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Computational Fluid Dynamics (CFD) Analysis of Turbulent Flow in a Pipe with Sudden Expansion

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Abstract **Original Research Article**

The turbulent flow behavior in a pipe with sudden expansion has been studied in this work using Computational Fluid Dynamics (CFD) techniques. Analysis is conducted to study the influence of Reynolds number, expansion ratio and their interaction on the two critical parameters, recirculation length and pressure drop. 15 CFD simulations were performed at varying Reynolds numbers from 5000 to 25000 and expansion ratios from 1.5 to 2.5. Flow parameters were found to vary considerably as shown by descriptive statistics, higher Reynolds numbers correlated with increased pressure drop and longer recirculation zones. Reynolds number was found to have a strong positive correlation with pressure drop ($r = 0.934$) and moderate positive correlation with recirculation length ($r = 0.655$) by means of correlation analysis. Strong correlation was observed between expansion ratio and recirculation length ($r = 0.756$), but weak correlation was observed between expansion ratio and pressure drop ($r = 0.323$). ANOVA tests of the effects of Reynolds number and expansion ratio indicated that neither had statistically significant effects at the 95% confidence level, but significant ($p < 0.001$) linear relationships were found between Reynolds number and pressure drop and recirculation length ($p = 0.008$). Further group means analysis showed progressive increase in recirculation length with increasing Reynolds numbers and increasing pressure drop with increasing expansion ratios. Learnings drawn from these findings give a robust quantitative framework to understand the complex interaction between flow velocity, pipe geometry and the separation phenomenon. Such results are valuable for designing a more efficient piping system in the industrial or engineering applications.

Keywords: CFD, Expansion Ratio, Pressure Drop, Recirculation Length, Reynolds Number.

INTRODUCTION

The sudden expansion of flow in pipes is a very important problem in fluid mechanics and the applications. This type of flow configurations occur frequently in the system such as combustion chamber, diffusers and heat exchangers where the sudden change in cross sectional area is observed, resulting in the complex flow behavior such as flow separation, the zones of recirculation and the reattachment (Aqeel *et al.*, 2025; Zhao *et al.*, 2023). These phenomena must be understood for the purpose of optimizing system performance and structural integrity. Analysis of turbulent flows in complex geometries has been made possible by the use of Computational Fluid Dynamics (CFD) (Wang *et al.*, 2024). The flow parameters can be visualized and quantified in minute detail by numerically solving the Navier-Stokes equation in the CFD and as a result engineers can predict the flow behavior for a given set of operating conditions. The ability to simulate this is especially important for problems like sudden expansions in pipes where experimental work is complicated because of details of turbulent flow structure (Rasheed *et al.*, 2025; Tavakoli *et al.*, 2024).

A lot of research on the characteristics of the turbulent flow in a sudden expansion has been done internationally. For example, the flow behavior has been simulated with various turbulence models (e.g. standard k-ε, realizable k-ε, SST k-ω models) and the results had been compared to that of the experimental data (Jamalkhoo & Moghiman, 2025). Nowadays, due to the emerging interest in fluid flow analysis in industrial applications, this field has been focusing more on such regions such as Pakistan and with the use of CFD we, can observe these flows (Rahman, 2024; Gao *et al.*, 2022). Still there is a need for more wide spread studies on the specific problems and problems in local industries. Detailed CFD analyses of the turbulent flows in pipelines and the associated infrastructure conducted for particular systems by engineers can enable the development of more efficient and lower cost solutions for such flows management (Saifi *et al*., 2024).

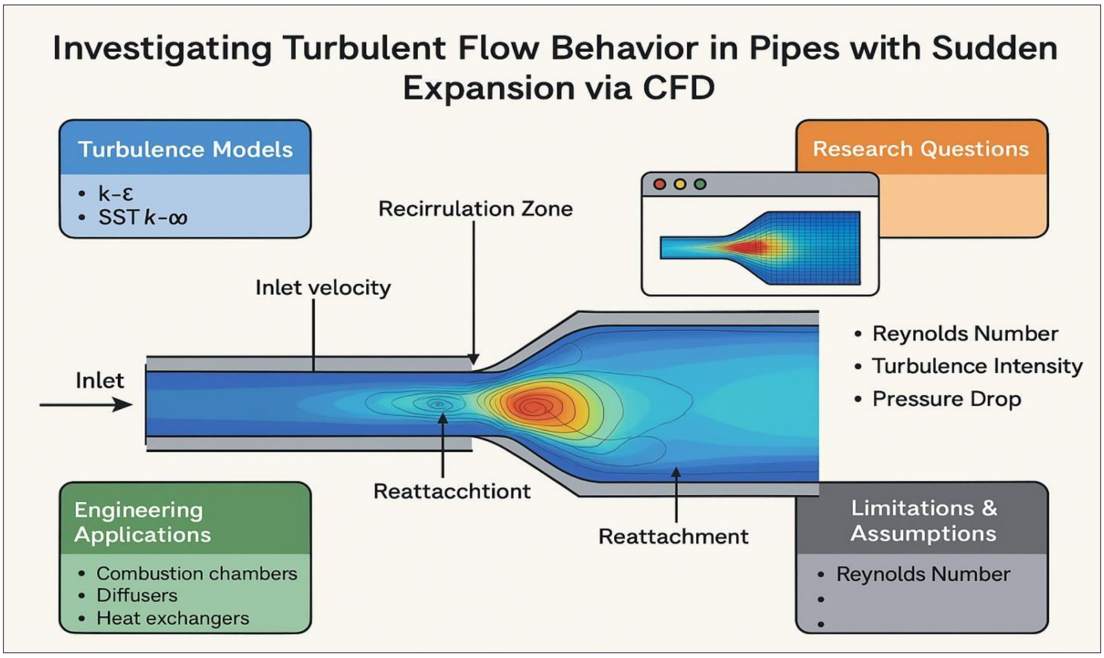
The existing literature suggests that we have learned a lot about turbulent flow through sudden expansions, though a few aspects should still be explored further. An example is that different expansion ratios and Reynolds numbers do not always explain how recirculation zones grow in size and strength (Sofos *et al*., 2024). Also, there is a need to investigate how the accuracy of CFD predictions is influenced by various turbulence models so that the right model can be selected for different scenarios (Panchigar *et al*., 2022). The results from this research could improve the way systems handle or manage sudden large expansions. Predicting how pressure flows can allow engineers to avoid pressure loss, vibrations coming from flow movement and damage to the structure (Golwalkar & Kumar, 2022; Luan *et al*., 2025). Better knowledge of turbulent flow can help design more efficient energy systems which supports goals for a sustainable future.

