Numerical Analysis of Incompressible Flow Leakage in Short Pipes

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Abstract

An incompressible pipe flow with leak was investigated numerically in the present study to provide the understanding of how different parameters including leak-pipe diameter, inlet mass flow, and main pipe length can affect leak. Computational Fluid Dynamics (CFD) has been carried out to simulate the leakage in water pipe under different conditions. The present CFD data show that the effect of the inlet mass flow rate is more significant on total pressure drop and pressure change at the leak location than that of the main pipe length. The effect of these two factors on leak mass flow rate becomes comparably important. The relationship between the pressure change at leak location and leak mass flow rate is approximately linear, with dominant effect of the inlet mass flow rate and negligible effect of the pipe length. When the leak quantity ratio smaller than approximately 2%, the pressure change at leak-location is negligible with no difference observed. The present study proves that CFD analysis could be an effective and less-costly means to investigate pipe flow with leakage, so as to provide scientific understanding of the underline mechanism on flow leakage.

Nomenclature

d	diameter of the main pipe
dL	diameter of the discharge pipe for leakage
dL^*	Leak size ratio ($dL^*=dL/d$)
m_{in}	inlet mass flow rate
m_L	leak mass flow rate
m_L^*	leak quantity ratio ($mL^*=mL/min$)
u	velocity in x direction (flow direction)
v	velocity in y direction (vertical direction)
w	velcotiy in z direction (span-wise direction)
x,y,z	spanwise direction, vertical direction, and flow direction respectively
xL	leak location
DP	pressure drop
DPL	pressure change at leak-location (DPL=PL@down – PL@up)
DPT	total pressure drop of the main pipe ($DPT=Pin – Pout$)
L	main pipe length
P	pressure
P_{in}	inlet pressure
$P_{out\text{-}main}$	outlet pressure of the main pipe
$P_L@up$	pressure at upstream of 0.0127m from leak location
$P_L@down$	pressure at downstream of 0.0127m from leak location
Greek symbols	
ρ	density of water
μ	dynamic viscosity of water

1. Introduction

Pipeline transportation is one of the most efficient and economic ways to convey the transport of oil and natural gas. Due to corrosion and pressure surges, the pipeline rupture cannot be avoided which leads to leaks in pipeline. Fluid leakage may cause serious pollution, injuries, and fatalities if it cannot be detected and repaired promptly [1]. The majority of these pipelines is buried and passes through crowded cities as well as remote areas such as farms and forests, which makes it more difficult to detect and locate the leakage. Although there are some references in this research area [1-3], the underline mechanism governing the leakage is yet not clear and needs to be further explored. Therefore it is of significance and necessity to investigate flow characteristics in pipe flow with leakage.

In this study, Computational Fluid Dynamics (CFD) will be carried out to simulate incompressible pipe flow under different conditions including flow rate, leak-pipe diameter, and pipe length. The effect of these factors/parameters on flow variables such as the leak flow rate, total pressure drop along the main pipe and the pressure change before and after the leak location will be investigated.

2. Model configuration and computational Method

A straight pipe with water as working fluid is considered in the present study, while the leak is performed by a discharge pipe to atmosphere. All the dimensions were set the same values as the experimental work [4], as shown in Figure 1.

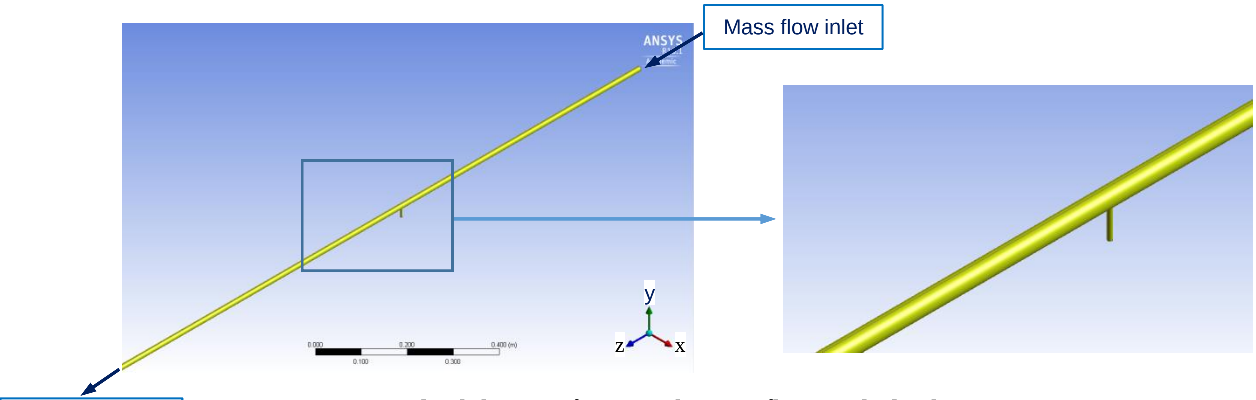

Figure1 Fluid domain for straight pipe flow with discharge pipe

Three-dimensional governing equations for steady state, incompressible water flow in Cartesian coordinate are expressed by

