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# Mathematical modeling of orifice downstream flow under flow-accelerated corrosion

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## ABSTRACT

The main objective of this paper is to establish an analytical model to evaluate the rate of corrosion in a horizontal pipe downstream of an orifice under flow-accelerated corrosion (FAC). FAC is a major issue causing the wall thinning of carbon steel piping in power plants. In this work, the dimensional analysis was employed using the method of repeating variables and the Buckingham Pi Theorem. It was found that the Sherwood number and the relative distance from orifice are the main dimensionless parameters influencing FAC downstream of an orifice. Concerning the available experimental data, two different cases considered; orifice ratio (OR) of 0.25 and 0.5. The result of mathematical modeling agreed with the experimental data. The maximum value of the FAC rate could be well-predicted for the OR of 0.25, while the location of the maximum FAC rate could be well predicted for the OR of 0.5. It was found that the maximum value of FAC rate increases with decreasing orifice ratio and also the maximum value will be located between 1 and $4d_p$ downstream of the orifice in both cases. This work could be useful for professionals in industry and researchers in the field and could be the starting point for a new way of evaluating the FAC rate downstream of a flow's singularity.

## 1. Introduction

FAC damages have been reported since 1981 (Kastner et al., 1990) but the problem has been brought up after a rupture in a condensate line at the Surry Nuclear Power Plant in 1986 (Petric and Ksiazek, 1997). In 1999, an extensive steam leakage from the rupture of the shell side of a feed-water heater at the Point Beach power plant (USA) was reported (Yurmanov, 2009). FAC is higher in components such as orifices, valves, expansions or contractions, elbows and tees; this is due to an important change in the direction of the flow and instabilities downstream these flow singularities. Several research papers have been published in the recent years to evaluate the metal loss due to FAC in these components, but nothing consistent has been published to develop a practical correlation to evaluate FAC rate downstream of a flow singularity. In June 1987 at Trepan, FAC occurred not only in elbows but also in straight pipes (Kastner et al., 1990). There is also a lack of modeling of corrosion controlled mass transfer near the wall. For predicting the rate of mass transfer between phases in flowing fluids, numerous empirical approaches have been offered. However, a thorough understanding of the fundamental transfer mechanism is necessary for analyzing of a pipe corrosion in single phase flow.

Sydberger and Lotz (1982) analyzed the mass transfer in a turbulent pipe flow using electrochemical measurement. Particular attention was made to the case of flow downstream an orifice. They aimed to link mass transfer and corrosion for disturbed turbulent high flow rate. They stated that acceleration of corrosion attack due to a high flow rate of a liquid medium could be due either to mechanical removal of corrosion products or mass transfer effects. In practice, most corrosion attacks are due to diffusion. An example is the corrosion of carbon steel exposed to natural waters which is due to the flux of oxygen towards the metal/rust surface. Corrosion of Copper alloys at low flow rate has been reported to be dominated by diffusion of copper ions far from the metal surface (Sydberger and Lotz, 1982). Under conditions of a low flow rate protective layer of corrosion products formed and they might be dissolved at high flow rates of the same medium. Formation of the corrosion product is due to mass transfer at the surface of the metal, and the magnitude at the metal-liquid interface is sometimes necessary for the creation of passivating films (Sydberger and Lotz, 1982).

Postlethwaite et al. (1986) stated that metal loss of carbon steel piping carrying slurry was mostly due to corrosion controlled mass transfer of oxygen and that the role of the solid particles was to prevent the formation of the protective layer that reduces the loss rate. The surface roughnesses, as well as an increase in turbulence within the mass transfer layer, were found by Lotz and Postlethwaite (1990) (Postlethwaite et al., 1986) to be the factors governing the mass transfer of oxygen.

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**Nomenclature**

| | |
|---|---|
| $FAC$ | flow accelerated corrosion |
| $CR$ | corrosion rate |
| $Re$ | Reynolds number |
| $Sh$ | Sherwood number |
| $Fr$ | Froude number |
| $Eu$ | Euler number |
| $m$ | meter |
| $s$ | second |
| $u$ | fluid velocity |
| $\rho$ | fluid density with |
| $\mu$ | fluid dynamic viscosity |
| $D$ | mass diffusivity |
| $d_o$ | distance from orifice |
| $d$ | orifice diameter |
| $d_p$ | pipe diameter |
| $\Delta P$ | pressure difference |
| $\Delta T$ | temperature change |
| $g$ | gravitational force |
| $C$ | concentration of species |
| OR | orifice ratio |

Poulson (1999) found factors such as piping component's orientation, piping material and fluid temperature as governing factors of flow accelerated corrosion. On the other hand, mass transfer at the wall, near wall turbulence and wall shear stresses are identified by Chen et al. (2006) as the governing hydrodynamic factors responsible for FAC. Hydrodynamic parameters controlling FAC in two-phase (liquid–gas) flows were found by Kim et al. (2007) to be more complex than for single-phase flows. This is due to the interactions between the liquid turbulence structure and gas phase as well as the phase redistribution. The FAC rate is a function of the mass flux of ferrous ions when the flow effects are important. The mass flux is also function of the mass transfer coefficient (MTC) and variation of the concentration within the boundary layer (where MTC is a strong function of the surface geometry), roughness, flow rate, local turbulence, void fraction (in the case of two-phase flow) as well as physical properties of the transported fluid (Pietralik and Schefski, 2011). Figs. 1 and 2 as well as Table 1 show some examples of FAC in the nuclear power plants which indicate the importance of investigation on FAC.