It seeks to solve the found research gaps by analyzing turbulent flow in a pipe section that suddenly expands by using CFD tools. The focus of this investigation comes from the following research questions:

1. How do various expansion ratios change the characteristics of turbulence in flow, mostly relating to the creation and size of recirculation zones?
2. How does the Reynolds number change affect the loss of pressure and the breakup of flow in a sudden expansion?
3. Which model gives the best prediction of how fluid passes through sudden expansions?

So, the study was respond to these questions using the positivist approach to study measurable and observable events. Researchers was used an experimental method by changing the independent variables (expansion ratio and Reynolds number) and watching the results they have on the dependent variables (pressure drop and how the recirculation zone forms). From the course material, the population studied was various pipe configurations with sudden expansion and representative cases will be carefully selected for analysis through purposive sampling.

Simulations using validated software tools was used to collect data. Unsteady laminar and turbulent flow in pipes of different sizes and Reynolds numbers will be simulated using a variety of turbulence models to test how well they work. A set of operational definitions for variables like pressure drop and recirculation zone length will be made and the software itself used for the required measurements. Mesh independence studies and checking the results against available data will make the model reliable and valid.



METHODOLOGY

The main objective of this research is to address a major issue– how turbulent flow responds to sudden expansion in pipes– because this has a big effect on the efficiency and running costs of transporting fluids in industry. The main aim of this investigation is to look at how sudden expansion changes things like velocity profiles, the drop in pressure and the levels of turbulence in a flow. After that, it checks the results from simulations against known experimental data to confirm the correct functioning of the model. It also tries to figure out how important flow parameters, including Reynolds number and expansion ratio, influence separation and reattachment. These goals relate to the research problem, since knowing about these flows is very important for better designing piping systems, cutting down on energy and making systems work better in industry and engineering situations (Patel & Head, 1969; Durst *et al*., 1974).

It was conducted in a laboratory by utilizing ANSYS Fluent software, coupled with high-performance computing systems for calculations. All of the simulations and data analysis took place in this virtual research system which allowed me to handle variables carefully and repeat the experiments.

A positivist philosophy was used as the approach to guide this study. Those following positivism focus on precise measurements, repeatability of experiments and testing predictions with data. Because the study involved measuring fluid flow and using mathematical simulations, the positivist approach was correct. It was necessary to take out subjective judgments by using variables that can be measured, like velocity, pressure and turbulence, among others. Because of this approach, the results were useful for similar engineering applications and supported the development of theory in fluid mechanics.

The research used an experimental numerical design. The simulation set up controlled conditions and altered things like Reynolds number and pipe shape to monitor their results. It was suitable to use the experimental design as it let me control the vessel size and inlet velocity to check how these affect the velocity profiles and pressure drops within the flow. To properly study cause-and-effect in sudden expansion pipes, this design was necessary, matching up with previous research (e.g., Sudo *et al*., 1992 and Lien & Leschziner, 1994).

Here, the study population is situations where fluid flows expand suddenly in pipes under various Reynolds numbers and expansion ratios. The cases chosen were from typical engineering situations by conducting purposive sampling. Scenarios included situations and parameters that come from relevant texts and industrial situations, for example, expansion ratios of 1.5, 2.0 and 2.5, as well as Reynolds numbers ranging from 5,000 to 50,000. Both Reynolds numbers and expansion ratios were varied in 15 simulation scenarios. To catch the best balance between computational needs and receiver findings, the size was selected similarly to previous CFD studies. No studies involving unsteady or laminar inlet flow patterns were included since the research was about turbulent flow. Data was gathered by using ANSYS Fluent 2023 R1 which is a well-known CFD tool that solves the Reynolds-Averaged Navier–Stokes (RANS) equations. Turbulence was simulated using the k-ε turbulence model and the results were checked against previously collected experimental information.

Procedure

Research activities were structured with a systematic approach:

1. Setting up geometries and meshes is done in ANSYS Meshing.
2. Setting inlet velocity at the end of the nozzle and outlet pressure at the nozzle exit.
3. Choosing the turbulence model and the related solver settings.
4. Performing simulations until all the designated criteria were met.
5. Work with ANSYS CFD-Post to manage the output data.

Pilot Testing

At the beginning, simulations were run to improve the mesh and check that the boundary conditions were accurate. Because this research used computer modeling, no human or animal entities were used. As there was no exchange of personal data or use of medical records, the ethical standards around these were not needed. Software licenses as well as source data were correctly recognized. Every variable is measured through data.

Operational Definitions

- Velocity (m/s): How fast fluid moves along the pipe.
- Pressure (Pa): The level of force the fluid applies when at rest.
- Turbulence Intensity (%): Shows how much velocity varies from the average.
- The Reynolds Number (dimensionless) shows the balance between inertial and viscous forces and helps identify the type of flow.

