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Large Eddy Simulation of Impinging Jets with focus on the Inflow Boundary Conditions

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THIS paper deals with Large Eddy Simulation (LES) of submerged circular impinging jets. The main focus is on the imposed inflow conditions. The outcome of a numerical simulation strongly depends on the discretization scheme, the computational grid and the type of modeling. However, in case of unsteady simulations the inlet velocity field may be just as important for the quality and relevance of the results. The benefits having an accurate scheme, a fine grid a sophisticated SGS model may not be sufficient if not the appropriate inlet conditions are applied. In some applications, where the inflow is laminar or has limited influence on the region of interest, the simplest type of velocity data may be considered, i.e. a mean velocity profile with or without superimposed random perturbations. The major drawback with random perturbations is that there is no correlation in time and space. Furthermore, the energy distribution among the different scales is constant. The consequence is that the applied disturbances will quickly dissipate. This type of velocity signal can be defined as

$$v(r,t) = V(r) + 2A(Rand(r,t) - 1/2), \qquad (1)$$

where A is the amplitude of the perturbations and $Rand$ is a random function providing pseudo random numbers within the interval $(0,1)$. (The unphysically high viscous forces caused by the random fluctuations can, as stated by Friedrich et al., be overcome by artificially increase Re and then gradually decrease it to the desired value. By doing this the transient time is sufficient for the fluctuating energy to be distributed among all wave numbers.) In order for perturbations, provided at the velocity inlet, to influence the downstream development of the flow, at least, the temporal scale must be defined. This criterion may be fulfilled by applying a mean velocity profile in space with superimposed sinusoidal perturbations in time. By doing this one adds temporal correlation, determined by the defined frequency or frequencies, while the correlation in space is left undefined. This method, within here referred to as periodic forcing, is frequently used to trigger specific instability modes of a system and can be written as

$$v(r,t) = V(r) + sin(2\pi S_f t), \qquad (2)$$

where A is the amplitude and S_f is the forcing frequency, here expressed as Strohal number (fD/V).

Except from the type of excitation the shape of the applied mean velocity profile has a direct influence on the developing flow field. The within here considered mean profiles are the top-hat, the weakly mollified and the strongly mollified. Characteristic for the top-hat profile is that the imposed annular shear layer is not grid independent. This is so since the shear layer thickness is determined from the local grid resolution. This is of course not physically correct but may nevertheless be of insignificant importance if improper perturbations are considered. In a case where random perturbations are applied, which quickly dissipates, the top-hat profile may be an efficient tool in achieving growth of disturbances. Already at the first grid line downstream of the nozzle a physically relevant shear layer has developed, as the applied discontinuity has been smeared out by the action of viscous diffusion. The, still, strong mean velocity gradient is the driving force in growth of disturbances. However, in order to trigger growth some perturbations must exist in the system. These may be induced directly via Eq. (1) or indirectly via the numerics (always present). The objective applying a mollified mean velocity profile is to separate physical aspects from numerical. This is achieved by letting the annular shear layer be resolved by, let say, four to eight grid nodes. The obvious difference between these profiles is that growth of particularly small-scale structures becomes suppressed for the mollified ones.

When compared to experimental work on impinging jets the proximal region of the simulated jet should be treated with caution. Particularly if the top-hat profile is applied and the emanating jet in the experiment is laminar. However, further downstream the

