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Experimental and numerical investigation of a heated impinging jet for a small nozzle-to-plate distance and high Reynolds number

F. Gand¹, P. Grenson², I. Mary³, H. Deniau², P. Reulet², B. Aupoix²

Abstract This paper presents a comprehensive study of an impinging jet configuration [1], which has been selected for its high Reynolds number $Re_D = 60,000$, small nozzle-to-plate distance $H/D = 3$ and temperature difference between the heated jet and the ambient. First, the experiments are described and analysed, then numerical simulations (DNS, LES, ZDES and RANS) are assessed to evaluate the resolution level required to capture the salient features of this configuration.

1. Introduction

The impinging jet configuration is of widespread use in industrial applications due to the high heat transfer experienced by the impinged surface. Nevertheless, it remains an attractive and challenging configuration for turbulence modeling and numerical simulation assessment. A large number of published work deals with numerical simulations of impinging jets configurations [2] [3] [4] [5] [6], however at rather low Reynolds number and different nozzle-to-plate distances and based on often incomplete and scattered experiments.

The goal of the present paper is to assess the accuracy of a wide range of numerical methods - RANS, ZDES, LES and DNS- for the prediction of an impinging jet configuration using a single, well-documented experimental dataset created in the framework of an ONERA joint project for numerical validation purposes by Grenson et al. [1]. The configuration considered has been selected for its high Reynolds number $Re_D = 60,000$, small nozzle-to-plate distance $H/D = 3$ and temperature difference between the heated jet and the ambient.

From a technical point of view, a key quantity to predict is the heat transfer on the impinged plate, which presents a dual-shaped profile for the nozzle-to-plate distance considered. This is attributed to the dynamics of the plate boundary layer re-attachment which is challenging for turbulence modelling. The use of different levels of resolution in this paper aims at highlighting some trade-offs between accuracy and computational cost for the prediction of heat transfer.

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2. Experimental dataset

The main features of an impinging jet configuration are illustrated in Fig. 1. Three areas of interest are identified, namely the free jet issued from the nozzle (in the present case, the nozzle is actually a fully developed pipe), the stagnation area and the wall jet. The characteristics of the configuration studied in the present paper are given in Table 1. The nozzle-to-plate distance is equal to $H/D=3$, the flow in the pipe is heated up to 400 K so that the free jet is hot. The Reynolds number based on the pipe exhaust diameter is equal to $Re_D = 60,000$.

Fig. 1 Schematic description of a strong flow deviation

A complete description of the experiments and instrumentation can be found in [1] as well as the analysis of the results. The Nusselt number distribution on the impinging plate obtained by an inverse method displays a secondary maximum typical of such small nozzle-to-plate distance configurations (Fig. 2). Besides, PIV measurements enable to detect large coherent vortices created in the free jet area and track them during the impact, as depicted in Fig. 3. A detailed analysis of these vortex regions using time-accurate LDV measurements enabled to link the dynamics of the free jet and that of the wall jet. At last, the secondary maximum of the Nusselt number distribution was attributed to a possible separation in the decelerating flow region, which is a shared interpretation with previous works [4] [6].

Fig. 2 Measured Nusselt number distribution

Fig. 3 Location and size of the vortex regions

3. Simulations

3.1 Parameters of the simulations performed

Four simulations of increasing turbulence resolution level are evaluated in the present paper as summarized in Table 2:

- A RANS computation using the $k-\omega$ SST model is used as a reference of the industrial capabilities, although it is known that eddy-viscosity RANS models are not suited for this kind of configuration [3];
- A hybrid RANS/LES simulation using the ZDES mode 2 [7] is performed in order to assess the compromise of this approach in terms of CPU cost and resolution level since the attached flow on the impinging plate is treated in RANS mode. The use of mode 2 of ZDES makes it straightforward for the user since the RANS-to-LES switch is automatic [7], which makes this approach useful in an industrial context. The pipe is not included in this simulation. Instead, the pipe exhaust flow is generated using the Synthetic Eddy Method [8] to provide realistic unsteady turbulent content. This simulation is presented in [9], which focuses on the free jet area;
- A wall-resolved LES simulation provides a first assessment of the increased near-wall turbulence resolution level on the impinging plate. The pipe is included in the computational domain, and the inflow turbulence necessary to compute the pipe in wall resolved LES is generated using a combination of

vortex rings method near the wall and isotropic homogeneous turbulence in the center of the pipe. This simulation is presented and analyzed in details in [10];

- A DNS simulation is finally used as an even further resolved numerical dataset. The pipe is included in the computational domain, the Lund method is used to generate resolved turbulence in the pipe.