Continuity equation
$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \quad (1)$$

Momentum equation
$$\rho\left(u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}\right)=-\frac{\partial P}{\partial x}+\mu\nabla^2 u$$
$$\rho\left(u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}\right)=-\frac{\partial P}{\partial y}+\mu\nabla^2 v \quad (2)$$
$$\rho\left(u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}\right)=-\frac{\partial P}{\partial z}+\mu\nabla^2 w$$

CFD software ANSYS FLUENT [5] was utilized to solve steady three dimensional (3-D) Navier–Stokes equations to capture the flow phenomena. k-ε turbulence model was adopted here due to its applicability for fully developed flow with fast convergence. SIMPLE algorithm was employed for pressure-velocity coupling for fast convergence. Second order discretization scheme was employed for flow variables, turbulent kinetic energy and turbulent dissipation rate. A reduction in the maximum residuals by at least 3 orders of magnitude was used as the global convergence criterion for all simulations. In addition, simulation was considered converged when mass flow rate was statistically stable and not changing with additional iterations (i.e. at 1000, 2000 and 3000 iterations). Sufficiently fine tetrahedral mesh has been generated by ANSYS meshing with good mesh quality, and all the results have been validated to be grid-independent. For all the cases in this study, mass flow inlet and pressure outlet conditions were applied at the inlet and outlet, as well as no-slip conditions on the pipe walls. The length of the discharge pipe is longer than 5 times of its diameter to make the flow fully developed so as to make use of ambient pressure condition at its outlet.

In this study, two pipe lengths and four discharge pipe diameters at two inlet mass flow rate have been taken into account, while the diameter of the main pipe, leakage location, and the pressure at outlet remain unchanged. The dimensions and boundary conditions are listed in Table 1.

Table 1 Pipe dimensions and pipe flow boundary conditions

Boundary conditions	xL (m)	d(m)	Pout-main(Pa)	min (kg/s)	L (m)	dL (m)	dL*
Mass flow inlet & Pressure outlet	0.73	0.0127	81	0.13 & 0.32	3.35 & 2.23	0	0
						3.20E-03	25.20%
						5.20E-03	40.94%
						7.20E-03	56.69%
						1.00E-02	78.74%
Note that dL*=0 represents no-leak case, and total 20 cases are simulated.							

3. Results and discussion

Several cases in the experimental work [4] were selected as validation cases to validate the present CFD modelling. The pressure drop at the two locations with z1 = 0.05m and z2 = 1.5m and the leakage quantity between the present simulation data and the previous experimental data have been compared and the comparison is listed in Table 2. The deviation between CFD and experimental data for different cases is within the range of 3.88% - 31.38%, with smallest difference for middle leakage 20% and largest difference for small leakage quantity 8%. Considering the unknown uncertainty of experiment data and the computation error in numerical simulation, 30% difference is still within the acceptable range [6].

Table 2 Comparison of present CFD and previous experimental data [4]

Conditions	DP (KPa) = P@z1 - P@z2		$m_L^* = m_L/m_{in}$	
L=3.35m dL=3.2e-3m min=0.13kg/s	CFD	1.76	CFD	10.51%
	EXP	1.35	EXP	8%
	Difference(%)	30.37%	Difference(%)	31.38%
L=2.23m dL=5.2e-3m min=0.32kg/s	CFD	6.50	CFD	16.34%
	EXP	6	EXP	17%
	Difference(%)	8.33%	Difference(%)	3.88%
L=2.23m dL=7.2e-3m min=0.32kg/s	CFD	5.31	CFD	26.34%
	EXP	4.6	EXP	31%
	Difference(%)	15.43%	Difference(%)	15.03%
L=2.23m dL=1.0e-2m min=0.32kg/s	CFD	4.18	CFD	38.03%
	EXP	3.5	EXP	49%
	Difference(%)	19.43%	Difference(%)	22.39%

