Numerical Simulation of Flow through a Sudden Contraction Split into Four Parallel Round Jets

John Njoroge¹ and Puzhen Gao¹,*

¹Fundamental Science on Nuclear Safety and Simulation Technology Laboratory, College of Nuclear Science and Technology, Harbin Engineering University, Harbin 150001, China

*Corresponding author email: gaopuzhen@hrbeu.edu.cn

Abstract. Parallel jets are of profound importance in design of nuclear reactor components as well as other industrial applications. Vertical flow through a sudden contraction split into four round jets was numerically investigated using computational fluid dynamics (CFD). Results showed that jet spacing and jet size are the main parameters influencing the resulting flow field. In the upstream, both radial and streamwise velocity profiles drastically changed on approaching the contraction plane. Downstream, the flow field remained symmetric about the main axis. Velocity decay rate was found to be influenced by jet spacing, size and mixing characteristics. The results provide useful insights into mixing of multiple confined jets.

Keywords: Parallel jets; Turbulence intensity; Jet spacing, Velocity; Pressure distribution.

1. Introduction

Parallel jets have been an important component of industrial systems and continue to find use in more complex engineering applications. Aerodynamics, industrial processes, power generation systems, heat exchangers and ejectors are some of the applications that have utilized parallel issuing jets. Jet mixing forms an important reference for some next generation salt and gas cooled reactor concepts. Most of the literature involving parallel jets mixing focus on jet interaction after the exit, while only a handful give insights into the entry behavior of the jets [1]. Jets may be classified as axial, radial and tangential; while with regard to interaction with surrounding, jets can be free or confined [2]. A free jet issues into an infinite medium while a confined jet is bound by enclosure walls which influence its hydrodynamic characteristics. Other relevant works include wall jets and special abrupt contractions which lead to contraction jets [3]. Research into twin parallel jet mixing issuing from a common exit plane have a long history. Initial studies described the mechanism through which two jets merge into a single jet stream. The established interference pattern downstream constitutes three distinct regions as shown in Fig.1 (left). In the converging region between the jets, a low-pressure zone is formed that cause pressure gradients which facilitate jet deflection. Depending on jet spacing and size, a recirculating fluid may be entrained in the low pressure zone. The end of this recirculating fluid in the converging region is the merging point (MP) which mark the beginning of the merging region. At merging point, the streamwise velocity at the symmetry axis is zero. Rigorous fluid mixing and momentum exchange take place in the merging region. The combining point (CP) is a point on the symmetry axis where combined streamwise velocity is maximum, and separates the combined region from the merging region. The flow attains self-similarity in the combined region. Recent researches have investigated mixing of twin parallel submerged rectangular jets using experimental methods [4]. The present work is an extension to four parallel confined round jets issuing from an abrupt contraction. The jets are short in height and are
therefore not fully developed. Consequently, the resulting flow field may slightly differ from that of fully developed jets in a similar configuration. Some flow features upstream and downstream of the contraction have been introduced to serve as an impetus to more detailed studies. The end goal is to obtain some useful information that can be applied as a reference in experimental design phases and instrumentation of similar works.

2. Numerical Modelling

2.1. Flow Domain
The general flow domain is as shown in Fig.2 (left). It is comprised of an abrupt contraction split into four round jets, leading to symmetric parallel jets. The downstream confinement diameter, \( d = 0.05 \text{ m} \), has been used as reference parameter except where specified otherwise. The height \( h \) of the jets is maintained at \( 0.2d \) while the upstream channel diameter is maintained at \( 4d \). Other parameters shown in schematic Fig.1 (right) ensure fully developed flow reach the contraction. The region of interest extends from upstream where contraction effects are experienced to the combined point downstream. Three jet sizes \((d_j = 0.16d, 0.20d \text{ and } 0.28d)\) at jet spacings of \((S = 0.269d, 0.354d \text{ and } 0.438d)\) have been investigated, where \(d_j\) and \(S\) are jet diameter and two jet centers separation respectively. Note that due to the fixed confinement size, the jets \(d_j =0.28d\) have only been investigated at \(S = 0.354d\). Water at room temperature is chosen as the working fluid.

![Figure 1. Interference pattern of twin jets (left) and simplified schematic of flow domain (right).](image)

2.2. Boundary Conditions and Numerical Set up
Velocity inlet boundary condition is applied at the channel inlet, no – slip condition is applied at the walls while constant gage pressure outlet condition is applied at the outlet. Turbulent flow in the range of Reynolds number \(\text{Re} = 9950 – 49700\), based on the inlet diameter is modelled using the standard \(k – \varepsilon\) model. PRESTO scheme is used for pressure discretization and SIMPLEC algorithm is used for pressure – velocity coupling. Second order discretization scheme has been applied for momentum, turbulent kinetic energy and turbulent energy dissipation rate. Steady state solutions are considered converged when residuals of the conservation equations fall below \(10^{-5}\).