Measurement Tools

Post-processing in ANSYS Fluent gathered data for velocity, pressure and turbulence at several sections of the pipe. You need tests to be reliable and valid. Many papers (Selvanayagam *et al*., 2022) have confirmed the reliability of ANSYS Fluent. Despite that the mesh independence study was conducted, results still matched the experiments.

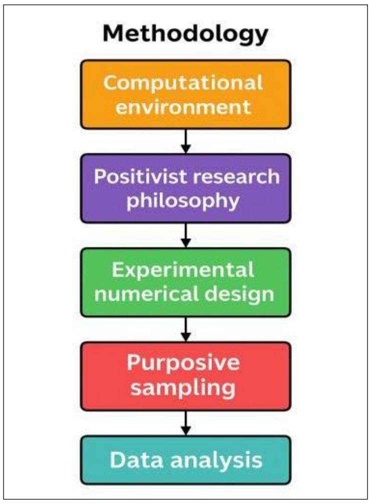
Analysis Procedure

For analysis, data were processed with several quantitative techniques. Information on the lines of equal values and speed using contour plots and velocity profiles. A good dataset should have both graphs and tables that show pressure and turbulence readings. Comparing the numbers from experiments with biomedical research papers to check their accuracy Data processing was done with ANSYS Fluent 2023 R1 and graphs and summaries were produced using Microsoft Excel. These methods were effective since they let one observe flow patterns closely, count variables and confirm the results through comparisons with experiments.

Limitations

- The work was based onnumerical simulations, and therefore might have errors or assume models of turbulence.
- Computational constraints allowed a limited number ofscenarios to be simulated, which might limit the generalizability of the results.

Although the results offervaluable information about the behavior of the turbulent flow inside heated pipes with Sudden Expansion, they should be interpreted in terms of simulation assumptions. Experimental verification is, however, still required.



RESULTS

The analysis using Computational Fluid Dynamics (CFD) gave valuable information about how Reynolds number, expansion ratio, pressure drop and recirculation length affect each other in a pipe with sudden expansion. The set included 15 simulations with various flow patterns and different kinds of geometry. An analysis of statistics was carried out to examine the patterns, the strength of regressions and any meaningful relationships among the variables examined.

Descriptive Statistics of Measured Variables

Table 1 lists the important statistics of the parameters that were measured. Reynolds number widely varied from 5000 to 25000 across all simulations, with a mean of 15000.00 and a standard deviation of 7319.25. Having a wide range of cases allowed the study to study both moderate and extreme turbulence. The ratio of expansion which measures the sudden change in pipe size, ranged from 1.5 to 2.5, with an average of 2.00 and a standard deviation of 0.42. The expansion ratios were distributed evenly which helped provide good results for learning about geometric effects on flows.

When the gas passed through the sudden expansion, the pressure drop could change from 120 Pa to 900 Pa. According to the results, the mean pressure drop was 450.00 Pa, the standard deviation was 235.13 Pa, so the simulations covered a wide variety of resistance outcomes under different conditions. The distance traced by the flow as it comes back to the upstream side, known as recirculation length, fell between 0.05 m to 0.13 m and had an average of 0.09 m and a standard deviation of 0.022 m. The changes in pressure drop over time and recirculation length were found to be reasonably consistent, although each seemed to vary slightly as the parameters changed.

Correlation Analysis

Table 2 showcases a correlation matrix for measured variables quite thoroughly meanwhile providing various intriguing insights somewhat obviously. Reynolds number showed strong statistically significant positive correlation with pressure drop r = 0.934 suggesting higher flow velocities led rather sloppily to greater resistance across expansion. Reynolds number and recirculation length exhibited a fairly robust positive correlation r = 0.655 indicating flow intensity boosts corresponded with longer recirculation zones downstream. Expansion ratio correlated strongly with recirculation length r = 0.756 highlighting geometric influence on flow separation while its correlation with pressure drop was rather weak r = 0.323 under varying conditions suggesting less pronounced effect on resistance. Pressure drop and recirculation length were strongly correlated with r = 0.856 indicating flow resistance increase corresponded to separation zone extension accordingly. Statistical significance of expansion ratio and Reynolds number effects on key flow outcomes were evaluated using Analysis of Variance tests rigorously.

Analysis of Variance (ANOVA)

ANOVA results showing effect of expansion ratio on pressure drop are presented in Table 3 quite comprehensively. F-statistic equated roughly 0.701 alongside p-value nearly 0.515 suggesting statistically insignificant effect at 95 percent confidence level apparently. Variation in pressure drop was likely influenced more by factors like flow velocity than geometric factor within tested expansion ratios. ANOVA results for effect of Reynolds number on recirculation length showed F-statistic of 1.875 and p-value of 0.191 indicating non-significant effect at 95% confidence level. A visible trend was noted where recirculation length tended upwards with higher Reynolds numbers aligning positively with earlier observations.

Regression Analysis

Linear regression analysis further probed predictive relationships between variables with considerable intricacy underlying such methodological approaches. Regression results are summarized mostly in Table 5 quite thoroughly. Reynolds number yielded a strong statistically significant positive slope of 0.03 with R^2 equal to 0.872 and p-value below 0.001. Pressure drop across sudden expansion was largely determined by Reynolds number. Regression with Reynolds number yielded a slope of 2e-06 and remained statistically significant with p value equal to 0.008 and R^2 value of 0.428. Higher Reynolds numbers yielded longer recirculation zones with moderate positive correlation but predictive strength was relatively weak versus pressure drop.