The RANS, ZDES and LES simulations involve an isothermal boundary condition at $T=298.15$ K for the impinged plate. On the other hand, the experimental temperature profile was used as a boundary condition for the DNS simulation in order to match exactly the conditions during the PIV measurements.

The RANS, ZDES and LES simulations were performed with the elsA software of ONERA [11]. The DNS simulation was carried out with the LES/DNS dedicated code Funk of ONERA.

Name	Turbulence modelling	Inflow	Grid count	Spatial scheme	Time scheme	Time step(μ s)	Simulated time
k- ω SST	RANS-k- ω SST	-	17.10^6	2 nd order AUSM+P	Implicit Gear		-
ZDES	ZDES mode 2	SEM	17.10^6	2 nd order AUSM+P	Implicit Gear	1.	38xD/U
LES	LES (no SGS)	Vortex rings + THI	350.10^6	6 th order Fosso et al.	Explicit RK4	0.07	35xD/U
DNS	DNS	Lund	500.10^6	2 nd order AUSM+P	Implicit Gear	0.04	100xD/U

Table 2 Simulations performed

The difference in resolution on the impinged plate between the three eddy-resolving simulations assessed in this paper is illustrated in Table 3. This is also an indicator of the cost of the simulations. Note that the ZDES grid is 20 times smaller than the LES one and 30 times smaller than the DNS one.

Simulation	Δx^+	Δr^+	$r\Delta\theta^+$
ZDES	1	[20;200]	[20;200]
LES	2	25	25
DNS	0.2	10	10

Table 3 Grid sizes on the plate (x is the wall normal direction relatively to the plate)

3.2 Pipe exhaust conditions

Mean and fluctuating velocity profiles close to the pipe exhaust are plotted in Fig. 4. All simulations match the experimental velocity profile, and satisfactory turbulent statistics are achieved. The ZDES simulation which involves SEM to

generate these statistics does not reproduce the near-wall turbulence intensity peak due to the setup of the SEM which was only aimed at reproducing isotropic core jet turbulence [9] (for user-friendliness purposes).

Fig. 4 Pipe exhaust conditions

3.3 Jet flow development

Fig. 5 presents instantaneous visualizations of the ZDES, LES and DNS simulations. The difference in resolution level is self-evident, especially on the impinging plate where fine scale turbulence is resolved in the LES and DNS simulations whereas only larger detached eddies are captured in the ZDES simulation.

Fig. 5 Instantaneous visualizations of the simulations (Q criterion)

The time-averaged fields depicted in Fig. 6 provide qualitative insights on the accuracy of the simulations. All simulations agree fairly well with the experiment for the velocity magnitude. Conversely, significant discrepancies appear for second order statistics in the mixing layer. The DNS and ZDES simulations seem to

underestimate the thickness and intensity of the shear layer, while the LES simulation displays the opposite trend. The turbulence levels also seem to be overestimated in the wall jet area for the LES simulation, which is further studied in section 3.4.

Fig. 6 Mean velocity (first row), streamwise velocity fluctuations (second row) and radial velocity fluctuations (third row)

The profiles extracted in the free jet at $x/D = 1.5$ presented in Fig. 7 confirm the previous observations. Overall, the simulations are in fair agreement with the experiment. The ZDES simulation provides arguably the best agreement with the streamwise and radial experimental velocity fluctuations, which is consistent with several previous works with ZDES and jets and free shear flows [7] [9] [12]. Regarding the RMS temperature fluctuations, the DNS is closer to the experiment. The shear layer in the LES simulation is too large and intense which may be related to a travelling spurious pressure wave inside the pipe [10].

