LEAK FLOW ANALYSIS THROUGH NARROW CRACKS FROM HIGH-PRESSURE PIPELINE MATERIALS

Abstract

The occurrence of cracks in high-pressure duct systems is common and proven to be hazardous for various power and process plants. Safety issues are driven by piping design methodology and loss of coolant accident scenario especially in nuclear power stations. The present work analyses the leak flow through narrow circumferential cracks on stainless steel pipes of predefined geometry at varying high pressure water conditions and different areas of crack openings using computational simulation methods. The results of this analysis showcase the behaviour of leak flow properties flowing through the crack perpendicular to the main flow for a set of boundary conditions. The results indicate at normal temperature the leak flow pattern is primarily driven by the stagnation pressure for single phase leaks. Generated data for high-pressure pipelines are applicable for various industrial scenarios crucial for crack detection and safety measures before any severe accident occurs.

Keywords: Leak flow, Circumferential cracks, High-pressure ducts, Stainless steel pipes, Crack detection

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I. INTRODUCTION

The pipeline in a power plant is a significant part that deals with the transportation of fluids. High-pressure system design requires a mandatory safety analysis through the methodology of Leak Before Break (LBB). This is a cost-efficient and sustainable methodology for piping design where the formation and growth of cracks due to corrosion, erosion and other defects are scrutinized before the entire system experiences a disruption. The primary system pipelines in nuclear reactors carry radioactive substances, and safety is a prime concern. Therefore, measurements of leak along with detection of leak are a part and parcel of LBB analysis, which also offers valuable information of probable crack morphology [1]. These phenomena are quite usual in various oil or gas transporting pipelines causing pipeline leakage. If not monitored carefully, leakages can have massive impacts on human and marine life [2]. The application of the Finite Element Method in studying fracture mechanics has been well documented in various literature discussing pipeline integrity and the interactions caused by corrosion defects [3,4]. Advanced numerical techniques have been employed to accurately determine the extent of crack growth that occurs as a result of stress corrosion cracking [5]. Additionally, these techniques have also been used to analyze the through-wall cracks that may occur under high-temperature and high-pressure pipe flow [6]. Some numerical techniques have been used to determine leak flow through crack and corresponding through-wall crack opening under high-pressure [7]. By utilizing these methods, engineers can gain critical insights into the behaviour of materials subjected to extreme environments and develop effective strategies to mitigate the risk of catastrophic failures for sustainable development.

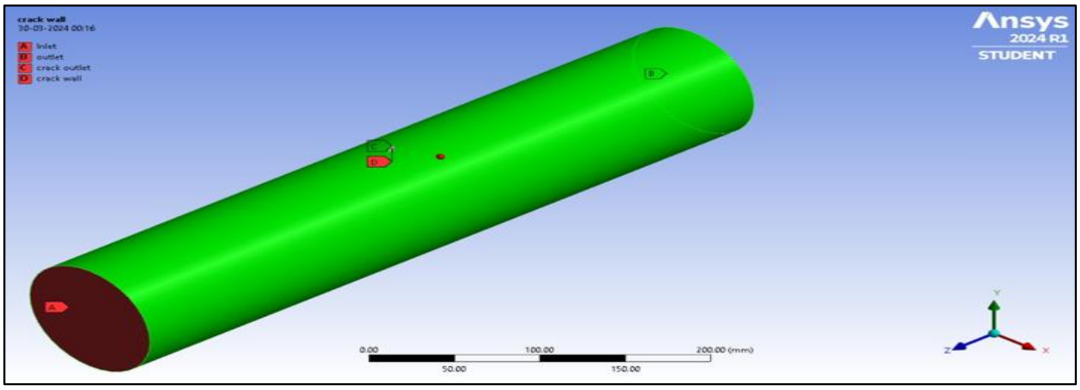
In the applications of high-pressure pipelines used in several power plants and chemical industries, various materials are used based on their unique properties. Carbon steel can withstand high temperatures and but it faces corrosion when exposed to moisture, chemicals and acids [8]. To mitigate this, protective coatings are applied to the surface of the pipelines. Stainless steel, on the other hand, is regarded as one of the ideal materials used in various pipelines. It is highly resistant to corrosion, even in acidic and high-moisture environments. Despite the associated cost, its durability and corrosion-resistant properties make it a preferred choice in various industries inclusive of Nuclear Power Plants [10]. Pipelines often have a type of damage called a dent crack, which looks like a semi-ellipse. Several crack detection techniques using sensors have been reported in literature [11]. A number of studies have focussed on the determination of critical leak flow evaluations through predefined cracks or slits through theoretical and experimental investigations [12-14]. CFD simulations have emerged as a popular alternative regarding the prediction of leakage mass flux under variety of boundary conditions [15]. However, there is a lot of scope to simulate various analytical models to evaluate the effect of stagnation pressure and crack morphology on pipe leaks causing severe accidents in key power stations. This paper aims to analyze the behaviour of a high-pressure pipeline with a predefined circumferential crack of rectangular and circular profile under various pressure conditions. Mass flow rate and leakage flow patterns have been studied for various boundary conditions through CFD simulations techniques to address a sustainable solution regarding loss of coolant accidents especially faced in nuclear power plants.

