WAVE PROPAGATION IN RUPTURED PIPELINES AND GAS RELEASE RATE FROM RUPTURED AREAS

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ABSTRACT

In the present paper, a numerical solution is developed to estimate gas release rate from accidentally damaged pipelines and to predict the behavior of gas in pipe after rupture which can be used for detecting the location of the rupture. The solution is based on one-dimensional MacCormack's Technique. Results show that after accidental rupture some disturbances in pressure and other variables involving the problem will appear and propagate through the fluid. Finally release rate from damaged area is calculated by modeling the flow at leakage as a flow through a converging nozzle.

INTRODUCTION

Pipelines are considered as the safest and most economical means to convey dangerous substances such as natural gas. Unavoidably they may be damaged by some reasons consisting of corrosion, accidents and human errors, etc. When the pipeline is damaged the gas will be released from the damaged area. It is very important to predict the location of ruptured area and estimate the mass flow rate from releases areas in the gas pipeline in order to perform the hazard analysis and estimate the large amount of energy which is released in such accidental phenomenon. In 1997 Montiel [1] introduced two basic models for estimating release rate from ruptured pipelines including hole model in which the pipe being considered to be like a tank and pipe model which is useful in cases that the pipeline is fully ruptured. In 2002, Yuhua and Huilin [2] reported a mathematical model based on thermodynamical concepts and gas dynamic equations to estimate the release rate from damaged pipelines. Luo and Zheng [3] in 2005 presented a mathematical simplified model by neglecting some terms of governing equations for estimation of release rate. Since all the works mentioned above solve this problem by mathematical and analytical models and as we know no numerical solution has been done for compressible flows to solve this problem [6], in the present work a numerical solution of the governing equations has been performed. As it will be shown this solution will predict some disturbances that propagate in the pipe and these disturbances can be used for detecting the location of the rupture. Gas release rate from leakage can also be calculated from this solution.

GOVERNING EQUATIONS

We consider the problem shown in fig.1 in which an ideal gas flows in the pipeline. A rupture suddenly happens in the middle of pipeline and gas will be released from generated leakage. Equations governing such this flow are, equation of state, continuity, momentum and energy equations. The frictional effects have been taken into account as reported by Stojkovic in 2001 [4]. So the governing equations in differential form are as below where λ is the friction coefficient.

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho V)}{\partial x} = 0$$

$$\rho \frac{\partial V}{\partial t} + \rho V \frac{\partial V}{\partial x} + \frac{\lambda \rho}{2D} V^2 = -\frac{\partial P}{\partial x}$$

$$\rho \frac{\partial e}{\partial t} + \rho V \frac{\partial e}{\partial x} - \frac{\lambda \rho}{2D} V^3 = -P \frac{\partial V}{\partial x} \tag{1}$$

$$e = C_v T \ , \quad P = \rho R T \tag{2}$$

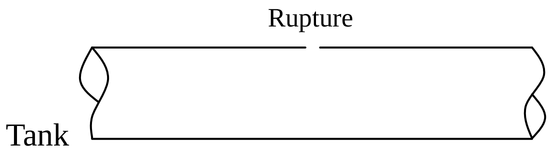

Fig.1. Schematic diagram of ruptured pipeline

The dimensionless form of equations (1) in a suitable form to be used by MacCormack method are [5]:

$$\frac{\partial \rho^*}{\partial t^*} = -\rho^* \frac{\partial V^*}{\partial x^*} - V^* \frac{\partial \rho^*}{\partial x^*}$$
$$\frac{\partial V^*}{\partial t^*} = -V^* \frac{\partial V^*}{\partial x^*} - \frac{1}{\gamma}\left(\frac{\partial T^*}{\partial x^*} + \frac{T^*}{\rho^*}\frac{\partial \rho^*}{\partial x^*}\right) - \frac{\lambda \rho}{2D} V^{*2}$$
$$\frac{\partial T^*}{\partial t^*} = -V^* \frac{\partial T^*}{\partial x^*} - (\gamma - 1) T^* \frac{\partial V^*}{\partial x^*} + \frac{\lambda}{2D} \rho \gamma R V^{*3} \tag{3}$$

Where dimensionless variables are introduced as:

$$T^* = \frac{T}{T_0},\ \rho^* = \frac{\rho}{\rho_0},\ x^* = \frac{x}{L}$$
$$V^* = \frac{V}{a_0},\ t^* = \frac{t}{L/a_0},\ a_0 = \sqrt{\gamma R T_0} \tag{4}$$

The solution divides the problem into two parts. The first one is the flow inside the pipe from reservoir to damaged area which is solved by MacCormack's Technique and the second one is the flow through ruptured area which is modeled as flow through a converging nozzle and this part of the problem is solved analytically in gas dynamics contexts and just the inlet pressure of the nozzle will be calculated by the first part.

