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Unsteady heat transfer analysis of an impinging jet with high-order spectral element methods

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Abstract – Numerical simulations are a powerful tool to understand the kinematic and thermodynamic behaviour of impinging jet, which is of great interest in many industrial application. However, in addition to the usual difficulties of computer simulation of incompressible fluid motion and heat exchange, this flow also presents the added issue of involving severely truncated open boundaries. The most commonly used boundary conditions either cause numerical instabilities or have an exceedingly high computational cost.

A two-dimensional simulation of the confined impinging jet at $Re = 2500$ with a non-dimensional nozzle-to-plate distance $H/D = 2$ has been used to test the effectiveness of alternative boundary conditions designed to correctly reproduce the physics of the phenomenon. A large eddy simulation of the three-dimensional case with the same parameters has been performed as well. In both cases, the boundary conditions prevented the divergence of the simulation and the production of non-physical reflections.

1. Introduction

Impinging jets are a topic of great interest because of their importance and widespread usage in industrial applications; nevertheless, some of their physical aspects are not fully understood yet, due to the complexity of the flow field [1]. For instance, the influence of the vortical structures on the heat exchange and on the presence of a second peak of Nusselt number is an active research topic. Impinging jets are characterized by a high heat transfer rate, for both heating and cooling purposes, which is function of a large number of parameters, such as Reynolds and Prandtl numbers and geometric features like the nozzle-to-plate distance.

In the present work, the incompressible Navier-Stokes equations are solved through high-order spectral element methods in Nek5000 in order to simulate the flow field around the jet and the heat exchange at the wall. Numerical simulations of a two-dimensional confined impinging jet have been performed at $Re = 2500$ and $Pr = 1$, with a nozzle-to-plate distance of two jet diameters. The novel feature of the present analysis is an assessment of the conditions imposed on the open boundaries, which is a known source of numerical instabilities [2] as well as possible numerical artifacts [3]. To investigate turbulent flows, the three-dimensional case has been studied as well, with a large-eddy simulation of the round jet.

2. Numerical setup

The object of the simulations is a cooling jet impinging on a heated wall, on which a constant heat flux boundary condition has been imposed. On both top and bottom walls no-slip conditions are considered on velocity, but the conditions for the open boundary is less obvious due to the truncation of the unbounded domain. The use of the outflow boundary condition already present in the Nek5000 solver has not been possible, since it caused the divergence of the simulation as soon as vortices reached the open boundary. On the other hand, the boundary condition presented in [4] has been found the be effective in discharging the vortices from the domain without the production of non-physical instabilities. Moreover, compared to other

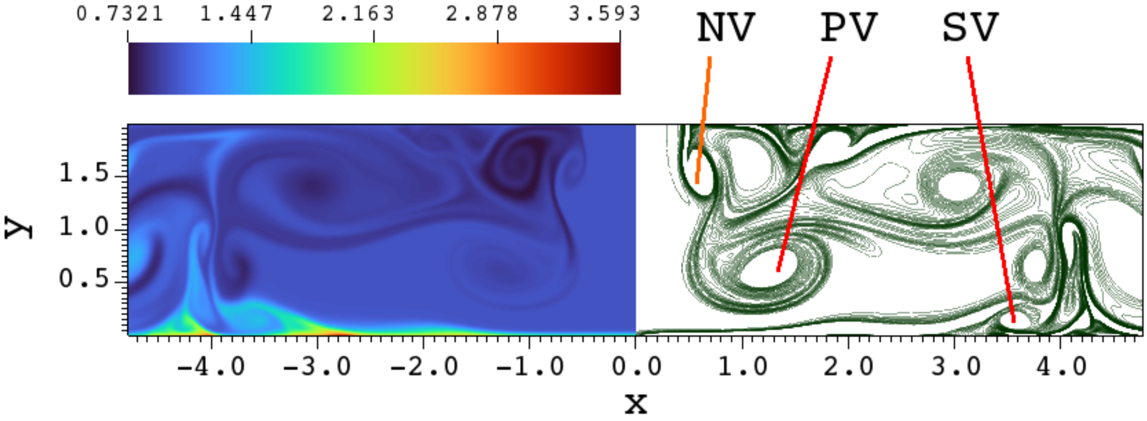

Figure 1: Fields of temperature (left-hand side) and vorticity (right-hand side) at time $t = 39.75$ and $Re = 2500$ for the two-dimensional impinging jet. The primary vortex (PV) can be observed as well as the secondary vortex (SV), whose presence is relevant to the investigation of the behaviour of Nusselt number at the wall. With a certain periodicity, a new vortex (NV) forms on the jet and a cyclic phenomenon can be observed.

approaches such as the use of a sponge region, it allows for the use of a relatively small-sized computational domain with a consequent reduction in computational cost.

A non-standard condition on the open boundary has been adopted for temperature as well since the zero-flux Neumann-type boundary condition $\nabla T \cdot \hat{\mathbf{e}}_\mathrm{n} = 0$ available in Nek5000 produces non-physical reflections when vortical structures are present, causing alterations of the temperature field upstream. To prevent this phenomenon, the energy-stable boundary condition in [3] has been implemented, with the omission of the unsteady term. This condition solved the reflection problem and did not cause the alteration of the field upstream, but only had a local impact on the temperature field of the vortices exiting the domain.

