Large-Eddy Simulation of the Interaction of Wall Jets with External Stream

I.Z. Naqavi and P.G. Tucker

1 Introduction

The jets issuing tangentially to a solid surface are called wall jets. Plane two dimensional wall jets are the simplest and have been studied extensively [5]. The wall jets are used in heat, mass and momentum transfer along the walls. A large part of wall jet study is concerned with the search for the existence of self-similar parameters [3, 13].

Bradshaw and Gee [1] made early fundamental studies on the wall jets with an external stream. It was shown that for thin incoming boundary layer with no wake, the jet shear layer can absorb the boundary layer in a short distance. However, the presence of external stream results in the involvement of several parameters, determining the evolution of the wall jet. These external parameters can be controlled to produce the desired effects in the wall jets, depending on their application. The two major applications of wall jets with external streams are cutback trailing edge (TE) film cooling in gas turbines and the control of the boundary layers over high lift bodies e.g. Coanda jets [9]. In both of these cases wall jets are interacting with the external stream, however, the desired outcome of the interactions are completely opposite. In case of TE thin film cooling a cold stream is introduced as a wall jet along the trailing edge. The objective is to keep the external hot stream (combustion gases) away from the wall and to avoid the mixing of the two streams as far downstream as possible. For the Coanda jet a strong mixing of two streams is required to prevent the boundary layer separation.

In case of TE film cooling major focus is the measurement and prediction of film-cooling effectiveness of this flow. Martini and Schulz [7] performed measurements

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on scaled-up trailing edge model with internal structures for coolant slot. These structures determine the turbulence character of incoming jet and have strong influence on the film cooling effectiveness. Recent LES of TE film cooling [10, 11] for a series of blowing ratios (i.e. jet to free stream velocity ratio), in the rage of 0.35–1.4, showed large coherent structures shed from the plate separating the two streams. These have dominant role in the heat transfer. The jet velocity ratio is usually around 1.5 or less for TE film cooling. Whereas for Coanda jets based flow control it is higher than 2.0 [9]. In previous studies the wake plate thickness separating the two streams is also of the order of the slot height for wall jets. In this work a high resolution LES is performed to study a geometrically simple model for wall jet with external stream and a thin wake plate. Two different velocity ratios are considered. The objective is to study the effect of the velocity ratios on the development of the coherent structures in the near field and the development of the mean flow properties downstream.

2 Problem Formulation and Validation

The interaction of wall jet with external stream is simulated with filtered conservation of mass and momentum equations for incompressible flow. A finite volume code with second order collocated descretization and semi-implicit time advancement scheme is used. The subgrid-scale (SGS) stresses are modeled with Lagrangian-averaged dynamic eddy-viscosity model [8].

In this study the blowing ratios U_j/U_∞ of 0.75 and 2.30 are considered. The U_∞ is free stream velocity of external incoming boundary layer and U_j is the wall jet bulk velocity. The domain is shown in the schematic Fig. 1. This case has been studied experimentally by [4]. At the inlet plane of the computational domain, mean streamwise velocity profiles for the wall-jet and boundary layer from the experiment are used. A channel and a boundary layer flow simulation based on [6] are used to generate time dependent turbulence fluctuations for inlet profiles. The slot height of wall jet is $h = 2.767\delta_0^*$ and the thickness of the plate separating the two streams (wake plate) is $w = 0.126,\ h = 0.349\delta_0^*$. The inlet Reynolds number based on the displacement thickness δ_0^* of external boundary layer is $Re_{\delta_0^*} = 2,776$. The Reynolds numbers for slot jet based on slot height are $Re_h = 5{,}760$ and 17,700, for

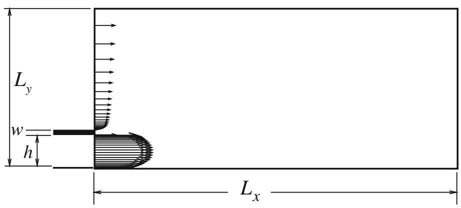

Fig. 1 Schematic of the domain for wall jet and external stream

Table 1 Summary of the domain and grid

Grid	L_x/h	L_y/h	L_z/h	N_x	N_y	N_z
Coarse	80.0	16.0	5.5	512	147	66
Fine	45.0	16.0	5.5	1,026	220	130

$U_j/U_\infty = 0.75$ and 2.30, respectively. Two different grids are used in this simulation and their details are summarised in Table 1.

