Effect of nozzle turbulent intensity in multiple round jets using openFOAM®

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Abstract. The present work is about the effects of turbulent intensity on the flow field of turbulent multiple jets. The simulations are carried out by using an open-source Computational Fluid Dynamics C++ code OpenFOAM®. The governing equations invoked are Reynolds Averaged Navier Stokes equations by using simpleFoam solver. The standard two-equation turbulence model is used along with the mean flow equations to account for turbulence effects. The solved flow field shows a significant effect of turbulent intensity on the potential core of both single and multiple jets which is supported by reference literature. Downstream the potential core, the turbulence intensity does not affect the decay rate of turbulent jets considered in the study. The performance parameters show that the higher initial values of turbulent intensity is favorable only for the single jet simulations. In contrast, the lower initial values of turbulent intensity is favorable for multiple jet simulations.

1. Introduction

Turbulent jets [1–3] form a family of free shear flows that have many industrial applications such as mixing in combustors of large scale gas turbines intended for power generation and also in diffusers of HVAC devices. The flow field of turbulent jets are described by several reference and original research works which consist of theoretical, computational and experimental data.

The focus on turbulent jets has shifted from circular jets to non-circular jets and multiple jets due to its advantages [4–12]. The usage of advanced nozzles and passive control devices help in better mixing and noise mitigation. The earlier studies reported in the above paragraph are concerned about the usage of multiple jets mostly intended for industrial, aerospace and building cum environment applications. To enhance the usage of turbulent jets in the above-said applications and also to reduce the pollution effects resulting due to improper mixing, the research focus was in parallel was towards the tweaking of jet flow mixing. The tweaking of the jet flow field was achieved by providing disturbances in an active or passive manner in the upstream of the flow. The upstream disturbance propagates downstream and influences the mixing characteristics [11,12].

The presence of a booster blower or pump near the diffuser outlet delivers turbulent flow which directly affects the flow downstream of the nozzle/orifice. Also, the studies about the performance of upstream turbulent intensity in the multiple jets compared to single jets have not been studied to date. To achieve this, multiple jet simulations with different turbulent intensities are proposed in this work.
along with the simulations of single jets with various turbulent intensities to throw deeper insight on the physics and computational aspects.

2. Methodology
The computational method for the present work is followed by the reference literature [9]. However, a simple and brief description is provided here. A large computational domain is chosen for the jet flow simulations. An open-source code [7,13,14] based on C++ is used for the present study. figure 1 a and b shows the grid from the frontal side and the internal vertical cut view. The domain (200D in axial direction and 150D in lateral direction, where D is the equivalent diameter of nozzles) along with the initial (Re=11,000) and boundary conditions (uniform velocity for nozzle, zero-gradient on outlet and lateral surfaces, wall for nozzle plate) are used for simulations. The multiple nozzle has a central nozzle surrounded by four adjacent nozzles with 4D separation. The grid (1 million cells) is refined for capturing the velocity gradients developed by the turbulent jet flow in the regions of the near nozzle field and the axis. The simulations are performed on a Linux based computer with a GCC compiler.

![Grid](image1.png)

**Figure 1.** a) Frontal view of domain with grid. b) A vertical cut view of the domain with grid refinements.

For more details on grid independent study, validations and initial/boundary conditions, readers are advised to refer the reference literature[9,11,12]. The post-processing is carried out by a VTK based open-source tool called Paraview. The flow field of simulated jets are described in the following material.

Figure 2 shows the flow field of multiple jets in the internal vertical cut plane. The initial development of the jets is seen along with the merger and combined development in the far-field region. figure 2 also shows the streamline patterns for the multiple jets. White-colour streamlines are seeded from the entrainment boundary and the pink-colour streamlines are seeded from the nozzle downstream. The integrated streamlines filled the domain and show the flow of physics clearly. The streamlines show the development of jets and also the entrainment phenomenon. Three-dimensional entrainment is also seen from the streamlines.
3. Results and Discussion

The post-processed results are discussed under various subdivisions listed below to have continuity on the flow physics and also to facilitate effective reading.

3.1. Effect on potential core

3.1.1. Single jet. The effect of upstream turbulent intensity on the potential core of single turbulent jets is seen from figure 3. The increase in turbulent intensity from 0.1 to 1 % does not show any difference in the potential core. But the further increase of its value from 1 to 5 % and subsequently to 10 % shows a rapid decrease in the length of the potential core as reported in the reference literature. This is due to the faster mixing introduced by the turbulent fluctuations on the shear layer just outside the nozzle exit.

3.1.2. Multiple jets. The effect of upstream turbulent intensity on the potential core of multiple turbulent jets is seen from figure 4. The case for multiple jets with 0.1 % is not shown in the plots which are due to the divergence of simulations introduced by the initial conditions. The increase in turbulent intensity from 1 to 5 % and subsequently to 10 % shows a rapid decrease in the length of the potential core as seen in the single jet results from figure 4. This is also due to the faster mixing introduced by the turbulent fluctuations but with a comparatively smaller nozzle when compared to the
single jet case. The potential core is followed by the transition region and the fully developed region. The results of the same are discussed in the following section.