II. PHYSICAL PROBLEM AND COMPUTATIONAL SETUP

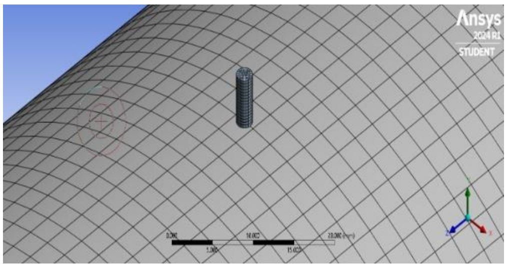
The current CFD analysis has been conducted for a computational domain of water flowing through a circular pipe made of steel. A circumferential crack has been generated through 3D modelling nearby the middle of the test section. The study has been done by designing leak locations of various circular and rectangular dimensions. This physical problem for CFD analysis represents the actual life scenario of crack formation in the high-pressure pipelines of a duct system of a nuclear power plant.

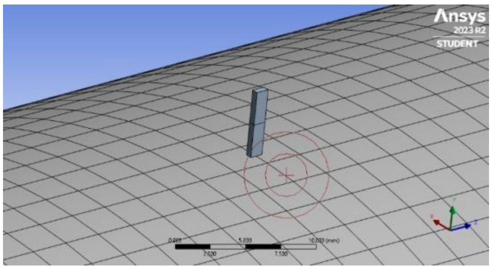
1. Geometry and Mesh

The dimensions of the pipe whose flow domain is taken into account are 500 mm (length) x 100 mm (diameter) having 5 mm thickness. Three circular-shaped minute cracks of diameter 1 mm, 1.5 mm, and 2 mm and three rectangular-shaped narrow cracks of length 1 mm, 2 mm, 3 mm, and breadth 0.5 mm each have been taken into consideration for the analysis. The geometry is designed using the ANSYS Design Modeller tool. The geometry of the flow domain of the circular pipe is shown in Fig. 1 (a). Similarly, Fig. 1 (b) & 1 (c) shows a zoomed picture of the small circular crack and the narrow rectangular crack respectively. The thickness of the pipe is taken into consideration while designing the crack openings. Mesh of the geometry is generated as shown Fig. 2. The various sections of the geometry are named before generating the mesh, namely, inlet, outlet, pipe wall, crack outlet, and crack wall. In the generated mesh, average orthogonal quality of 0.99 and average element quality of 0.86 was maintained.



(a)





(b) **(c)**

Figure 1: (a) Computational domain of 500 mm x 100 mm circular pipe with circumferential narrow crack **(b) C**ircular crack geometry **(c)** Rectangular crack geometry

2. Computational Setup

The computational fluid dynamics simulation has been performed using Fluent code in ANSYS platform. The 3D analysis has been conducted using double precision setting. The viscous model used for the setup is k-epsilon. The material selected for the fluid flow domain simulation is water in liquid state. The boundary condition given for the simulations are pressure inlet and pressure outlet at the outlet of the flow domain and crack opening. The pressure set at the inlet ranges from 70 bar to 110 bar and the pressure set at the outlet ranges from 69 bar to 109 bar respectively (the pressure difference between the inlet and outlet is kept 1 bar for all the test cases). The pressure at the crack opening is set at 1 bar which is the atmospheric pressure under normal conditions. Solution of the continuity and momentum equations were done on the basis of standard convergence criteria.