The maximum grid size for the fine grid is $\Delta x < 47.0$ and $\Delta z < 38.0$ in wall units. In the wall normal direction first grid point is $y^+ < 1.0$. The mean flow profiles and Reynolds stresses are compared with the experiments [4] at $x = 10h$ in Fig. 2. The simulations give same trends as in the experimental data for mean flow and Reynolds stress. The mean velocity profiles for both jets are in good agreement with the experimental data numerically. The higher velocity ratio jet simulation give better agreement for Reynolds stresses $\langle v'v' \rangle/U_\infty^2$ and $\langle w'w' \rangle/U_\infty^2$. However, the peak $\langle u'u' \rangle/U_\infty^2$ and $\langle u'v' \rangle/U_\infty^2$ are higher than the experimental values. This over-prediction may be the outcome of the uncertainty at the inlet in the simulation and in the hot-wire measurements. The Reynolds normal and shear stresses for $U_j/U_\infty =$ 0.75 jet are an order of magnitude smaller than $U_j/U_\infty = 2.3$ jet.

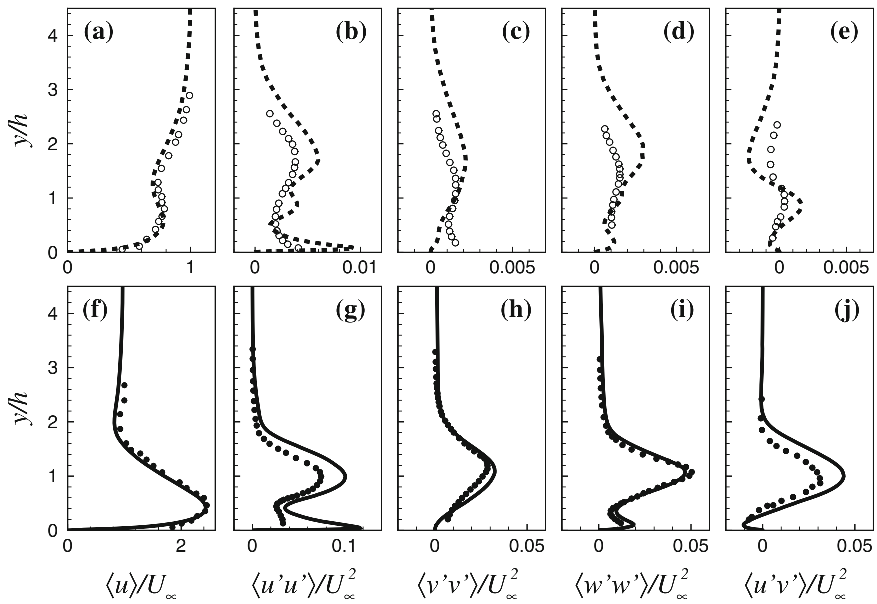

Fig. 2 Comparison of $\langle u \rangle/U_\infty$, $\langle u'u' \rangle/U_\infty^2$, $\langle v'v' \rangle/U_\infty^2$, $\langle w'w' \rangle/U_\infty^2$ and $\langle u'v' \rangle/U_\infty^2$ profiles at $x = 10\,h$ with the experimental data [4]. *Top* $U_j/U_\infty = 0.75$, *bottom* $U_j/U_\infty = 2.3$: *line* simulation, *symbols* experiment

3 Results

In this work the interaction of a wall jet with the outer boundary layer is studied when the separation between the two streams i.e. w is small. Previous studies, with larger separation [9, 10], have shown the existence of large scale coherent structures in the near wake region. Those determine the mixing of momentum and heat between the wall jet and outer stream.

In current simulation various kind of vortical structures are involved. There are streamwise near wall structures coming in from the incoming boundary layers and the slot jet. Apart from these structures, the interaction of the boundary layer with a wall jet generates further dynamic complexity, instability and more large scale structures. The coherent structures are visualised through the isosurfaces of the second-invarient of the velocity gradient tensor $Q = -(\partial\langle u_i\rangle/\partial x_j)(\partial\langle u_j\rangle/\partial x_i)$. Figure 3 shows the coherent structures in the near wake region up to $x = 4.0\,h$. The right frames in the figure show the span wise vorticity at the plane $z = 0.0\,h$, which give the foot prints of the structures presented through the Q isosurfaces. The span wise structures generated for the low velocity ratio jet lose the coherence very quickly. However, the foot prints in the span wise vorticity contours show that structures are similar to von-Karman type shed vortices in the wake region. The high velocity ratio jet presents a very different picture. The structures appear like roll structures, resulting from the jet shear layer Kelvin-Helmholtz instability. At higher wall jet velocity, shear layer on the jet side is strong and it drags the shear layer from the boundary layer side of the wake. The roll structures interact and merge with each other downstream.

This vortical structure evolution in the near field is also confirmed by the mean flow in the wake as shown in Fig. 4. The streamlines for low velocity ratio jet gives a counter rotating vortex pair in the wake, which is the average outcome of von-Karman type structures. The high velocity ratio jet gives a single recirculation lobe in the wake. This single lobe results from the drag of the boundary layer flow along with the high velocity jet shear layer.