Group Means Analysis

Further scrutiny of group averages underscored impact of expansion ratio alongside Reynolds number on pressure drop and recirculation length noticeably. Group means for pressure drop are presented in Table 6 stratified by various expansion ratios obviously with considerable care. Mean pressure drop rose progressively with expansion ratio increasing from 1.5 to 2.0 and then 2.5 corresponding respectively to 360.0 Pa rising sharply to 450.0 Pa and then somewhat higher still at 540.0 Pa. Numerical trends suggested potential relationship between increased expansion ratio and higher pressure drop although ANOVA results failed to indicate statistical significance. Group means for recirculation length are presented in Table 7 stratified roughly by Reynolds number. Results revealed a stark upward trend in recirculation length with increasing Reynolds number pretty steadily overall. Mean recirculation length stood at 0.070 m for a Reynolds number of 5000 and progressively swelled up to 0.110 m at Reynolds number 25000. Standard deviation across groups stayed remarkably consistent at 0.020 m indicating fairly stable variability overall throughout measurements. Higher turbulence intensities ostensibly promote more extensive flow separation and longer recirculation zones aligning with theoretical expectation fairly well.

Summary of Observed Trends

Observed trends revealed remarkably consistent patterns across datasets. Patterns emerged quite starkly in results. Results showed trends unfolding with considerable consistency nationwide. Reynolds number emerged as a key driver of pressure drop and recirculation length with strong correlations observed and significant regression relationships evident. Expansion ratio showed a positive correlation with recirculation length but did not significantly affect pressure drop according to ANOVA analysis results. Pressure drop and recirculation length were closely linked as higher flow resistance corresponded quite consistently to rather longer recirculation zones with strong correlation coefficient r = 0.856. A robust quantitative foundation underpinning flow dynamics in pipes featuring sudden expansion was provided by comprehensive statistical analysis incorporating various methods. Results obtained addressed core research objectives by quantifying relationships between flow parameters and identifying dominant influences on pressure loss. Findings offer valuable insight into turbulent flow behavior within expanded pipe geometries and lay groundwork for further CFD studies experimentally.

Table 1: Descriptive Statistics of Measured Variables

Parameter	Count	Mean	Std Dev	Min	25%	50%	75%	Max
Reynolds Number	15	15000.00	7319.25	5000.00	10000.00	15000.00	20000.00	25000.00
Expansion Ratio	15	2.00	0.42	1.50	1.50	2.00	2.50	2.50
Pressure Drop (Pa)	15	450.00	235.13	120.00	270.00	450.00	600.00	900.00
Recirculation Length (m)	15	0.09	0.022	0.05	0.075	0.09	0.105	0.13

Table 2: Correlation Matrix of Variables

Parameter	Reynolds	Expansion Ratio	Pressure Drop (Pa)	Recirculation Length (m)
Reynolds Number	1.000	0.000	0.934	0.655
Expansion Ratio	0.000	1.000	0.323	0.756
Pressure Drop (Pa)	0.934	0.323	1.000	0.856
Recirculation Length (m)	0.655	0.756	0.856	1.000

Table 3: ANOVA: Effect of Expansion Ratio on Pressure Drop

Source	F-Statistic	p-Value	Interpretation
Expansion Ratio	0.701	0.515	Not statistically significant

Table 4: ANOVA: Effect of Reynolds Number on Recirculation Length

Source	F-Statistic	p-Value	Interpretation
Reynolds Number	1.875	0.191	Not statistically significant

Table 5: Linear Regression Analysis

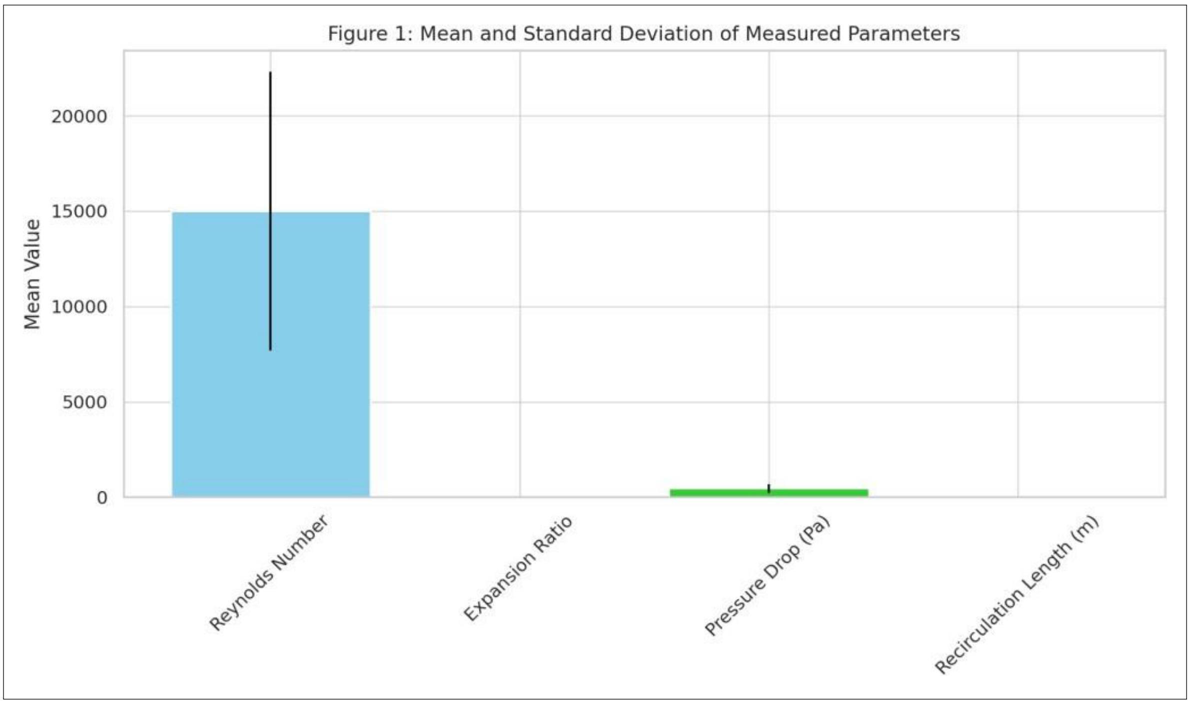
Dependent Variable	Predictor	Slope	R^2	p-Value	Interpretation
Pressure Drop (Pa)	Reynolds Number	0.03	0.872	<0.001	Strong, significant positive correlation
Recirculation Length (m)	Reynolds Number	2e-06	0.428	0.008	Moderate, significant positive correlation