III. RESULT AND DISCUSSION

The table 1 & 2 shows the predicted mass flow rate at the crack location, as calculated by the CFD module for various pressures ranging from 70 bar to 110 bar. To assess the functional relationship between the mass flow rate and crack area at various pressures, the feasible input variations were considered for the analysis. A similar kind of analysis is done for two types of cracks generated at various pressures. The various crack area gives the maximum and minimum mass flow rates.

1. Rectangular Crack

Here we have used the steel pipes to analyse the relation between the mass flow rate and the area of the crack. For the rectangular crack under various pressures with various crack areas, the change of mass flux is shown in the table (1). Here we observed that mass flux increases with the increase of pressure. Throughout the process, the temperature is considered constant. The mass flow rate analysis under various pressures gives the change of mass flux.

Table 1: Predicted mass flux and velocity of leakage through rectangular crack opening

Sl. No.	Inlet Pressure (bar)	COA x10^{-6} (m^2)	Mass Flux (kg/m2s)	Leak flow Velocity (m/s)
1	70	0.5	0.078	86.241
		1	0.081	87.559
		1.5	0.082	88.483
2	80	0.5	0.084	92.358
		1	0.086	93.754
		1.5	0.087	94.682
3	90	0.5	0.089	98.224
		1	0.092	99.673
		1.5	0.093	100.642
4	100	0.5	0.094	103.774
		1	0.097	105.275
		1.5	0.098	106.276
5	110	0.5	0.099	109.193
		1	0.102	110.762
		1.5	0.104	111.829

The variation of the maximum leak flow velocity in accordance to the inlet pressure can be depicted from the graph in fig. 2. The maximum leak flow velocity increases with the increase in the pressure at the pipe inlet. Also, the variation of the mass flux with the inlet pressure is shown in the graph in fig. 3. It is seen that the mass flux increases with the increase in the inlet pressure. The pressure and velocity contours found in the simulation result are presented in fig.4 and fig. 5.

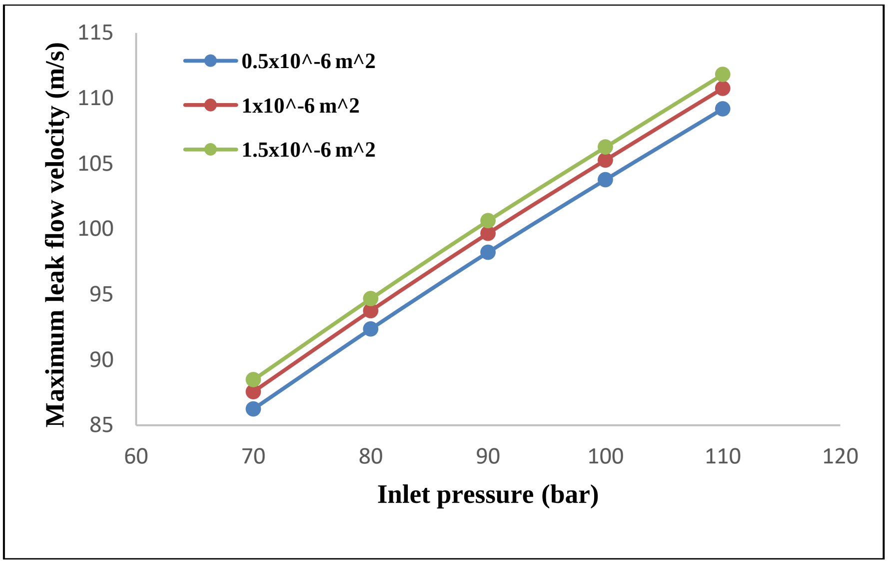


Figure 2: Variation of maximum leak flow velocity with pressure for rectangular cracks

