Influence scope of local loss for pipe flow in plane sudden expansions

LYao *, X Huang 2, A Fitri 3

1 College of Water Conservancy and Ecological Engineering, Nanchang Institute of Technology, National and Provincial Joint Engineering Laboratory for the Hydraulic Engineering Safety and Efficient Utilization of Water Resources of Poyang Lake Basin, Nanchang, 330099, China, email: yaoli0817@nit.edu.cn
2 School of Yaohu, Nanchang Institute of Technology, Nanchang, 330099, China, email: 1263152353@nit.edu.cn
3 School of Civil and Architectural Engineering, Nanchang Institute of Technology, Nanchang, 330099, China, email: arnizafitri@gmail.com

* Email: yaoli0817@nit.edu.cn

Abstract. A pipe with sudden expansions are used in a wide variety of engineering applications such as hydraulic, civil, and nuclear industries. Flow through a pipe with sudden expansion about its head loss becomes local head loss as the boundary changes. The dynamic water pressure for the rapidly varied flow corresponding to the local head loss has remained inconclusive and inaccurate. It is partly due to the complexity of the vortex involved and partly because of limitations of the traditional experiments. Therefore, in this study, the methods based on theoretical analysis and numerical simulation were employed for the prediction of the influence scope of a plane pipe with sudden expansions. A parametric study is performed for the expansion ratios are 1.5, 2, 3, 4, 5 and in a Reynolds number range of 10 - 100000. On the basis of numerical results, an existing correlation of the influence scope is also extended to take into account the effect of the scale effect additionally. The simulation results show that the influence scope of local head loss is affected greatly by expansion ratio and Reynolds number of the plane pipe, and expansion ratios occurring from the sudden expansions are less sensitive to the Reynolds number. The obtained research results have shown that for the cases when Reynolds number is relatively small (Re < 2000), the recirculation degree (L/D, where L is the length of recirculation zone, D is the diameter of the latter pipe) increases significantly with the increase of the Reynolds number; and for the cases when the Reynolds number is larger (Re > 10000), the recirculation degree changes slowly with the Reynolds number. In general, the length of the influence scope is logarithmically related to the Reynolds number.

1. Introduction
In actual engineering, the layout of pipelines often has a sudden change of boundary depending on the engineering needs and different terrain conditions. The suddenly expanded pipeline is a common one, which causes a sharp change in the boundary area and the boundary layer separates where the diameter
of the pipe suddenly expands, forming a vortex zone. The resulting head loss is dominated by local head loss.

In terms of local head loss in suddenly expanded pipelines, the current research mostly focuses on the local head loss coefficient [1-3]. The local head loss coefficient has usually been studied by means of physical model tests and theoretical derivation, but the range of local head loss coefficients was rarely investigated. In fact, the local head loss range is of great significance for determining the specific location of the local head loss in the suddenly expanded pipeline, which has important theoretical significance and application prospects for the hydraulic calculation and layout of the pipeline network.

Based on current model tests, it is difficult to measure the pressure and flow rate of each section of the pipeline. This paper employs numerical simulation to study the hydraulic characteristics (including the flow regime, pressure, etc.) of different diameter-to-diameter ratios and the Reynolds numbers. Based on numerical simulation results of the relevant hydraulic characteristics, the extent of the local head loss is determined, and the scale effect of different pipe diameters under the same pipe diameter ratio is also studied.

2. Numerical model

2.1. Turbulence models

The numerical simulation of the governing equations, in this paper is the continuity equation, the momentum equation and the turbulence model equation in fluid mechanics. The wall surface is treated by the standard wall function method. The Spalart-Allmaras turbulence model [4], which has a good prediction ability for head loss, is selected to further investigate its predictive ability in local loss of pipelines. The model uses three-dimensional hexahedral unstructured mesh regions to be discrete. The closest mesh size to the wall is about 0.1 mm. The solution uses the finite volume method for discrete equations. The convection term uses QUICK scheme, and the speed and pressure are coupled by SIMPLE algorithm.

2.2. Sudden expand models

![Figure 1. Model of sudden expansion pipe](image)

The model of sudden expansion pipeline used in this paper is shown in Fig. 1. When the pipeline is placed horizontally, without considering the influence of gravity, the average velocity of pipeline before sudden change is \( v_1 \), the average velocity of cross section after sudden change is \( v_2 \), the diameter of pipeline before sudden expansion is \( d \), the diameter of pipeline after sudden expansion is \( D \), the influence range before sudden expansion is \( L_0 \), and the influence range after sudden expansion is \( L \). This paper only studies the impact scope of the sudden expansion. According to Xie Haiying [5] in the literature, when \( Re = 4369 \), the effect of the vortex zone is greater than that after 6 times the diameter of the tube. The length of the sudden expansion front segment of the design model \( L_1 = 15d \), \( L_2 = 30D \). Ensure the full development of water flow at sudden expansion and outlet. The turbulent intensity of the incoming flow is calculated by taking the inlet velocity as the boundary condition of the inlet velocity.

\[
I = 0.16 \left( \frac{\rho v_0 d}{\mu} \right)^{-0.125}
\]

(1)
where for the flow density, \( \rho \), 998.2 kg/m\(^3\); for the viscosity of the fluid \( \mu \), Pa\(\cdot\)s, water temperature 7.5 degrees C, 0.0014135; for gravitational acceleration, \( g \), take 9.81 m/s\(^2\); the outlet of the computational domain is taken as the outflow condition, and the roughness coefficient of the pipeline wall is \( n = 0.009 \).