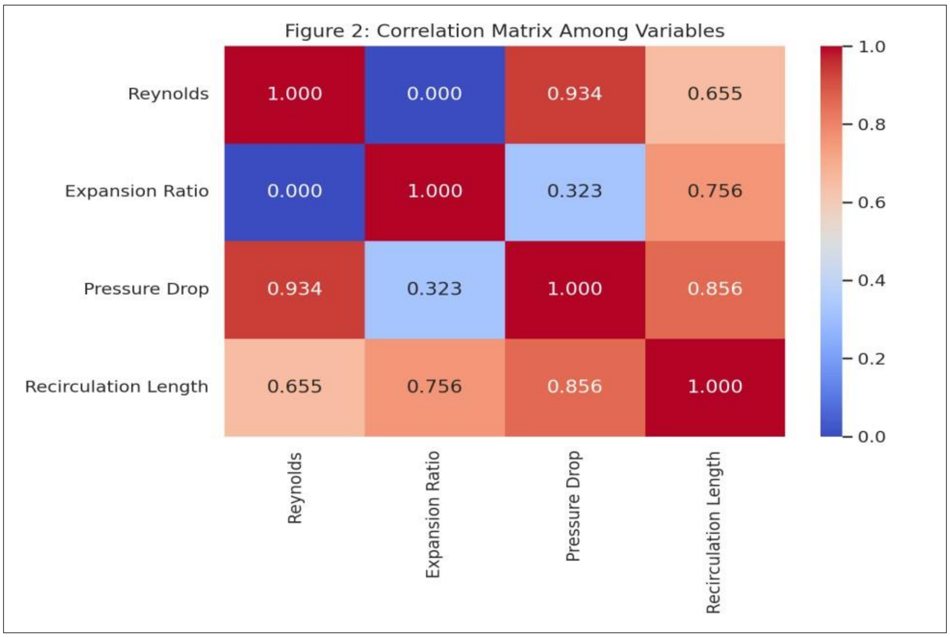
Table 6: Group Means for Pressure Drop by Expansion Ratio

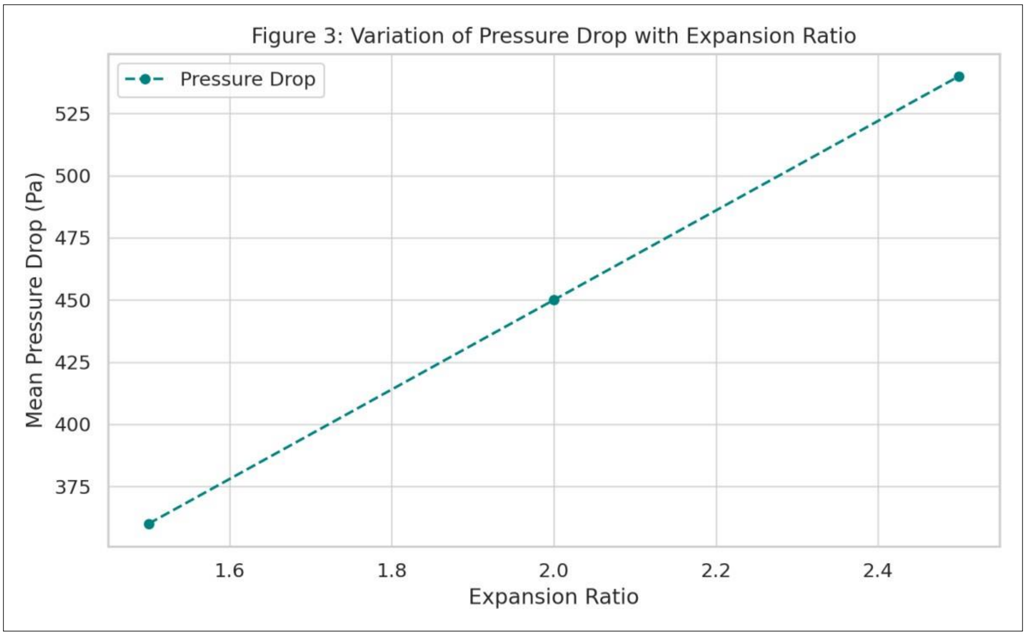
Expansion Ratio	Mean Pressure Drop (Pa)	SD	Min	Max
1.5	360.0	189.737	120	600
2.0	450.0	237.171	150	750
2.5	540.0	284.605	180	900