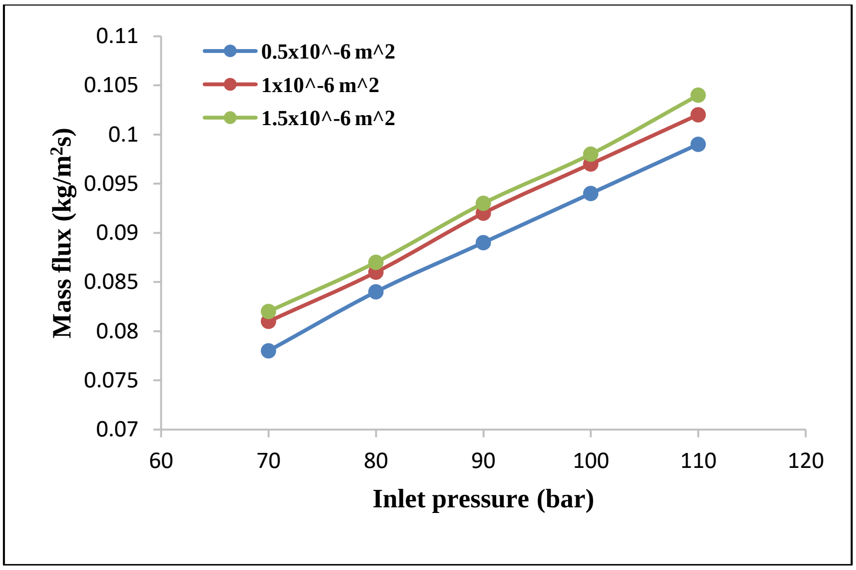
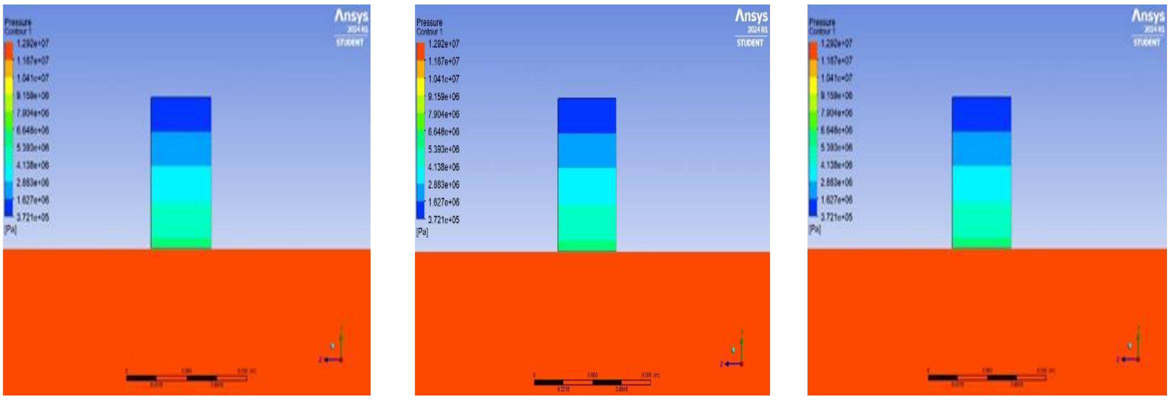
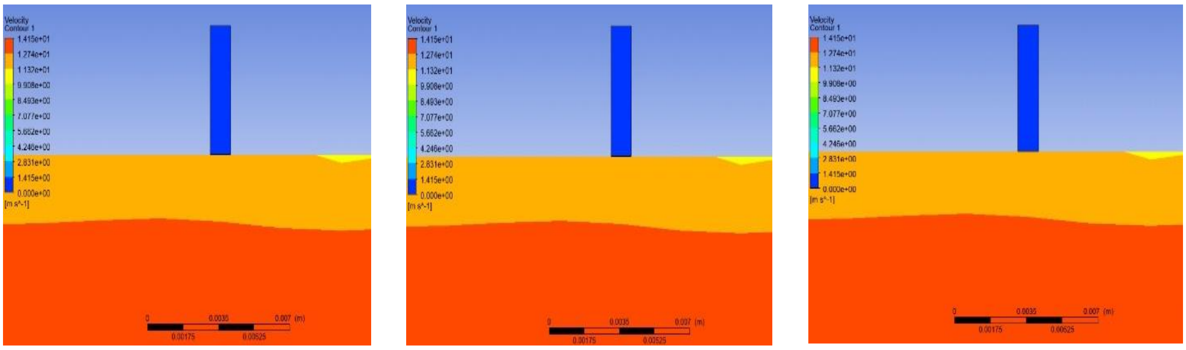