Pietralik and Schefski (2011), experimentally and numerically investigated the mass transfer in bends under flow-accelerated corrosion; they presented the flow parameters influencing FAC in bends, such as surface geometry.

Nesic and Postlethwaite (1991a,b) analyzed the effects of disturbed flow on erosion-corrosion due to mass transfer using a numerical simulation of turbulent flow in a sudden expansion. Their model was good in predicting the loss rate of carbon steel. They related mass transfer to turbulence near-wall, in the presence of rust films, fluctuations affect both mass transfer and mechanical removal of the film. In a situation where mass transfer drives corrosion, Keating and Nesic (1999) affirmed that wall mass transfer coefficient and corrosion rate could be related to each other. Two-phase liquid-particle flow has been modeled by Keating and Nesic (1999) and they investigated the effects of such a flow on mass transfer in a 180-degree bend. They found a significant effect of the bend orientation on the particle motion. They observed that the maximum mechanical removal of materials was at the extrados on side walls close to the outlet of the bend. Velocity seems to be the most important parameter governing FAC in multiphase flow. This is regarding the work done by Bozzini et al. (2003) who numerically analyzed the effects of a four-phase flow of two immiscible liquids, gas and solid particles on erosion-corrosion. Two-phase steam-liquid flow has been numerically simulated by Ma et al. (1998) in various bend configurations, the predicted critical FAC locations and those obtained from plant measurements were in good agreement. They also found that the critical FAC locations are mostly at pipe bend layout.

Experimental study of FAC degradation in 180-degree bends has been done by Poulson (1999) under single and two-phase air/water flow. FAC was important along the intrados in single phase condition while it was significant along the extrados in the two-phase annular flow. Ahmed (2010) from his investigation of 211 inspection data of 90° elbows in carbon steel of several nuclear power plants, indicated a significant increase in the wear rate of about 70% due to proximity. Four years before Chen et al. (2006) have identified piping elbows as one of the most common components affected by FAC. Flow in 90° bend undergoes changes in the flow direction, resulting in the development of flow separation and/or secondary flows (El-Gammal et al., 2012). A pressure drop along the elbow is created by the secondary flows and increases the wall shear stresses and the flow turbulence near the wall.

This work is based on the application of known mathematical techniques to predict an industrial problem. The practical aim of this works is to improve existing mathematical modeling of flow downstream of an orifice under flow-accelerated corrosion. However, there is no correlation to predict flow-accelerated corrosion after an orifice in the literature while FAC is very important for nuclear power safety. Prediction of the rate and the place of the corrosion after an orifice is one of the important matters in the nuclear industries. In this research, a model has been developed in this regard based on available experimental data.

## 2. Procedure

### 2.1. Non-dimensional analysis of the flow accelerated corrosion downstream of an orifice

We named *FAC rate as CR* ($\frac{mm}{day}$) and from the literatures, CR is a function of the fluid velocity, as the flow velocity increases, so does the FAC rate. The increase of fluid velocity means that the inertial forces are getting larger than the viscous forces henceforth, therefore, one of the important parameters is the fluid velocity. We also include the pipe diameter, fluid density and viscosity along the axial velocity as our parameters governing FAC. CR is also due to the electrochemical reaction occurring at the interface between the metal and oxide layer at the pipe wall which is followed by a chemical erosion that dissolves the aforementioned oxide layer. CR process ends with a mass transfer of the particle to the bulk of the flowing fluid namely water. Therefore, we can consider mass diffusivity, the concentration of oxygen in air, the diameter of the orifice (hydrodynamic factor), the pressure drop due to

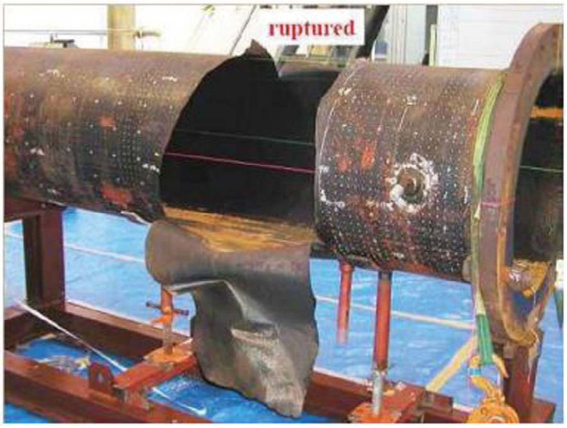

**Fig. 1.** Mihama pressurised water reactor (Uchida, 2006).