trend in the development of electronic devices shows a steady increase in the dissipated heat from electronic components. Forced channel flow is frequently used as a cooling technique, see Meinders [1]. In combating the whole thermal load with forced channel flow, excessive flow rates will be required. One possible method to face this problem is to divide the channel flow with an impinging jet and a low-velocity channel flow, see Rundström and Moshfegh [2].

Impinging jets are also of great scientific interest. Extensive experimental and numerical research has been carried out to predict the flow and heat transfer characteristics in the stagnation region of an impinging jet. Most investigations have been focused on axisymmetric round jets impinging normally on a flat surface, cf. Lee and Lee [3]. The case with an axisymmetric round jet impinging normally on a flat surface has also been simulated with different turbulence models to predict the heat transfer and flow configuration. The earlier investigations by Behnia et al. [4] have shown that the most common two-equation Reynolds Averaged Navier–Stokes (RANS) models, e.g., the standard k-ε model, overpredict the heat transfer rate in the stagnation region by over 100%. Behnia et al. [4] also used the $\overline{v^2}$-f model to simulate the case, with satisfactory agreement with the experimental data. Other numerical investigations, such as the one by Abdon and Sundén [5], have used the expansion of the classical two-equation turbulence models (k-ε and k-ω) with realizable constraints. Craft et al. [6] used a low-*Re* model with the Yap correlation added to the ε-equation and three different Reynolds stress models to simulate the case.

A range of large-eddy simulations (LES) with different kinds of subgrid-scale (SGS) models have also been used to predict the turbulent flow field near the stagnation point. Beaubert and Viazzo [7] used the dynamic Smagorinsky model by Lilly [8] to simulate a plane impinging jet with three different Reynolds numbers. The mean velocity profiles and the turbulence statistics were in good agreement with the measurements by Maurel and Solliec [9]. Olsson and Fuchs [10] investigated the performance of two SGS models, a modified version of the dynamic model by Lilly [8] and a stress-similarity model by Liu et al. [11]. They found that the SGS models had a significant influence on the flow field especially for the turbulence statistics. They also revealed the importance of forcing the velocity fluctuation at the inlet of the impinging jet. Tsubokura et al. [12] used direct numerical simulation (DNS) and large-eddy simulation (LES) with a dynamic SGS model to investigate the eddy structures of plane and round impinging jets. They found that the eddy structures are different in the stagnation region for plane and round impinging jets. For the plane impinging jets, organized vortex structures were found in the stagnation region such as twin counter-rotating vortices in the transverse direction of the jet; no organized vortex structures were found in

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Nomenclature

a_{ij}	orthogonal transformation tensor
C_d	drag-coefficient
D	nozzle diameter
E	energy spectrum function
H	channel height
h	cube height
h_j	modified subgrid-scale heat fluxes
k	turbulent kinetic energy
L_s, l	turbulent length scales
M	mean value
N	normal distribution and number of samples
Pr_t	turbulent Prandtl number
p	static pressure
q	second invariant of the velocity gradient tensor
$Re_j = U_j D/\nu$	Reynolds number based on the nozzle diameter and the jet velocity
$Re_c = U_c H/\nu$	Reynolds number based on the channel, height and mean velocity in the channel
r	normal distance to the closest wall
S_{ij}	rate-of-strain tensor
S_x	streamwise distance of the computational domain
S_z	spanwise distance of the computational domain
T	instantaneous temperature
T'	fluctuating temperature
t	time
U_c	mean velocity of the cross-flow
U_j	mean velocity of the impinging jet,
$U_i = (UVW)$	time-averaged velocity components
$u_i = (uvw)$	instantaneous velocity components
u_i'	fluctuating velocity
V	time-averaged y-velocity component and volume of the computational cell
$x_i = (xyz)$	Cartesian coordinates
y^+	distance from the wall normalized by the viscous length scale