Figure 3: Variation of maximum mass flux with Pressure for rectangular cracks



(a) **(b)** **(c)**

Figure 4: Pressure contour of the rectangular crack of 0.5x10^{-6} m^2 at **(a)**70 bar inlet pressure, **(b)** 80 bar inlet pressure, **(c)** 90 bar inlet pressure



(a) **(b)** **(c)**

Figure 5: Velocity contour of the rectangular crack of area 1.5x10^{-6} m^2 at **(a)** 70 bar inlet pressure, **(b)** 80 bar inlet pressure, **(c)** 90 bar inlet pressure

2. Circular Crack

The analysis of circular cracks was conducted to determine the relationship between pressure, mass flux, and velocity of the crack. The results of the analysis are presented in Table 2, which shows the changes in mass flux due to variations in pressure and Area. The analysis was conducted under the assumption of constant temperature. The results of the analysis revealed that an increase in pressure led to a corresponding increase in mass flux. The fluid flow rate through the crack was influenced by the pressure gradient and the crack size. Overall, the analysis provides valuable insights into the physics of fluid flow through circular cracks, and it underscores the importance of understanding the underlying mechanisms that govern fluid flow to optimize the design and operation of fluidic systems.

Table 2: Data table of the mass flux and velocity through circular crack opening at various pressure conditions

Sl. No.	Inlet Pressure (bar)	COA x10^{-6}(m^2)	Mass Flux (kg/m^2s)	Leak flow Velocity (m/s)
1	70	7.06	0.027	121.745
		12.56	0.022	98.274
		19.63	0.023	100.441
2	80	7.06	0.027	105.334
		12.56	0.022	104.298
		19.63	0.023	107.552
3	90	7.06	0.023	109.421
		12.56	0.024	110.651
		19.63	0.024	114.457
4	100	7.06	0.024	116.278
		12.56	0.025	115.336
		19.63	0.026	119.548
5	110	7.06	0.026	121.745
		12.56	0.027	121.275
		19.63	0.028	126.354