NUMERICAL IMPLEMENTATION

Equations 3 are solved using an explicit one-dimensional MacCormack method in both conservation and non conservation forms. In a time marching approach we know the flow field variables at time t and we use the difference equations to solve explicitly for the variables at time t+Δt As the MacCormack method is a predictor-corrector method we set up spatial derivatives as forward difference in predictor step and as backward difference in corrector step. The mass flow release and energy release at the ruptured point are calculated from analytical gas dynamic equations by modeling the release at leakage as a flow in a converging nozzle and then are subtracted from continuity and energy equations at ruptured grid. Another aspect of the numerical solution is that of boundary conditions, as the flow is considered subsonic through the pipeline, we allow one variable to float in inlet boundary. Here velocity is chosen to be floated. All other flow-field variables are specified. Since the inlet boundary is considered as the reservoir, we stipulate the density and temperature at inlet boundary to be their stagnation values ρ and T in the tank respectively. These are held fixed, independent of time. Hence in terms of dimensionless variables, we have:

$$\rho_1 = 1, T_1 = 1$$
$$V_1 = 2V_2 - V_3 \tag{5}$$

In order to accelerate the fluid in the reservoir to the pipe flow, the pipeline is connected with a converging nozzle to the tank and this will help the gas to flow easily through the pipe to simulate gas flow through a real industrial pipeline. For the outlet boundary as it is supposed that the flow will remain subsonic one variable must be specified and others will be floated [5]. Here pressure is considered as the specified variable.

CALCULATION OF TIME STEP

Regarding stability considerations, a stability constraint exists on this system because the system of governing equations are hyperbolic with respect to time so to solve stability problems time step is restricted to

$$\Delta t = \frac{C}{a + V} \tag{6}$$

In which C is the Courant number. A stability analysis of a linear hyperbolic equation gives result that C≤1 for an explicit numerical solution to be stable. Because of this restriction existing on time step, time steps will be different at different points and different times. To solve this problem and obtain a uniform progress in time for any grid and at any time minimum value of time step for all grids and all time steps is considered to be a fixed time step for the solution.

GRID TESTING AND CODE VALIDATION

A mesh testing procedure was conducted to guarantee a grid independent solution. Three different mesh sizes were tested for grid independency by calculating release rate from the leakage at the same situations. In order to verify the validity of the solution, the results of the present work for released mass flow at steady times, have transformed into an applied dimensional example which was reported by [2], and then the results of both works were compared. The comparison between present work and Yuhua [2] which is shown in fig. 3 in section 5 shows that they are in good agreement with eah other.

RESULTS AND DISCUSSION

One of the most important aspects of accidental ruptures in gas pipelines is to estimate gas release rate from ruptured areas both for economical and environmental reasons[7]. In fig. 2. dimenssionless values of gas release with respect to ratio of leakage diameter to pipe diameter which are obtained from the present code are ploted. The plot shows that as the amount of diameter ratio is larger the gas release will increase more rapidly. These results are used for a specific example described below to verify them by a similar example done by Yuhua [1]. It is supposed that a gas pipeline has a length of 872(km) with an inner diameter of .66(m), gas pressure at the initial point of the pipe is 5 (Mpa) and gas temperature at that point is 293(k).

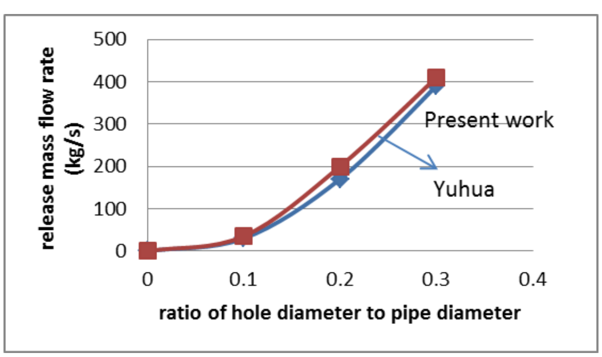

Fig.2. Relationship between the ratio of hole diameter to pipe diameter and release rate at steady time

In fig. 3. strong influence of working reservoir tank pressure on release rate is shown. The result show that gas release is strongly a function of working tank pressure. The code is runned for 5 Mpa and 2 Mpa of working pressure. The differences in gas release values for these values of pressure are bigger at higher diameter ratio.