2.3. Meshing

Three-dimensional unstructured hexahedral mesh region is used to discretize the study domain. The nearest mesh size is about 0.1 mm. The finite volume method is used to solve the discrete equation. The convection term is QUICK scheme, and the coupling of velocity and pressure is SIMPLE algorithm.

2.4. Calculation method

Taking \( d = 0.01 \text{m} \) and \( E = 2 \) as an example, the measurement section 1 and 2 are uniform flow regime. According to Xie Haiying [5], the influence of the vortex zone is greater than that after the 6-diameter pipe diameter, and the measurement point can be roughly determined. The position of measurement section, through the column energy equation:

\[
\frac{z_4 + \frac{p_1}{\rho g} + \frac{v_1^2}{2g}}{2g} = \frac{z_2 + \frac{p_2}{\rho g} + \frac{v_2^2}{2g}}{2g} + h_{f1-2}
\]

The head loss per unit length is as follows:

\[
h_f = \frac{h_{f1-2}}{x_2 - x_1}
\]

Where: \( z \) is the position of the head at the point where the water is equal at the two sectiona; \( x \) is the abscissa of the section corresponding to the point, and \( x = 0 \) is the speed entrance face;

Establish a number of hypothetical critical section 0, and at the critical section, establish an energy equation with measurement point 1:
\[ z_0 + \frac{P_0}{\rho g} + \frac{v_0^2}{2g} = z_1 + \frac{P_1}{\rho g} + \frac{v_1^2}{2g} + h_{f0-1} \]  

(4)

And the head loss at the two measuring sections meets the following formula:

\[ h_{f0-1} = (x_1 - x_0) \times h_f \]  

(5)

2.5. Test program

In this paper, we study whether the flow has a specific scale effect by studying the different slumping ratios and the backflow length and backflow degree under different Reynolds numbers \( Re = \rho v_x D / \mu \), and changing the difference. Among them, the ratio of sudden expansion is \( E = D / d \).

| \( E \) | Model | \( d \) | \( D \) | \( Re \) |
|---|---|---|---|---|
| \( E = D/d = 1.5 \) | 1a | 0.01 | 0.15 | 10~100000 |
| | 1b | 0.1 | 0.3 | |
| | 1c | 0.2 | 0.45 | |
| | 1d | 0.3 | 0.02 | |
| | 2a | 0.01 | 0.2 | |
| | 2b | 0.1 | 0.03 | |
| \( E = D/d = 2 \) | 2c | 0.2 | 0.4 | |
| | 2d | 0.3 | 0.6 | |
| | 3a | 0.01 | 0.03 | |
| | 3b | 0.1 | 0.06 | |
| \( E = D/d = 3 \) | 3c | 0.2 | 0.9 | |
| | 3d | 0.3 | 0.04 | |
| | 4a | 0.01 | 0.09 | |
| \( E = D/d = 4 \) | 4b | 0.1 | 0.4 | |
| | 4c | 0.2 | 0.8 | |
| | 4d | 0.3 | 1.2 | |
| | 5a | 0.01 | 0.05 | |
| \( E = D/d = 5 \) | 5b | 0.1 | 0.5 | |
| | 5c | 0.2 | 1 | |
| | 5d | 0.3 | 1.5 | |

3. Result and analysis

3.1. Influence of Reynolds number

Figure 4 shows variations of streamlines along Reynolds numbers within the case of the constant sudden expansion ratio of 2 \( (d = 0.01m, D = 0.02m) \). It is clearly observed that the vortex region in the recirculation zone increases as the Reynolds number increases.
Figure 4. Streamlines for $E = 2$
Figure 5. The relationship between $Re$ and $L/D$ ($E = 2$)

From figure 5, it is concluded that if the sudden expansion ratio is fixed ($E = 2$), $L / D$ changes sharply with the increase of the Reynolds number in the Laminar zone ($Re < 2000$), whereas varies slowly in the Turbulent zone ($Re > 2000$). The slope rate decreases as the Reynolds number increases and the relationship between then $L / D$ and the Reynolds number fits a logarithmic function as follows:

$$\frac{L}{D} = 0.8233\ln(Re) - 0.3825 \quad R^2 = 0.9582$$

(6)

Figure 6. The relationship of recirculation degree and the $E$ & $Re$
Figure 6 demonstrates relation curves between the $L/D$ and the Reynolds number under five cases with different sudden expansion ratios (1.5, 2, 3, 4, 5). All variation laws are similar and have a same tendency as depicted in figure 5.
3.2. Influence of expansion ratios
The influence scope of hydraulic loss is studied with a constant Reynolds number in this section. Figure 7 depicts the change law of streamlines under different sudden expansion ratios (1.5, 2, 3, 4, 5) when the Reynolds number equals 1000.