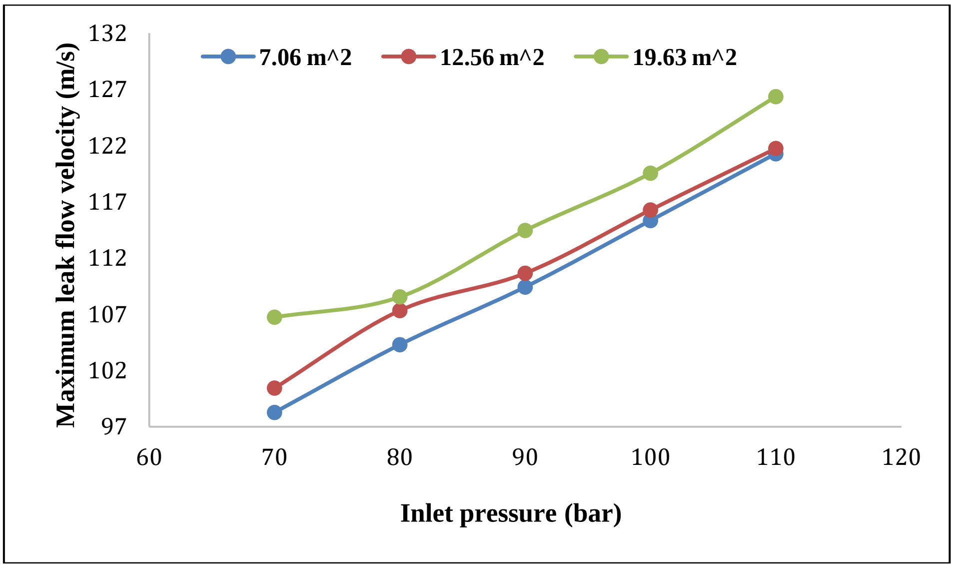


Figure 6: Maximum leak flow velocity vs. Pressure graph for circular cracks

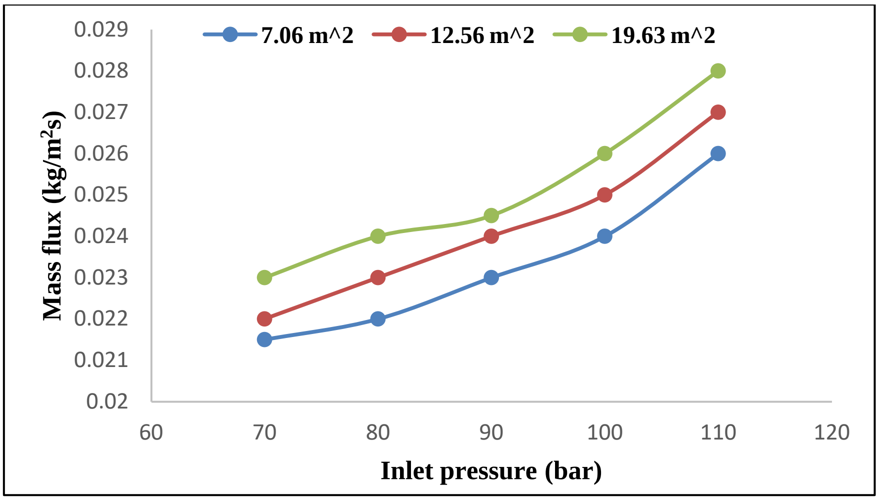
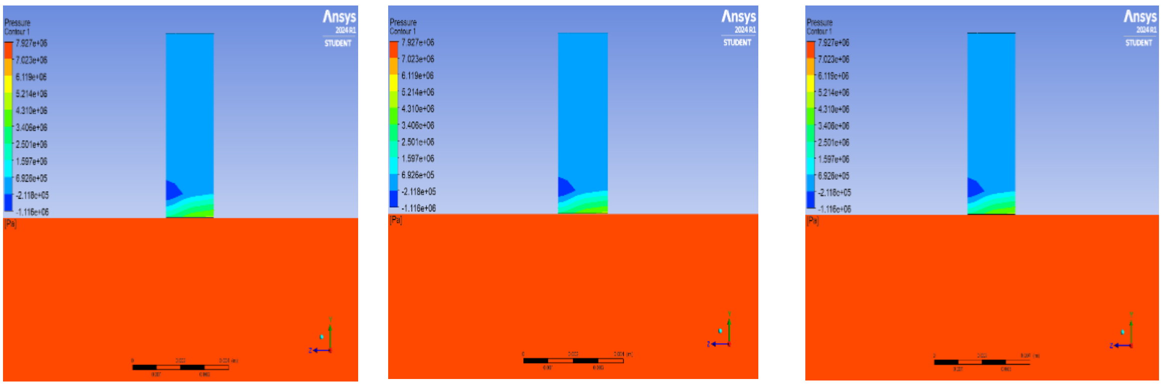