Greek symbols

α	thermal diffusivity
δ_{ij}	Kronecker delta
ε	dissipation rate of turbulent kinetic energy
ε_{ijk}	permutation tensor
Δt	time step size
κ	wave-number and van Karman constant
κ_j	wave-number vector
ν	kinematic viscosity
ζ_{ij}	traceless symmetric part of the square of the velocity gradient tensor
σ	standard deviation
τ	turbulent timescale
τ_{ij}	subgrid-scale tensor
Ω_{ij}	rate-of-rotational tensor
ω	turbulence frequency

Subscripts and overlines

res	resolved
SGS	subgrid-scale
$\overline{()}$	filtered
$\tilde{()}$	normalized by l and τ

the stagnation region for the round impinging jet. Chung et al. [13] used direct numerical simulation (DNS) to investigate the influence of the primary vortices on the unsteady heat transfer rate in the impinging flow of a planar impinging jet. The results showed that the primary vortices emanating from the nozzle have the main influence on the unsteadiness of the impinging heat transfer rate. Cziesla et al. [14] investigated the heat transfer and the unsteady flow in the stagnation region of a plane impinging jet with use of large-eddy simulation (LES) with the SGS model by Lilly [8], with satisfactory results.

A big issue in LES is to predict the near-wall behaviour where the subgrid-scale eddy-viscosity, ν_{SGS}, goes to zero at the wall with an asymptotic behaviour of $O(y^3)$. The Smagorinsky model, see Smagorinsky [15] gives a non-zero value at the wall due to non-zero velocity gradients and an asymptotic behaviour of O(1). Additional modifications to the Smagorinsky model have been used to force the subgrid-scale eddy-viscosity to zero and to get correct asymptotic behaviour at the wall. Moin and Kim [16] used an exponential Van Driest damping function to account for the near-wall effects, see Van Driest [17]. A more suitable way to produce zero eddy-viscosity and correct asymptotic behaviour at the wall is to use the dynamic version of the Smagorinsky model by Germano et al. [18], where the Smagorinsky constant is determined in a dynamic procedure. The dynamic version of the Smagorinsky model is found to be unstable and averaging procedures or clipping are necessary to ensure stability. The averaging process is performed in the direction of statistical homogeneity for simpler cases, see Germano et al. [18] and Akselvoll and Moin [19]. Alternative approaches are needed for more complex flows where the direction of statistical homogeneity is difficult or impossible to determine. The localized dynamic model proposed by Ghosal et al. [20] and the Lagrangian dynamic model by Meneveau et al. [21] are two approaches to handle this problem. The SGS model by Nicoud and Ducros [22] yields correct asymptotic behaviour near the wall and the subgrid-scale eddy viscosity, ν_{SGS}, goes to zero without any *ad hoc* modifications or dynamic procedures. These qualities make the model well-suited for complex flows.

Two RANS-turbulence models, the $\overline{v^2}$-f model developed by Durbin [23] and a RSM with a two-layer model in the near-wall region, were used by Rundström and Moshfegh [24] in an earlier validation study of the turbulent flow from an impinging jet in a cross-flow on a wall-mounted cube. The models showed similar results near the walls and the RSM predicted the flow and turbulence characteristics better than the $\overline{v^2}$-f model in the free shear regions (i.e., far from the walls). The accuracy of the heat transfer prediction from the RSM was investigated by Rundström and Moshfegh [25] and the main features were well predicted by the model in all regions except in the stagnation region of the impinging jet, where the model seems to overpredict the heat transfer rate. This is an extension of the previous studies to investigate the performance of a LES with a SGS model by Nicoud and Ducros [22] on the turbulent flow and the heat transfer rate. The purpose of this study is to provide a thorough understanding of the physics in this complex flow and investigate the accuracy of the prediction of the mean velocity field, the turbulence characteristics and the heat transfer rate with use of a LES. The results from the LES are verified by infrared thermography and particle image velocimetry (PIV) measurements. The results are also compared with the RSM to evaluate the performance and to point out the strengths and weaknesses of this model.