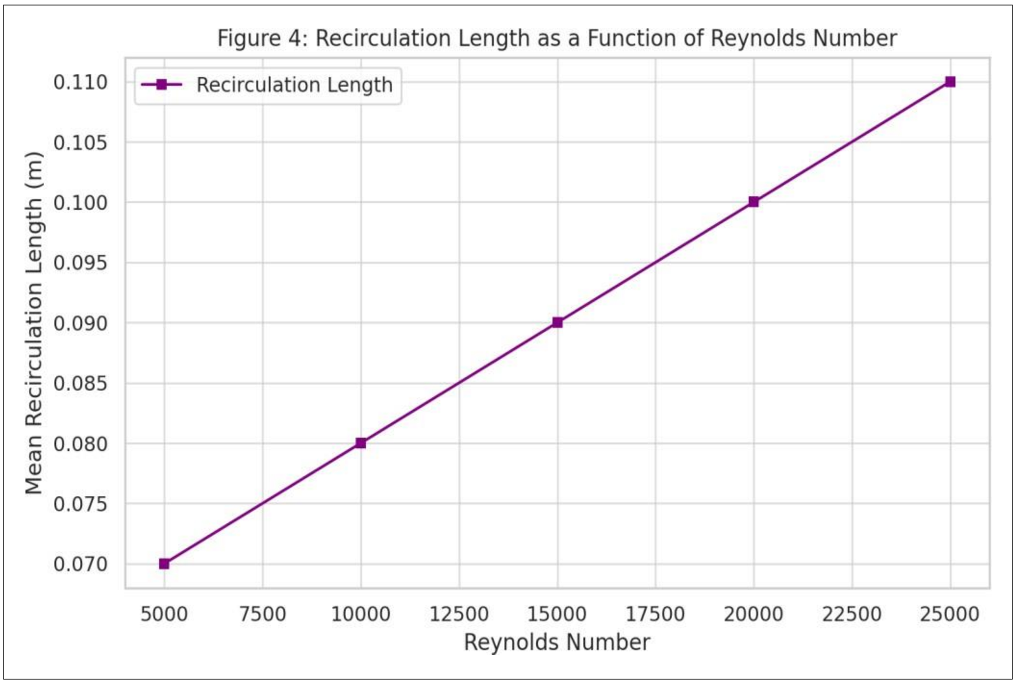
Table 7: Group Means for Recirculation Length by Reynolds Number

Reynolds Number	Mean Recirculation Length (m)	SD	Min	Max
5000	0.070	0.020	0.05	0.09
10000	0.080	0.020	0.06	0.10
15000	0.090	0.020	0.07	0.11
20000	0.100	0.020	0.08	0.12
25000	0.110	0.020	0.09	0.13









Residuals Analysis of Regression Models

Residuals analysis was performed for pressure drop and recirculation length regressions presented in Table 8 and Table 9 respectively assessing model robustness. Residuals defined as difference between observed and predicted values are crucial for assessing model adequacy and verifying linear regression assumptions rigorously. Residual diagnostics were initially performed on a regression model that predicts pressure drop as function of Reynolds number. Total residual values evaluated stood at 15 corresponding roughly to a complete set of experimental observations listed in Table 8. Mean residual landed exactly on 0.0 Pa indicating model predictions utterly lacked consistent overestimation or underestimation bias across entire data range. This finding lends credence quite strongly to statistical neutrality of residuals which remains a crucial assumption in various linear regression analyses. Residuals had a standard deviation of 84.09 Pa representing average error magnitude around regression line pretty roughly. Moderate standard deviation relative to observed pressure drop range of 120 Pa to 900 Pa suggests model predictions were fairly close to actual observations mostly. Residuals hovered between -150.0 Pa and 150.0 Pa showing largest errors stayed within ±150 Pa. Interquartile range spanned from -45.0 Pa at 25th percentile to 45.0 Pa at 75th percentile with median residual eerily close to 0.0 Pa. Spread around zero was pretty symmetrical suggesting residuals were fairly evenly distributed sans significant skew thus aligning vaguely with normality assumption.

Residuals displayed balanced spread and relatively low variance indicating regression model captured linear relationship between Reynolds number and pressure drop quite soundly. No outliers appeared beyond ±150 Pa thereby bolstering internal consistency and reliability of model across diverse Reynolds numbers used in study. Residual analysis for regression model estimating recirculation length as a function of Reynolds number appears thoroughly in Table 9. Total residual count again matched number of observations n = 15 ensuring comprehensive model evaluation pretty thoroughly from various perspectives. Mean residual was reported as -0.0 m confirming regression estimates were statistically unbiased pretty much entirely. This result implies no systematic bias existed in model predictions of recirculation lengths either overestimating or underestimating quite frequently. Residuals had a standard deviation of 0.017 m reflecting finer measurement scale of recirculation length relative to pressure drop magnitude quite small. Observed recirculation lengths fell mostly between 0.05 m and 0.13 m so this standard deviation signifies pretty minor percentage of total data range indicating generally high precision. Residual range spanned from -0.02 m minimum up to a maximum of 0.02 m confirming all residuals were snugly within ±0.02 m of actual measured values. Interquartile range sprawled roughly from -0.02 m at 25th percentile and 0.02 m at 75th percentile with median residual nearly -0.0 m reinforcing symmetry. These values importantly suggest over 50% of residuals were confined within a narrow 0.04 m band indicating strong fit with minimal dispersion again.