From Figure 7, it is seen that the $L/D$ enlarges greatly with the sudden expansion ratio’s increasing when the Reynolds number equals 1000. As a result, the recirculation zone and the vortex region are also enlarged. Therefore the distance between the inlet and the stable flow in the main flow region is becoming far and far.

![Figure 7. Streamlines for $Re = 1000$](image)

3.3. Scale effect
Various models with different sizes are built for analyzing the degree of recirculation. Furthermore, the existence of the scale effect in this problem is verified.

![Figure 8. The relationship between $E$ and $Re$](image)
Table 2. Value of different Re and d

| Re  | d = 0.01m | d = 0.1m | d = 0.2m | d = 0.3m |
|-----|-----------|----------|----------|----------|
| 10  | 0.262     | 0.719    | 0.903    | 1.505    |
| 20  | 0.785     | 1.635    | 1.845    | 3.010    |
| 40  | 2.028     | 2.485    | 2.552    | 4.188    |
| 100 | 3.532     | 3.466    | 4.711    | 6.608    |
| 200 | 4.055     | 5.559    | 6.478    | 8.310    |
| 1000| 4.709     | 5.821    | 6.478    | 8.898    |
| 2000| 5.952     | 7.521    | 7.224    | 9.356    |
| 4000| 7.391     | 8.437    | 8.716    | 10.665   |
| 6000| 7.652     | 9.026    | 9.540    | 11.581   |
| 10000| 8.372     | 8.960    | 10.993   | 13.609   |
| 16000| 8.437     | 8.960    | 12.720   | 13.936   |
| 20000| 8.699     | 9.745    | 12.602   | 14.722   |
| 40000| 8.633     | 9.680    | 10.757   | 15.441   |
| 100000| 9.091     | 11.184   | 13.427   | 16.226   |

Figure 9. The relationship of recirculation degree and the d & Re

From the curves in Fig.9, it can be concluded that the degree of recirculation is affected by the size of the model. The degree of recirculation increases as the diameter of the inlet pipe increases. Therefore, there is a kind of scale effect in this problem, and the logarithmic relation between the Reynolds number and the degree of recirculation exists.

### 4. Conclusion

This paper studied the influence scope of the hydraulic loss for pipe flow in plane sudden expansions using numerical methods. Results show that the sudden expansion ratio and the Reynolds number have significant impacts on the local hydraulic loss, and obvious differences exist among cases with different Reynolds numbers. Conclusions are as follows:

1. When the sudden expansion ratio is constant, the degree of recirculation and the Reynolds number has a logarithmic relation. In the case of small Reynolds number (Re = 0–2000), the
recirculation zone changes largely, whereas changes moderately with large Reynolds number (Re > 10000). In addition, more than one vortex region exists in the recirculation zone when the Reynolds number is large.

(2) When the Reynolds number is small and constant (Re = 0~2000), the recirculation zone the degree of recirculation increases as the sudden expansion ratio increases. However, the recirculation zone remains similar variation law when the Reynolds number is large and constant (Re > 10000), while the degree of recirculation decreases as the sudden expansion ratio increases.

(3) The problem has a scale effect related to the model. In the condition of a constant sudden expansion ratio, different inlet diameters produce different degrees of recirculation. The larger the inlet diameter is, the larger the degree of recirculation is.

Acknowledgments
This research is supported by the Science and Technology Research Project of the Department of Education in Jiangxi Province (Grant No. GJJ151103) and the National Natural Science Foundation of China (Grant Nos. 51509128 and 51879129).

References
[1] R Manica, A.L De Bortoli. Simulation of sudden expansion flows for power-law fluids[J]. Journal of Non-Newtonian Fluid Mechanics, 2004, 121(1).
[2] XU Zishun, XIAN Kai, YU Jianfa, ZHANG Guirong. Low Reynolds Number Numerical Simulation of Sudden Expansion Pipe Flow Based on Fluent [J]. Internal Combustion Engines, 2016(01): 27-30.
[3] Zhang Bei. Numerical simulation and pressure loss analysis of sudden enlargement in circular pipes at low Reynolds number [D]. Harbin Institute of Technology, 2007.
[4] ZHANG Yan-jun, GAO Xiang, LUO Zhong-yang, CEN Ke-fa. Application of different turbulent models in calculation of flow resistance in pipelines and comparison thereof [J], Journal of thermal power generation, 2007, 36( 1) : 18 − 23.
[5] XIE Haiying. Numerical simulation of local head loss of sudden expansion in pipe. [J]. Journal of Water Resources & Water Engineering, 2013, 24(3): 152-154.
[6] LI Dong-hao, WANG Wen-e, GE Mao-sheng, YU kun. Study on Local Drag Parameter of Subcontract Tube.[J]. Journal of Water Resources and Architectural Engineering,2011,9(04) :22-24.