The total pressure drop from inlet to outlet (DPT) of the main pipe, and leakage quantity ratio (mL*) at different inlet mass flow rate, pipe length and leak size ratio are shown in Figures 2. A reasonable result of total pressure drop from inlet to outlet of the main pipe can be observed for all cases due to the pressure driven pipe flow. For the pressure change at the leak location, there is lower pressure at upstream of the leak, and higher pressure at downstream of the leak, which is consistent with the experimental results in experimental work [4]. The increase in pressure after leak is promoted by decrease in the downstream flow rate and kinetic energy due to leak. For all the simulation cases, consistent results from Figure 2 shows that for fixed pipe length and inlet mass flow rate, with an increase in leak size ratio, total pressure drop is reduced and leak quantity ratio is increased (see Figures 2a and b). With leak quantity ratio increasing, more mass flows through larger discharge pipe and less mass in the main pipe, which results in lower velocity and higher pressure at the outlet of the main pipe as well as lower total pressure drop through the main pipe. For total pressure drop and pressure change at leak-location as shown in Figures 2(a) and 4(a) respectively, the effect of inlet mass flow rate is more significant than that of the pipe length; with the pipe length effect is more substantial at larger inlet mass flow rate. For leak quantity ratio as shown in Figure 2(b), the effects of both mass inlet flow rate and pipe length are comparable resulting in larger leak quantity at lower inlet mass flow rate (0.13kg/s) and longer pipe length (3.35m).

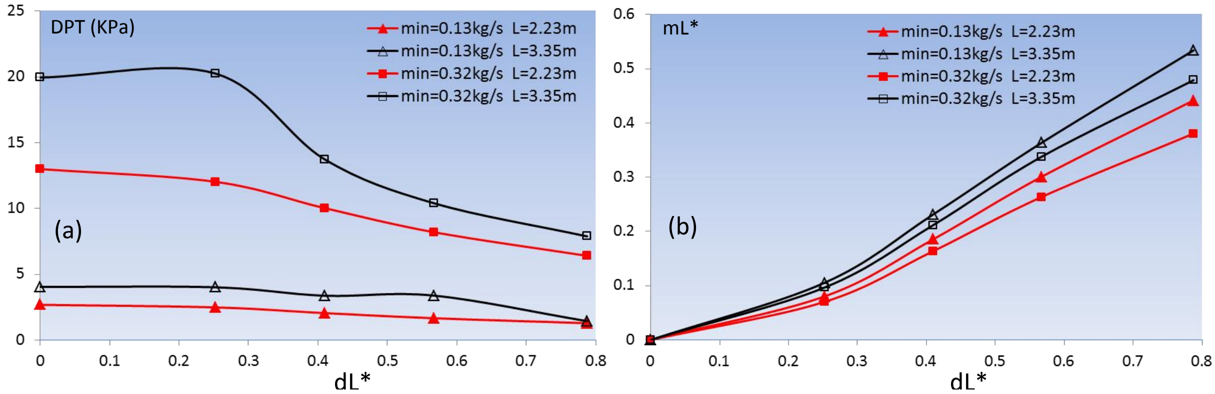

Figure 2 Flow and leakage variables .vs. leak size ratio at different inlet mass flow rate and pipe length: (a) total pressure drop from inlet to outlet, and (b) leakage quantity ratio.

Figure 3 shows the detailed flow and pressure contours in the vicinity of the leakage at the centre plane along flow direction. It is seen from Figure 3 that the pressure at the upstream of leak is lower and that at the downstream of leak is higher due to lower flow velocity downstream resulted from leak, which is consistent with the experimental data [4] and data shown in Figure 4 later.