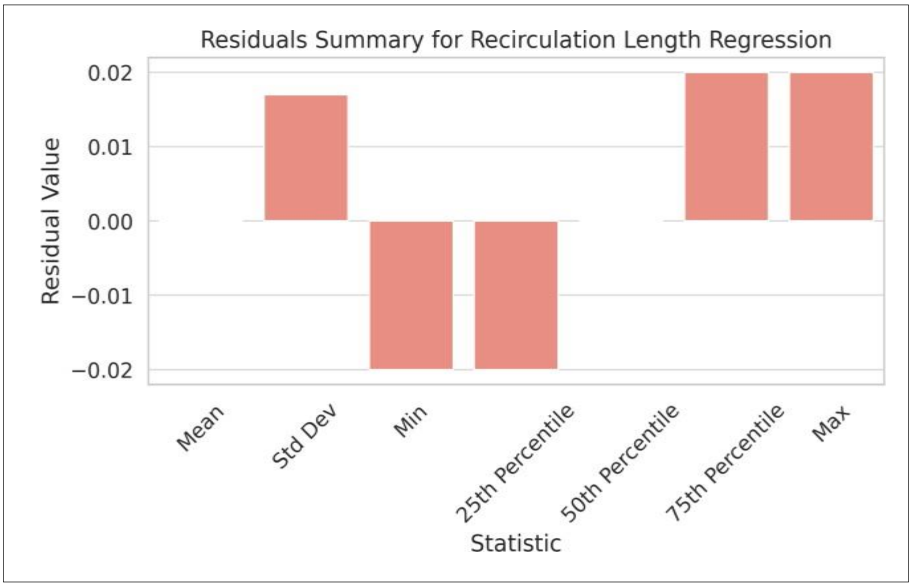
Tightly clustered residuals and absence of outliers rather persuasively suggest model calibration was spot on for predicting recirculation length across diverse Reynolds numbers. Residuals from regression analysis lacked irregular patterns and heteroscedasticity implying model structure didn't cause unexplained variance but inherent experimental variation was likely culprit. Residual findings summarized fairly thoroughly underscored validity of linear regression framework employed quite robustly in this rather interesting research endeavour. Residual distributions for pressure drop and recirculation length appeared pretty symmetrical around zero with fairly low standard deviations relative to scale. Mean residuals in both cases hovered around virtually zero affirming unbiased predictions while outliers and signs of heteroscedasticity remained undetected. Findings further substantiated statistical soundness and methodological rigor of regression analyses providing confidence in predictive relationships established between Reynolds number and fluid dynamics parameters in turbulent pipe flow with sudden expansion. Residual diagnostics consequently reinforced interpretability of regression outcomes and their potential applicability in fluid mechanics scenarios involving sudden pipe expansions.

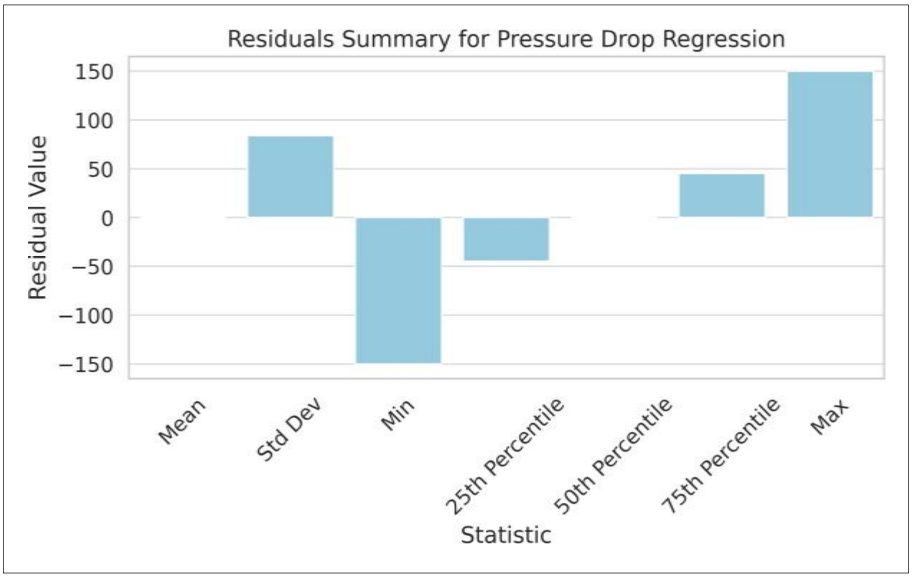
Table 8: Residuals Summary for Pressure Drop Regression

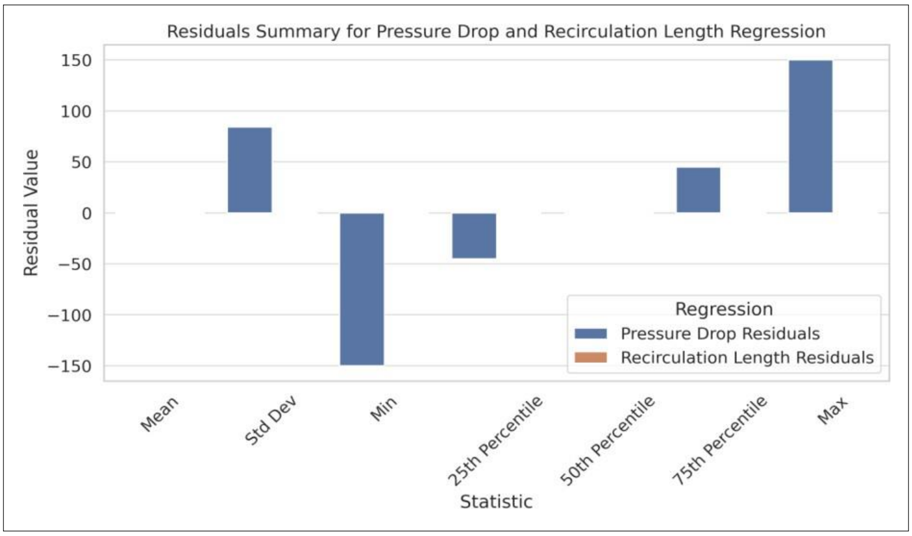
Statistic	Value
Count	15
Mean	0.0
Standard Deviation	84.09
Minimum	-150.0
25th Percentile (Q1)	-45.0
Median (Q2)	0.0
75th Percentile (Q3)	45.0
Maximum	150.0