2.3. Grid Sensitivity
In this study, unstructured hex-dominant grids have been used. Fig.2 (right) shows a mesh cross-section of the downstream channel close to the jet exit plane. Combined with enhanced wall treatment, a condition that at least ten prism layers are used from the inner wall surface ensure accurate resolving of
the wall boundary layer. All numerical simulations have been subjected to grid independence study. Fig. 3 shows typical grid test for the jets $d_j = 0.28d$ at $S = 0.354d$. For this case, it was observed that increasing grid elements beyond 4.9 million cells did not significantly alter the results, and this grid was thus chosen for study. Special flow features realized at both higher jet spacing and smaller jets warranted the use of highly refined meshes in order to accurately capture the flow physics.

2.4. Validation of Simulation Method

Validation of the standard $k - \varepsilon$ model was first carried out using recent twin rectangular parallel jet flow interaction [4]. Results of velocity profiles prediction shown in Fig. 4 indicated a fairly good prediction by the model; and was thus chosen for study albeit its known shortcomings. Further, the model offered a reasonable compromise between numerical computation accuracy and budget computational resources.
3. Results and Discussion

3.1. Upstream Velocity

Fig. 5 illustrates upstream streamwise velocity profile changes taking place with proximity to contraction plane. It was observed that the course of the central core remains unchanged while drastic changes in magnitude take place within very short distances. These observations are consistent with those observed in reference [1]. At the region close to the jet inlets, the fast flowing core flattened from a parabolic profile and then split to adjust to the inlet of the jets. While this was happening, velocity magnitude rose steeply in response to contraction effect. Flow recirculation was not observed at the point of flow division.

Upstream radial velocity profiles were compared in Fig. 6 at various jet spacings for the jets $d_j = 0.20d$. On approaching the contraction, the profiles were similar to those of an ordinary contraction flow. However, at about half confinement diameter upstream, presence of multiple jets was experienced and the profiles became malformed. This disturbance is offset by formation of radial sub-profiles in the space between the jets. The sub-profiles indicate crossflow between the jet spaces and become more prominent with increasing jet spacing.

![Figure 4. Velocity profiles predictions of the standard K-epsilon model.](image)

![Figure 5. Upstream streamwise velocity, $d_j = 0.200d$ Re = 19900.](image)
3.2. Downstream flow

3.2.1. Centerline velocity decay. Fig. 7 shows that as jet diameter was decreased for single jets, decay rate increased. This could be due to higher turbulent kinetic energy of the smaller jet which in turn increases turbulent dissipation hence higher decay rate. Installing four jets in the same confinement increases the decay rate due to mutual jet-jet interaction. Difference in decay rates amongst the four jets became explicit at about 0.7 confinement diameters. Presence of recirculation in the converging region enhances jet mixing, hence the disparity between the jets $d_j = 0.20d$ at $S = 0.269d$ and $S = 0.354d$. Generally, increasing jet sizes at fixed spacing lowers the decay rates.

3.2.2. Velocity profiles. Streamwise velocity contours are shown in Fig. 8. These reveal that mean flow remained symmetric throughout the mixing process. Although flow asymmetry ought to be observed due to sudden expansion effect, the jets in this study emerged at very high Reynolds number and the downstream flow was thus self modulating. Two kinds of recirculating flow were observed: Outer recirculation surrounding outer jet edges and an entrained recirculation between the jets in the converging region. As a result, both merging point and combined point were seamlessly determined. Occurrence of these reversed flows greatly depends on jet size and jet spacing.
3.3. Turbulence Intensity

Fig. 9 presents spanwise turbulence intensity distribution for the jets $d_j = 0.16d$ at $S = 0.269d$. Results indicated that turbulence intensity was higher at the edges of the outer shear layers, while it remained lower at the inner shear layers. This could be as a result of steep velocity gradients existing across the jets, which generate turbulence. These observations are in agreement with those in literature [4] and were present in all the jet spacings investigated.

In particular, streamwise turbulence intensity levels were generally high up to about ten confinement diameters, marking a decreased turbulent activity in the far downstream.

4. Pressure Distribution

Fig. 10 compares centerline and axial wall pressure distribution ($p_1$-p6) for the jets $d_j = 0.16d$, $S = 0.269d$. Pressure distribution was such that closer to the jet exits, wall pressure was higher than that at the centerline due to high velocity. With more downstream distance, pressure at the centerline rose.
steadily while that at the walls decreased, creating a pressure gradient that enabled jet spreading. Further downstream, pressure distribution attained uniformity in entire channel, signifying that intense mixing was complete.

Figure 10. Pressure distribution. $d_j = 0.160d$, $S = 0.269d$, $Re = 49700$.

5. Conclusions and Future Work

In this study, parallel jet mixing emerging from a contraction into a confined environment has been introduced. Flow field at both upstream and downstream of jet exits was established to vary with jet size and jet spacing. Future work will take into account fully developed jets, turbulence models sensitivity and experimental work using methods such as particle image velocimetry. Further, considering the sudden expansion effect at the jet exits, numerical simulations at lower Reynolds number are recommended in order to establish the critical Reynolds number at which flow asymmetry would occur at different jet configurations.

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