Fig. 7 Mean velocity, velocity fluctuations and temperature fluctuations in the jet at $x/D=1.5$

3.4 Flow on the impinged plate

Fig. 8 presents profiles in the wall jet area. The overall agreement between experiments and simulations is satisfactory. Contrary to what has been observed in the free jet area, the LES and DNS results for the velocity magnitude and fluctuations are closer to the experiments than the ZDES ones. This is attributed to the progressive switch to RANS mode of the ZDES as the wall jet reattaches, whereas it is fully resolved in the LES and DNS simulations. These discrepancies are likely to affect the heat transfer since it is a shared opinion [4] that the near-wall dynamics of the wall jet is responsible for the Nusselt number distribution – in particular the secondary maximum observed in Fig. 2.

Fig. 8 Profiles of streamwise, radial and crossed velocity fluctuations and temperature fluctuations near the impinged plate

3.5 Near-wall quantities on the impinged plate

Fig. 9 illustrates the dispersion of the numerical results in terms of heat transfer. On the left part of Fig. 9, the Nusselt number based on the pipe exhaust diameter is computed as $Nu_D = q_c(T_w - T_{aw})D/k_p$ where q_c is the heat transfer, T_w is the plate temperature, T_{aw} is the adiabatic wall temperature taken from the experiments and k_p is the thermal conductivity of air at T_w . The LES simulation matches the experiment in the stagnation region whereas the $k-\omega$ SST and ZDES overestimate the heat transfer. All simulations predict the existence of a secondary maximum but its intensity and location is not accurately captured. The LES is closer to the experimental data than the ZDES and $k-\omega$ SST simulations. An additional ZDES simulation was performed without injecting turbulence at the pipe exhaust (ZDES (no SEM) in Fig. 9). It is interesting to note that the results of this simulation do not exhibit a secondary peak which is attributed to the fact that the free jet is not correctly developed if the turbulence coming from the inside of the pipe is not taken into account (see [9]).

Since the DNS simulation was performed at the thermal equilibrium (conditions identical to the ones when the PIV measurements were carried out), the Nusselt distribution is not relevant for this simulation. To assess the DNS near-wall data, the wall friction is plotted on the right of Fig. 9. This quantity was not measured during the experiments, therefore the data from the experiments of [13] for a similar configuration ($H/D=3$ and $Re_D=44,000$) are shown. The secondary maximum for this quantity appears challenging to capture and only the DNS is able to predict it quantitatively. An inflexion point can also be seen in the LES curve, which is not the case for the ZDES simulation. The additional ZDES without SEM at the pipe exhaust provides a slightly lower friction coefficient than the one with injected turbulence near $r/D=2$, which is consistent with the results for the Nusselt number and illustrates the link between these quantities.

Fig. 9 Nusselt number and friction coefficient on the impinged plate. Experimental data for friction taken from [13]

4. Summary and conclusion

The comparison of different levels of turbulence modellings ranging from RANS to DNS with an extensive experimental dataset has enabled to identify the flow features that can be captured with each approach. Since the cost of the simulations roughly scale with the grid size and refinement of the method, this helps identify the best compromise between the accuracy required for the desired quantity and the computational cost / turnaround time.

It was shown that for the free jet area, the ZDES mode 2 approach – which acts as LES in the free jet – provides very satisfactory results insomuch as the pipe exhaust conditions are correctly taken into account (using SEM here, also refer to [9]). Some discrepancies have been observed between the ZDES, LES and DNS simulations regarding the shear layer intensity and growth rate, which is probably linked to the turbulence generation and resolution in the pipe, as well as grid stretching near the pipe exhaust.

Conversely, it was observed that some near wall turbulence resolution is required in the wall jet area in order to accurately capture the heat transfer and friction coefficient (this is consistent with previous studies [5] [6] [3]). The LES data tend to indicate that the heat transfer can be predicted with this approach, while DNS seems to be necessary to capture the friction coefficient profile. ZDES mode 2 reproduces some features of the heat transfer distribution but the switching back to RANS mode in the attached wall jet seems to be counterproductive in this regards.

In order to combine the good features of ZDES mode 2 in the free jet area and provide some near-wall turbulence resolution in the wall jet area, it would be interesting to implement ZDES mode 3 (*i.e.* Wall Modelled LES) in the wall jet area. This requires an increased grid density near the plate, which can be achieved effortlessly with the chimera approach while maintaining a computational cost compatible with industrial constraints. More accurate conclusions could also be reached by using the same numerical methods (turbulence generation, space and time schemes, boundary conditions, CFD software, etc.) and only refining the grid when the turbulence resolution approach requires it.

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