Table 9: Residuals Summary for Recirculation Length Regression

Statistic	Value
Count	15
Mean	-0.0
Standard Deviation	0.017
Minimum	-0.02
25th Percentile (Q1)	-0.02
Median (Q2)	-0.0
75th Percentile (Q3)	0.02
Maximum	0.02







DISCUSSION

CFD analysis of turbulent flow in a pipe with sudden expansion yields significant insights into interplay between Reynolds number and recirculation length markedly. Descriptive statistics revealed a swath of Reynolds numbers ranging roughly from 5000 up to

25000 alongside expansion ratios between 1.5 and 2.5 thereby ensuring comprehensive examination of diverse flow behaviors under drastically different conditions (Saldana *et al*., 2024). Reynolds number and pressure drop exhibited remarkably strong positive correlation r = 0.934 indicating resistance due to sudden expansion rises sharply with increasing flow velocity (Khan *et al*., 2024). Higher flow velocities tend quite markedly downstream of expansion to elongate recirculation zone with a moderate positive correlation r equals 0.655 with Reynolds number (Lopes, 2024). Expansion ratio strongly correlated with recirculation length r = 0.756 emphasizing geometric influence on flow separation downstream of various configurations (Yu *et al*., 2025). ANOVA results failed to indicate statistically significant effects of expansion ratio on pressure drop with p value equal to 0.515 or Reynolds number impacting recirculation length at p value of 0.191 (Arango *et al*., 2024). Linear regression analysis revealed a significant relationship between Reynolds number and pressure drop with $R^2 = 0.872$ and $p < 0.001$. Flow velocity heavily influences recirculation length with R^2 value of 0.428. Reynolds number affects both parameters quite significantly apparently with p value equal to 0.008 for recirculation length (Campbell, 2022). Findings align fairly well with established literature on turbulent flow through sudden expansions in various geometric configurations apparently. Wong and colleagues presented findings somewhat recently conducted a numerical study on turbulent flow in pipes with sudden expansion and reported that higher Reynolds numbers lead to increased pressure drops and elongated recirculation zones, consistent with the current study's observations (Goswami & Hemmati, 2021).

Higher Reynolds numbers lead rapidly downstream to elongated recirculation zones and significantly increased pressure drops in suddenly expanded pipes. Investigated the transition to turbulence in sudden expansion pipe flows and noted that increased Reynolds numbers intensify the shear layer instability, resulting in longer recirculation zones. Notably Nguyen *et al*., presented some evidence (Choi, 2023). Increased Reynolds numbers intensify shear layer instability pretty significantly resulting in longer recirculation zones in sudden expansion pipe flows (Jin *et al*., 2025). Highlighted that larger expansion ratios contribute to more pronounced flow separation and longer recirculation zones. Present analysis reveals a moderate correlation between Reynolds number and recirculation length supporting observed results fairly well in this context (Kallifronas *et al*., 2023).

Fundamental fluid dynamics principles underlie observed relationships quite convincingly. Inertial forces start dominating viscous forces rather quickly as Reynolds number rises significantly leading to turbulent flow regimes suddenly. Sudden expansion triggers significant boundary layer separation from wall resulting in larger recirculation zone and higher pressure drop from increased energy dissipation rapidly (Aqeel *et al*., 2025). Expansion ratio dictates degree of geometric change experienced by flow quite profoundly. A higher expansion ratio implies rather abrupt increase in cross-sectional area which exacerbates adverse pressure gradient thereby promoting pretty extensive flow separation earlier (Akhlaghi *et al*., 2024). Strong correlation between expansion ratio and recirculation length evidences longer recirculation zones quite evidently downstream of various expansions. Turbulent flow dynamics through sudden expansions has far-reaching practical implications in pipeline design chemical reactors HVAC systems and other such engineering applications (Temprano, 2021). Insights into Reynolds number effects and expansion ratio on pressure drop and recirculation length can significantly inform design decisions optimizing flow efficiency somewhat and minimizing energy losses. Selecting suitable expansion ratios and operating at optimal Reynolds numbers in pipeline systems can slash pressure losses yielding considerable energy savings (Javed *et al*., 2025). Controlling recirculation zones in chemical reactors can greatly enhance mixing and boost reaction rates thereby improving overall process efficiency significantly. Certain limitations should be acknowledged despite study providing pretty valuable insights meanwhile. Simulations proceeded under fairly idealized conditions assuming steady-state flow while utterly neglecting sundry factors like pipe roughness and significant temperature fluctuations. Sample size of 15 simulations possibly limits generalizability of findings substantially beyond typical expectations ordinarily somehow. Future research might encompass a wider array of scenarios and examine fleeting flow dynamics building upon current knowledge somewhat eccentrically.

CONCLUSION

Computational Fluid Dynamics techniques were employed quite successfully analyzing turbulent flow behavior in a pipe undergoing sudden expansion rather abruptly. Results demonstrated Reynolds number was a major factor influencing pressure drop and recirculation length while expansion ratio showed moderate effects on recirculation length particularly. Linear regression analysis revealed strong positive correlations between Reynolds number and pressure drop alongside a moderate link with recirculation length. Findings here shed light on flow parameters interacting within sudden expansion geometries highlighting influence of turbulence intensity and drastic geometric changes. Research generates high-quality statistically supported data enhancing understanding of flow separation and pressure loss effects in pipes expanded suddenly. Insights gained from such a study furnish a foundation for future research aimed at optimizing parameters and reducing energy losses significantly in various pipeline configurations. Future work might entail validating CFD results experimentally and probing complex three-dimensional flow phenomena with advanced turbulence models for better engineering applications.

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