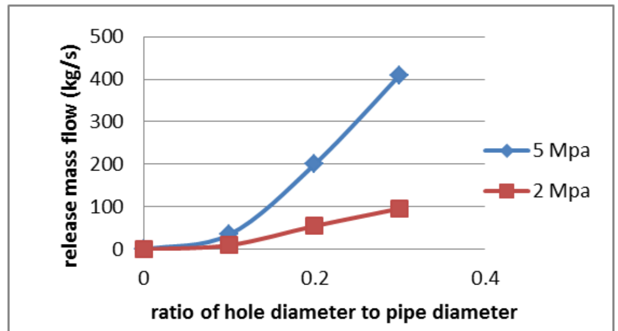

Fig.3. Relationship between the ratio of hole diameter to pipe diameter and release rate at steady time at different working pressures

The other aim of the present work is to show the wave propagation through the pipeline after the rupture happens. The results show that when the accidental rupture happens in the pipeline some disturbances in all the variables involving the problem such as pressure, mass flow through the pipe, temperature and local Mach number will be generated and propagate from ruptured point through the pipeline and then will be reflected back with adverse amplitude after reaching the end boundaries of the pipeline. In fact these open boundaries act as an obstacle for the moving disturbances and will reflect them back from the boundaries. Because of friction factors regarding to the pipe wall the amplitude of these disturbances will reduce while they are propagating through the pipeline. These disturbances in pressure and mass flow in different time steps will be discussed more detailed in figures presented below. Fig. 4. Shows fluctuations in pressure value after accidental rupture happens. As the results show in the few first seconds pressure value decreases very rapidly and after that it will fluctuate for some seconds and as time goes up these fluctuations will become damped gradually and pressure value will approach to it's steady state values which depends on the workig pressure of the supply tank, the leakage diameter, the pipeline diameter and the friction factor of the pipe. In this problem the rupture has occurred at time steps 11500 after the solution has started in order to obtain a steady solution in the pipe before rupture times.

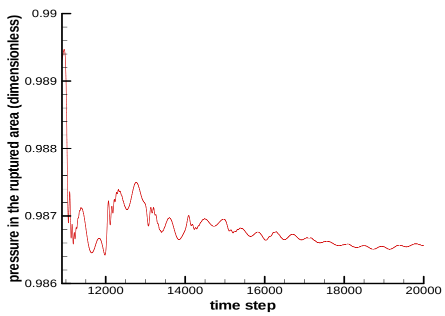

Fig. 4. variation in pressure at the leakage point after the rupture happens

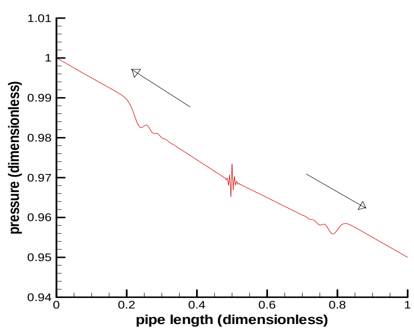

Fig. 5. Pressure disturbances propagation after the rupture happens

In fig. 5. The propagation of pressure disturbances through pipeline are shown. The decrease in pressure along the pipe before rupture is due to frictional effects regarding to the pipeline wall. As the rupture happens pressure at ruptured point will decrease and this slump in pressure will move through the flow from both sides and these reductions in pressure treat to the flow as some moving expansion waves that advance through the pipe. We call these disturbances as expansion waves because the pressure magnitude before them are less than it's value just after the pressure disturbance. These waves are shown in Fig. 6. at different times before being reflected by the end point of the pipe. Pressure and time steps in all of the figures are nondimensional as the governing equations are solved with dimensionless variables to obtain dimensional values of pressure and time they must be multiplied by the tank pressure and L/a_0 respectively. It can also be seen from fig. 6. that as these waves advance through the pipe their amplitude will be decreased because of frictional effects of the pipeline wall. In Fig. 7. similar disturbances in mass flow are shown. The horizontal line in the figure shows the mass flow before any accidental rupture. It can be inferred from this diagram that after the rupture the mass flow just before the rupture point will increase and it will decrease after the rupture point. These disturbances will also advance through the pipeline with reduction in their amplitude and they will be reflected back from boundaries of the pipe like pressure disturbances. Because all variables involving in the problem are dimensionless, the values of mass flow in the pipe are also calculated dimensionless and can be transformed to their dimensional values easily.