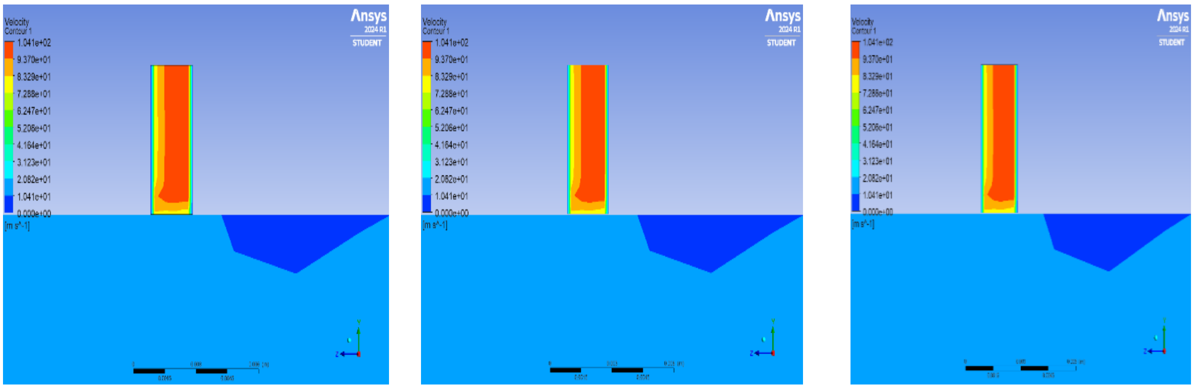
Figure 7: Mass flux vs. Pressure graph

In the case of circular cracks, the variation of the maximum leak flow velocity in accordance to the inlet pressure can be seen in the graph in figure 6. The maximum leak flow velocity increases with the increase in the pressure at the pipe inlet of the pipe flow domain. Also, the variation of the mass flux with the inlet pressure is shown in the graph in figure 7. It is seen that the mass flux increases with the increase in the inlet pressure for all the scenario of leak flow as reported in some experimental works. The pressure contour presented in fig. 8 shows that the maximum pressure drop inside the narrow slit resulting in critical leakage mass flux and associated velocity contours (fig. 9). Local flow acceleration within the crack and flow stagnation within pipe in nearby crack zone is evident in the contours. The behaviour found in the present work is analogous to several experimental findings [14, 15] reported in the literature as shown in figure 10.



(a) **(b)** **(c)**

Figure 8: Pressure contour image of the circular crack of area 12.56x10^{-6} m^2 at **(a)** 70 bar inlet pressure, **(b)** 80 bar inlet pressure, **(c)** 90 bar inlet pressure



(a) **(b)** **(c)**

Figure 9: Velocity contour image of the circular crack of area 12.56x10^{-6} m^{2} at **(a)** 70 bar inlet pressure, **(b)** 80 bar inlet pressure, **(c)** 90 bar inlet pressure

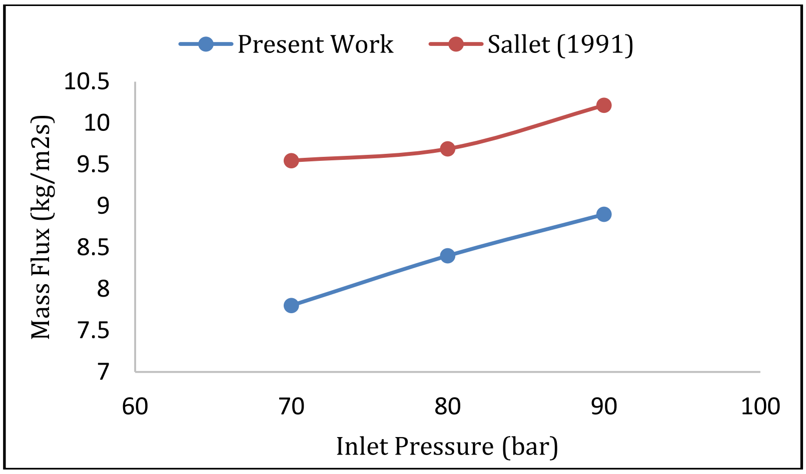


Figure 10: Comparison of leak flow behaviour with experimental research reports

IV. CONCLUSION

Leak flow prediction has been carried out for predefined narrow circular and rectangular circumferential cracks over steel pipes using computational simulations. The result of this analysis demonstrates a range of mass flux during leakage phenomenon for varying boundary conditions. It is observed that the mass flux through the point of leakage shows an increasing trend with increasing stagnation pressure. Choked flow has been observed while the inlet pressure was varied. These flow variations are critical in determining the severity of the crack and the necessary steps that need to be taken to rectify the situation. Moreover, the increase in pressure correlates with higher mass flux and velocity, potentially exacerbating the crack's size. Therefore, it is essential to monitor the pressure and mass flux to ensure that any potential issues can be identified and addressed promptly to prevent accidental hazards.

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