Figure 5 plots the streamwise velocity profiles for the two jets at various streamwise locations. To show the development of the flow in the farfield region, wall co-ordinates are used. Standard log-law profile $2.5\log(y^+) + 5.0$ and linear profile $\langle u\rangle^+ = y^+$ in the near wall viscous sub-layer region are also added for the comparison. The profile for the high velocity ratio jet, close to the inlet, at $x = 10.0\,h$, shows a sharp peak in velocity. Away from the wall, this reduces to outer stream velocity. Around $y^+ = 1000.0$ there is a narrow wake region. As flow moves downstream the sharp peak in the velocity profile reduces. The profile becomes flatter with jet spreading. The profiles generally resemble those for a plane wall jet, but are altered by the presence of the external stream. The low velocity ratio jet $\langle u\rangle^+$ profile at $x = 10.0\,h$ is quite different to the high velocity ratio. The peak in the jet region is lower and the wake is wider extending in the range of $y^+ = 200.0 - 1000.0$. The wake persist up to $x = 20h$. A comparison with log-law profile suggests that the velocity profiles for low velocity ratio jet are shifting towards the log-law in the farfield region i.e. developing towards a boundary layer. However there is an offset

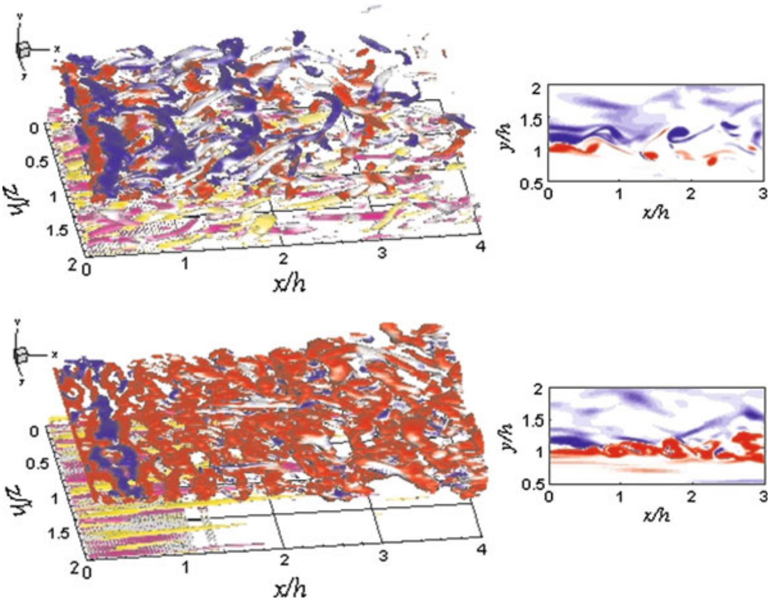

Fig. 3 Coherent structures in the near field region of wall jet and boundary layer interaction, using Q criteria. *Top* $U_j/U_\infty = 0.75$ and *bottom* $U_j/U_\infty = 2.30$. Isosurfaces are coloured with span wise vorticity Ω_z

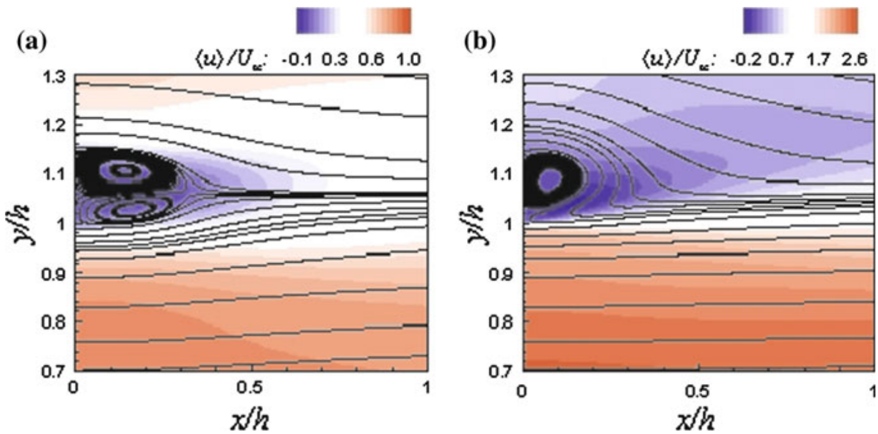

Fig. 4 Mean stream wise velocity contours and streamlines in the wake region near *inlet* plane. **a** $U_j/U_\infty = 0.75$ and **b** $U_j/U_\infty = 2.30$

due to the low value of wall friction coefficient. The mean velocity profiles for both jets in the near wall region are in agreement with the $\langle u\rangle^+ = y^+$ up to $y^+ = 8.0$. Hence, in this region the behaviour is identical to that for a classical boundary layer.