3.2. Effect on the far-field.
3.2.1. Single jet. The effect of upstream turbulent intensity on the far-field of single turbulent jets is seen from figure 5. The increase in turbulent intensity from 0.1 to 1 % does not show any difference in the far-field. But the further increase of its value from 1 to 5 % and subsequently to 10 % shows an earlier start of velocity decay from the end of potential core. The earlier start of mixing is followed by a linear increase for all the turbulent intensities considered in this study. As the upstream turbulent intensity increases, only a shift in the decay curve is seen without affecting the decay rate which is provided by the slope of the linear plot.

3.2.2. Multiple jets. The effect of upstream turbulent intensity on the far-field of multiple turbulent jets is seen from figure 6. The increase in turbulent intensity from 1 to 5 % and subsequently to 10 % shows an earlier start of non-linear velocity increase from the end of the potential core and before the start of linear variation. The non-linear phenomenon is followed by a linear increase for all the turbulent intensities considered in this study. As the upstream turbulent intensity increases, a shift in the decay curve is seen with a negligible effect on the decay rate as compared to the results of turbulent single jets.
3.3. Effect on Turbulent Kinetic Energy (TKE).

3.3.1. Single jet. The effect of upstream turbulent intensity on the Turbulent Kinetic Energy along the centerline of single turbulent jets is seen from figure 7. The increase in turbulent intensity from 0.1 to 1 % has no effect on Turbulent Kinetic Energy. But the further increase of its value from 1 to 5 % and subsequently to 10 % shows faster production of Turbulent Kinetic Energy in the near nozzle region. The Turbulent Kinetic Energy increases rapidly with the increase in upstream turbulent intensity in the near field region followed by almost a steady value (~ 0.1) in the downstream far field region for all the turbulent intensities considered in this study.

3.3.2. Multiple jets. The effect of upstream turbulent intensity on the Turbulent Kinetic Energy along the centerline of multiple turbulent jets is seen from figure 8. The increase in turbulent intensity from 1 to 5 % and subsequently to 10 % shows faster production of Turbulent Kinetic Energy in the near nozzle region which is similar to the single jet cases. The Turbulent Kinetic Energy increases rapidly outside the potential core followed by a dip due to merger phenomenon and gradual growth followed by almost a steady value (~ 0.1) similar to the single jet cases.
8. TKE for multiple jets.

3.4. Effect on Simulation Performance.

The effect of upstream turbulent intensity on the performance of simulations of both single and multiple turbulent jets are shown in tables 1 and 2. The increase in turbulent intensity from the lowest value to 10 % shows a decrease in number iterations and clock time for computations in the case of single jets. For multiple jet cases, the increase in turbulent intensity from the lowest value to 10 % shows an increase in number iterations and the clock time for computations. It is also to be noted that the simulations for multiple jet case with lowest turbulent intensity crashed around 4500 iterations and with highest turbulent intensity introducing oscillations in the residuals that lead to non-convergence. The instabilities are supposed to be introduced by the numerical schemes and also by the physics of the flow field.

Table 1. Performance details for single jet simulations.

| Turbulent Intensity | Iteration | Clock time | Time taken for first 100 iterations |
|---------------------|-----------|------------|------------------------------------|
| 0.1                 | 33678     | 416892     | 2991                               |
| 1                   | 34027     | 407663     | 2492                               |
| 5                   | 33018     | 406975     | 2849                               |
| 10                  | 30711     | 378946     | 2677                               |

Table 2. Performance details for multiple jet simulations.

| Turbulent Intensity | Iteration | Clock time | Time taken for first 100 iterations |
|---------------------|-----------|------------|------------------------------------|
| 0.1                 | *         | N/A        | 2165                               |
| 1                   | 28381     | 333298     | 2142                               |
| 5                   | 30553     | 425422     | 2271                               |
| 10                  | 95700     | 425282**   | 2178                               |
4. Conclusions

The present work describes the effects of upstream turbulent intensity on the flow field of turbulent multiple jets. The simulations were carried out by using OpenFOAM® and invoking Reynolds Averaged Navier Stokes equations along with a two-equation turbulence model. The post-processed results were discussed with the help of obtained results and the significant conclusions are drawn.

The results and discussions show a significant effect of turbulent intensity on the potential core of both single and multiple jets. Downstream the potential core, the turbulence intensity does not affect the decay rate of turbulent jets in the far-field region but shows an earlier start of decay outside the potential core. Faster production of Turbulent Kinetic Energy on the near nozzle for both single jet and multiple jet cases is seen with an increase in the upstream turbulent intensity.

The performance studies show that the higher initial values of turbulent intensity is favorable only for the single jet simulations. In contrast, the lower and optimum initial values of turbulent intensity is favorable for multiple jet simulations.

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