3. Results

The results of the simulations showed the generation of vortical structures that have been analyzed; an exemple of those can be found in Figure 1. The relationship of this structures with the oscillatory behaviour of the instantaneous Nusselt number has also been studied. In fact, it is well know from the literature [2, 3] that at moderate Reynolds numbers the strength of the vortices, consequence of an instability similar to that of Kelvin-Helmholtz, determines relevant unsteady phenomena regarding the distribution of the instantaneous Nusselt number at the wall, and its global maximum is likely to be found in locations differing from the stagnation point, which is a common result at lower Reynolds numbers. An example of the oscillatory behaviour of the Nusselt number is shown in Figure 2. The three-dimensional simulation has been carried out as a way to assess the effectiveness of the numerical setup with the contribution of turbulence, described by the use of large-eddy simulation models. For this purpose, a high-pass filter, as the one presented in [5], has been chosen to reproduce subgrid-scale dissipation. Figure 3 shows the results for the time-averaged Nusselt number at the wall, with at presence of the primary maximum at $r/D \approx 0.7$. At $r/D \approx 2.1$ there is a change in the slope of the curve in correspondence of where the secondary maximum is expected. This is in line with what was reported in [2], in which it is shown that the LES models have not been able to capture the local minimum in between the primary and secondary maximum.

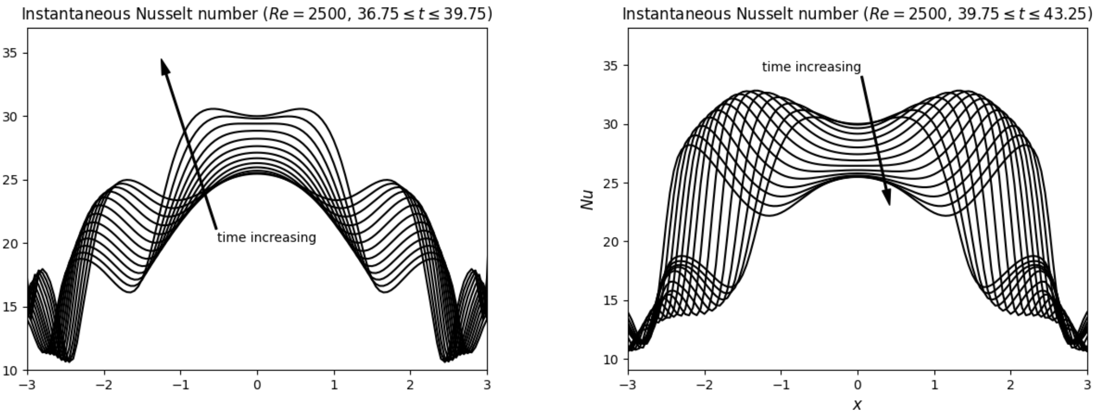

Figure 2: Cyclical growth (on the left) and decay (on the right) of the instantaneous Nusselt number at the wall for the for the two-dimensional impinging jet at $Re = 2500$.

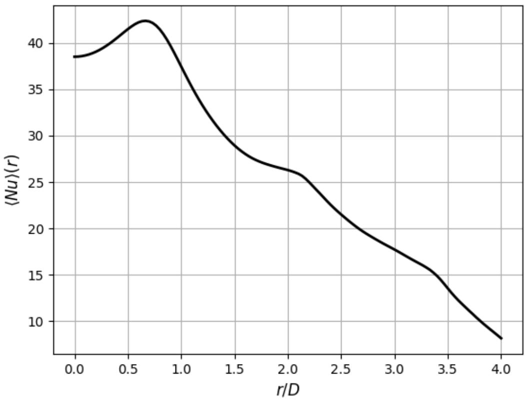

Figure 3: Time-averaged Nusselt number at the wall for the three-dimensional round impinging jet. Nusselt number calculated along the $x = z$ direction for positive x and z.

4. Conclusions

In this study, the use of energy-stable boundary conditions have been tested to prevent the issues due to the presence of open boundaries. In both the two and three-dimensional cases, the simulations were free of non-physical reflections on the boundaries that would have otherwise affected the thermal and velocity field.

In the two-dimensional case, the vortical structures have been identified and studying the time-averaged Nusselt number at the wall the presence of a secondary maximum has been detected, apart from the primary one at the jet axis. In the three-dimensional case the primary maximum shifted downstream, which is in line with what is reported in the literature for jet with low nozzle-to-plate distance. Due to the use of LES modelling, the secondary maximum is not clearly visible, but its presence can be detected through a slope change in the Nusselt number curve.

The use of energy-stable boundary conditions has been shown to be able to attain physically correct results while using a smaller dominion then other methods, such as the fringe region technique, allowing for a reduction in computational cost. Future work would be to use this advantage to perform higher-fidelity simulation at higher Reynolds numbers.

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References

1. G.M. Carlomagno and A. Ianiro. Thermo-fluid-dynamics of submerged jets impinging at short nozzle-to-plate distance: A review. *Exp. Therm. Fluid Sci.*, 58:15–35, oct 2014.
2. T. Dairay, V. Fortuné, E. Lamballais, and L.E. Brizzi. LES of a turbulent jet impinging on a heated wall using high-order numerical schemes. *Int. J. Heat Fluid Flow*, 50:177–187, dec 2014.
3. X. Liu, Z. Xie, and S. Dong. On a simple and effective thermal open boundary condition for convective heat transfer problems. *Int. J. Heat Mass Transf.*, 151:119355, apr 2020.
4. S. Dong and J. Shen. A pressure correction scheme for generalized form of energy-stable open boundary conditions for incompressible flows. *J. Comput. Phys.*, 291:254–278, 2015.
5. S. Stolz, P. Schlatter, and L. Kleiser. High-pass filtered eddy-viscosity models for large-eddy simulations of transitional and turbulent flow. *Phys. Fluids*, 17(6):065103, 05 2005.