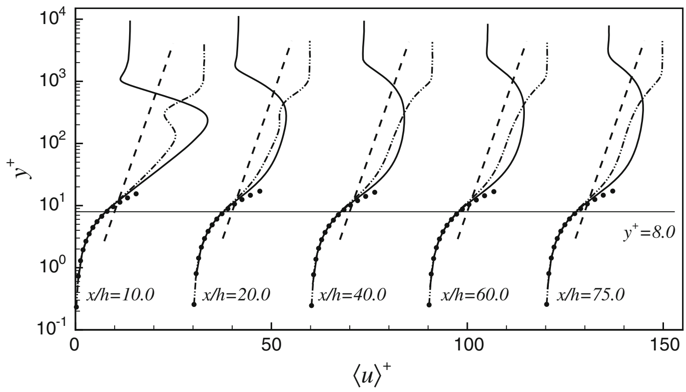

Fig. 5 Mean $\langle u\rangle^+$ profiles at various stream wise location, $U_j/U_\infty = 0.75$ (*dashdotdot*), $U_j/U_\infty = 2.30$ (*solid*), log-law (*dash*) and $y^+ = \langle u\rangle^+$ (*solid circle*)

The $U_j/U_\infty = 2.3$ jet has similarities with the plane wall jet. At large distance downstream $U_j/U_\infty = 0.75$ jet develops towards a turbulent boundary layer. The Reynolds stress profiles are compared with the plane wall jet measurements [2] and also with turbulent boundary layer data of [12] in Fig. 6. The Reynolds and shear stress profiles for low velocity ratio jet in the farfield attains the boundary layer behaviour. The stresses for high velocity ratio jet in the shear layer region are close to wall jet measured values. The u^+_{rms} for high velocity ratio jet has two peaks one in shear layer region and one near the wall. The low velocity ratio jet has near wall u^+_{rms} much higher than shear layer region. The shear stress profiles for high velocity ratio jet follow wall jet behaviour. For low velocity ratio jet $\langle u'v'\rangle^+$ peak in shear layer region is in opposite direction from high velocity ratio jet. It is the consequence of shedding type structures.

4 Conclusions and Future Work

The near field coherent structures for wall jet and external boundary layer interaction with a thin wake plate are different from previous studies [9–11]. The low velocity ratio jet results in shedding type von-Karman structures, whereas high velocity ratio jet give rise to Kelvin-Helmholtz instability and roll structures. The low velocity ratio jet develops towards a zero-pressure gradient boundary layer in the farfield. High velocity ratio jet behaves like plane wall jet. The velocity and Reynolds stress profiles in the near wall region scaled with inner or wall variables. In future a comprehensive study with a wider range of velocity ratios will be performed and detailed scaling behaviour and heat transfer properties near wall will be discussed.

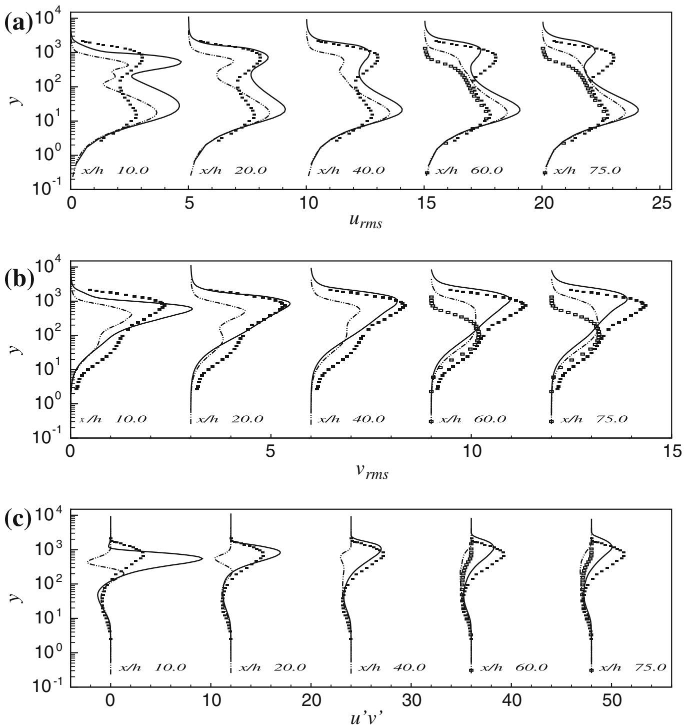

Fig. 6 Reynolds stresses at various streamwise locations. **a** u^+_{rms}, **b** v^+_{rms} and **c** $\langle u'v' \rangle^+$. [12] DNS boundary layer (*open squares*), wall jet measurements at $x = 20\,\text{h}$ [2] (*fill square*)

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