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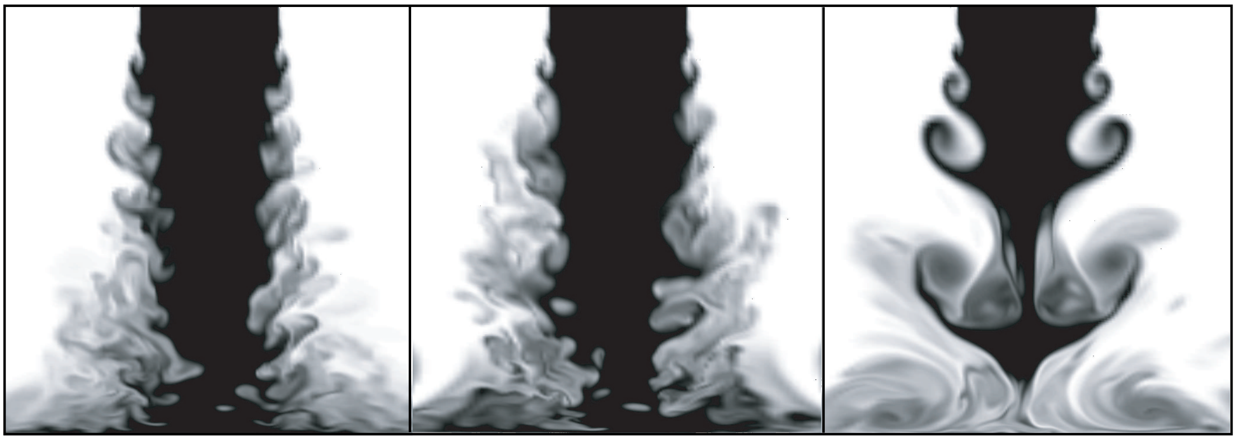

Fig. 1 Influence from boundary conditions on the instantaneous scalar field for a nozzle-to-plate spacing of four nozzle diameters. Left picture shows the *Top-Hat* case with imposed random perturbations. The middle picture shows the *Precursor* case. The right picture shows the weakly *Mollified* case with imposed random perturbations.

axial jet and along the impingement wall comparison is more fair. Thus, when not having the correct inlet conditions a region dedicated to flow field development should be considered. The remedy to this problem is to provide a velocity field with the appropriate space and time correlations and, also, relevant frequency spectra. There are several methods aimed at synthesize a turbulent velocity field. However, this type of artificial method has not been considered within this work.

The most justifying method is to directly use the velocity field from a precursor simulation without any further modification. Doing this the correct correlations and spectrums are achieved. There are some drawbacks though namely the needed amount of storage capacity and the high cost for the precursor simulation. This method is also relatively inflexible as an additional calculation must be performed if modifications to the velocity field is wanted. Within the present work pipe flow simulations have been conducted with the prescribed Reynolds number. These simulations have been performed in a periodic Cartesian domain with a length of $8\pi R$, where R is the pipe radius. The number of cells in (x, y, z) were $(162x162x194)$ on the finest out of four Multi-Grid levels, where z is the streamwise direction. At each time step the mid-plane (xy-plane) of the pipe was saved for future use (space correlations in x and y and time correlation in z). The Cartesian coordinate system is not the optimal for these kind of simulations as the grid can not, without complication, be stretched radially. Thus, the wall boundary layer can not be as efficiently treated as with cylindrical coordinates. However, the main objective was to create a velocity field featuring large scales that do not dissipate in the impinging jet calculation, correlations in space and time and spectra of physical character (large amount of energy in low wave numbers and low amount of energy in high wave numbers).

In a true high Re situation the mean profile is never felt by the flow field. We have found that with a non-perturbed mollified profile, even when weakly mollified, the formation of large scale ring vortices are strongly promoted. This is not the case for turbulent inflow conditions, where the flow field within the axial jet is significantly less structured. With a top-hat profile these large axisymmetric ring vortices are not as favored why the flow field becomes more similar to that with turbulent boundary conditions. This is clearly depicted in Fig. 1. Even though an instantaneous picture does not reveal any details of the flow field it can be concluded that the top-hat (far left) and the precursor cases (middle) are much of the same character, with initial formation of vortical structures in an axisymmetric fashion and successive breakdown to a highly unstructured state. The mollified case (far right), on the other hand, exhibits strong formation of axisymmetric vortices that survive far downstream. The energy is concentrated to this dominant mode why breakdown into a turbulent state is postponed to within the wall jet.

Results on mean velocities and mean scalar concentration as well as higher order statistics are presented. Also time resolved analysis, such as correlations, spectral content and intermittency have been considered. To increase the understanding also instantaneous realizations of the various flow fields are discussed.