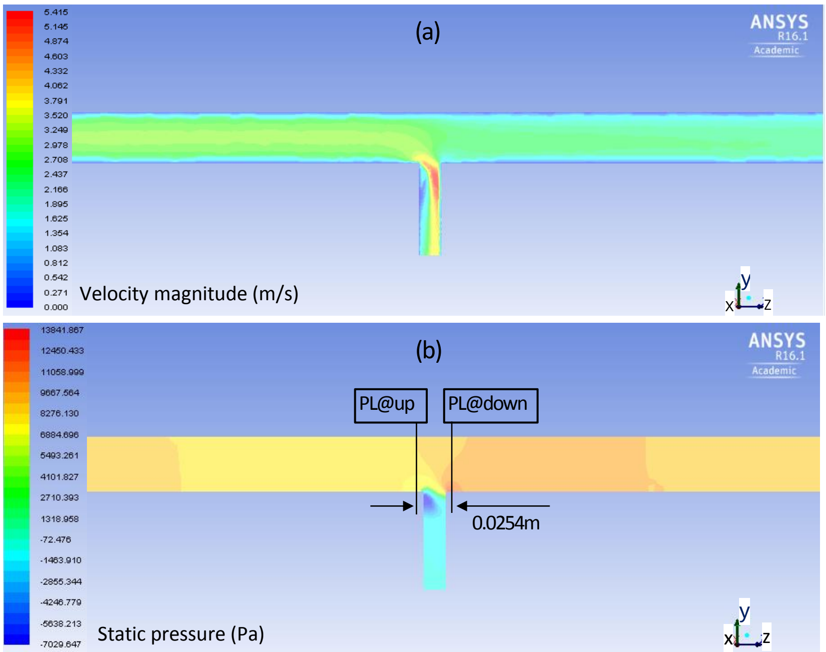

Figure 3 Velocity and pressure contours at leak-location at inlet mass flow rate 0.32kg/s, pipe length 3.35m and discharge pipe diameter 0.052m: (a) velocity contour, and (b) pressure contour.

The pressure change between upstream and downstream of leakage location (DPL) at different inlet mass flow rate and pipe length are summarized relative to the leak size ratio and leak quantity ratio, as shown in Figure 4. It is observed from Figure 4(a) that pressure change at leak location is negligible at the condition of the leak size ratio smaller than 0.25 for lower inlet mass flow rate (0.13kg/s) and two pipe lengths (2.23m and 3.35m), while the ratio is reduced to 0.16 and 0.05 for larger inlet mass flow rate (0.32kg/s) at shorter pipe length (2.23m) and longer pipe length (3.35m) respectively. For the pipe without leak, the pressure change at the same location as the leak location is negative. Regarding the relationship between the pressure change at leak location and leak quantity ratio (see Figure 4b), it is approximately linear, and the inlet mass flow rate has dominant effect while the pipe length effect is negligible. When the leak quantity ratio smaller than approximately 2%, the leak-location pressure change is observed to be zero, which means that the difference of the pressure at upstream and downstream of leak location is negligible.

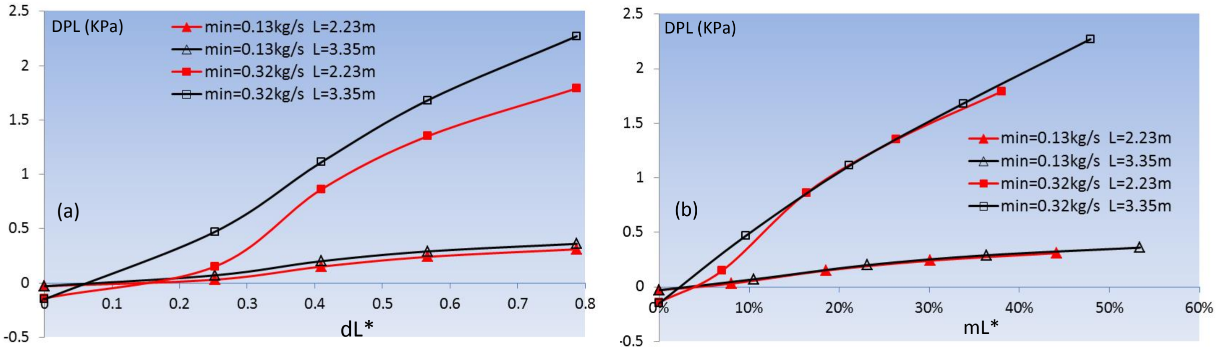

Figure 4 Pressure change at leak-location at different inlet mass flow rate and pipe length .vs. (a) leak size ratio, and (b) leakage quantity ratio.

4. Conclusions

An incompressible pipe flow with leak was investigated numerically in the present study. Different inlet mass flow rate, leak-pipe diameter, and pipe length were considered to investigate the effect of these parameters on leak quantity, total pressure drop along the main pipe and the pressure change upstream and downstream of the leak location. The simulation results show that the effect of inlet mass flow rate is more significant than that of on total pressure drop and pressure change at the leak location, than that of the pipe length. Regarding leak quantity ratio, the effects of both inlet mass flow rate and pipe length are important and comparable. The relationship between the pressure change at leak location and leak quantity ratio is approximately linear, with dominant effect of inlet mass flow rate and negligible effect of the pipe length. When the leak quantity ratio smaller than approximately 2%, the leak-location pressure change is observed to be zero, which means that the difference of the pressure at upstream and downstream of leak location is negligible. The present study verifies that simulation is an effective and economic tool to investigate pipe flow leakage, which can help to understand the flow phenomena. However, the present study is a preliminary study and further experiments will be conducted next.

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