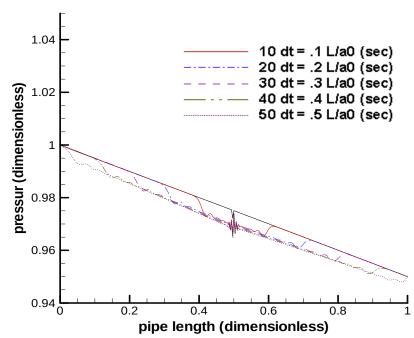

Fig. 6. Pressure disturbance propagation at different times after the rupture before reaching the end of the pipeline

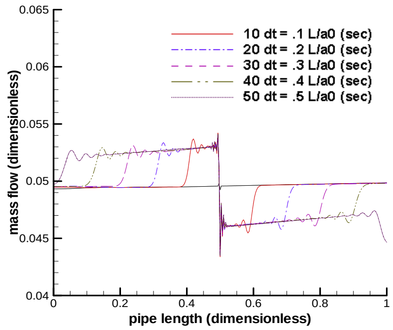

Fig. 7. Mass flow disturbance propagation at different times after the rupture before reaching the end of the pipeline

In figures 8 and 9 we plot pressure and mass flow through the pipe at steady state times respectively. It is inferred from figures mentioned that at the rupture pressure varies continuously but mass flow will drop suddenly. The difference between mass flow before the rupture and after that shows the released amount of mass from the leakage. Fig. 8 also shows that pressure value decreases more rapid before the rupture than after that along the pipeline and the rupture has pushed the pressure curve down at the center where rupture has occurred.

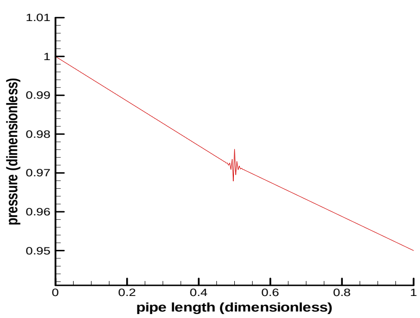

Fig. 8. Pressure values along pipe at steady times

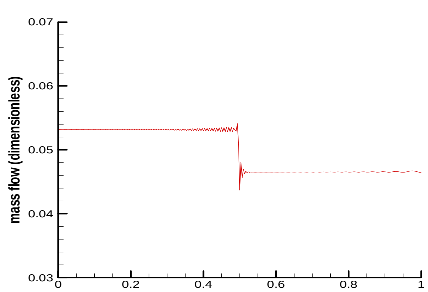

Fig. 9. Dimensionless mass flow values along pipe at steady times

CONCLUSIONS

Some conclusions can be drawn from the results as follows.

1. The release rate is strongly function of the working pipeline pressure and proportion of leakage diameter to pipe diameter and will increase more rapidly at higher proportions.

2. Disturbances in pressure will propagate through the pipeline in both forward and backward side with the same behavior.

3. The amplitude of pressure disturbances will decrease with time because of frictional effects and finally they will be damped completely and the flow will become steady.

KEYWORDS
Wave Propagation, Release Rate, Ruptured Pipeline, MacCormack's Technique

ACKNOWLEDGMENTS
The authors finally thank the Fajr Jam refinery for its great support to implement this work.

REFERENCES

1. Dong Yuhua,Gao Huilin,Zhou Jing,en, Evaluation of gas release rates through holes in pipelines, Journal of Loss Prevention in the Process Industries, 15(2002)423-428

2. Helena Montiel, Juan A.Vilchez, Mathematical modeling of accidental gas release, Journal of Hazardous Materials, 59(1998)211-233

3. J.H.Luo, M.Zheng, X.W.Zhao, Simplified expression for estimating release rate of hazardous gas from a hole on high pressure pipelines, Journal of Loss Prevention in the Process Industries, 19(2006)362-366

4. D.Stojkovic, V.D.Djordjevic, On the effect of friction in steady flow of dense gases in pipes, International Journal of Heat and Fluid Flow, 22(2001)480-485

5. John.D.Anderson, JR, Computational Fluid Dynamics, McGraw Hill, 1995

6. Abdulrahman M.AL. Khomairi, Simulating unsteady pipe flow with a sudden leak event, Kuwait J.Sci.Eng.36 (2B) pp.45-66, 2009

7. Yang-Do Jo, Bum Jong Ahn, A simple model for the release rate of hazardous gas from a hole on high pressure pipelines, Journal of Hazardous Materials A97 (2003) 31-46