CHAPTER II

LITERATURE REVIEW

2.1 Flow-Assisted Corrosion (FAC) of CANDU Feeder Pipe

CANDU reactor is a Canadian-designed Pressurized Heavy Water Reactor (PHWR) which uses heavy water, Deuterium (D_2O), as a moderator and coolant.

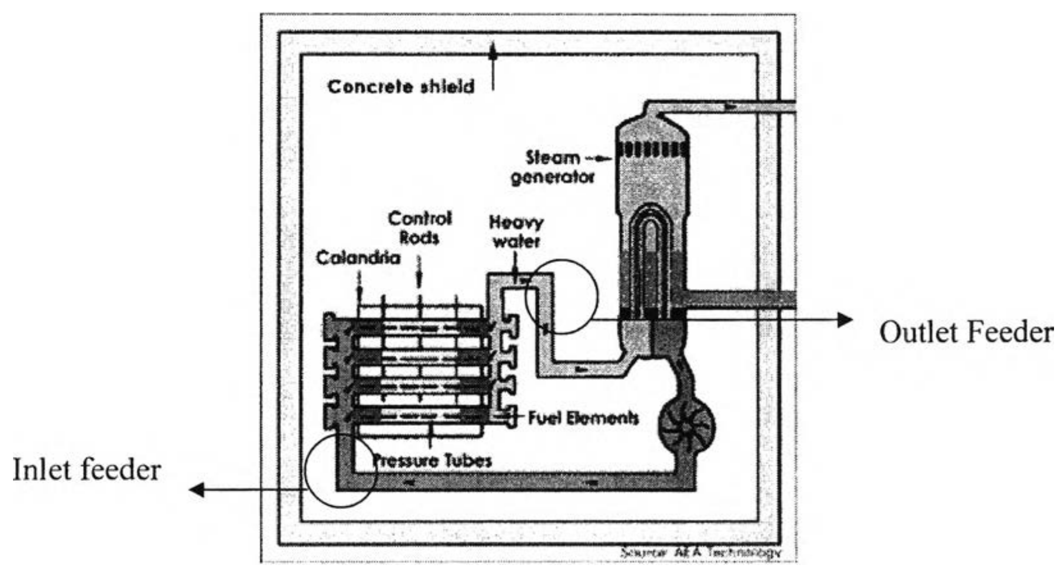

Figure 2.1 Schematic of primary coolant in CANDU reactor

As describe in Figure 2.1, fuel channels are fixed horizontally in a tank called a calandria. Heavy water coolant is pumped through the channels containing the fuel assemblies to pick up the heat generated from the nuclear reaction. Then the coolant moves to the steam generators to produce steam from ordinary water and then returns to the reactor. The heavy water is expensive but it permits the use of natural uranium as fuel.

After the inspection of the outlet feeders at Point Lepreau during 1995-1996 at places close to the reactor face, it was found that excessive thinning of the first few meters of the outlet feeders was widespread due to FAC. Since the discovery there have been many attempts to understand the mechanism of this FAC and correlate the corrosion rate with operating variables. (Lister, 1997)

Flow-Assisted Corrosion (FAC) – sometimes called erosion-corrosion - is a mixture of surface dissolution, which is an electrochemical process, and erosion induced by flow. The outlet feeder is susceptible to corrosion because the temperature of the coolant increases after passing through the reactor core, which causes a higher solubility of the normally protective oxide. The high turbulence within the first few meters after the end fitting promotes FAC.

The thinning rate due to FAC depends on many factors such as coolant velocity, geometry, water chemistry, surface composition, temperature. The accelerated thinning can lead to a scalloped surface which has a distinctive wave-like appearance with a smooth bottom and sharp crests. The scalloped surface supporting a thin oxide layer is observed in many situations involving FAC. Figure 2.2 shows a scalloped surface on the inner surface of a carbon steel feeder pipe.

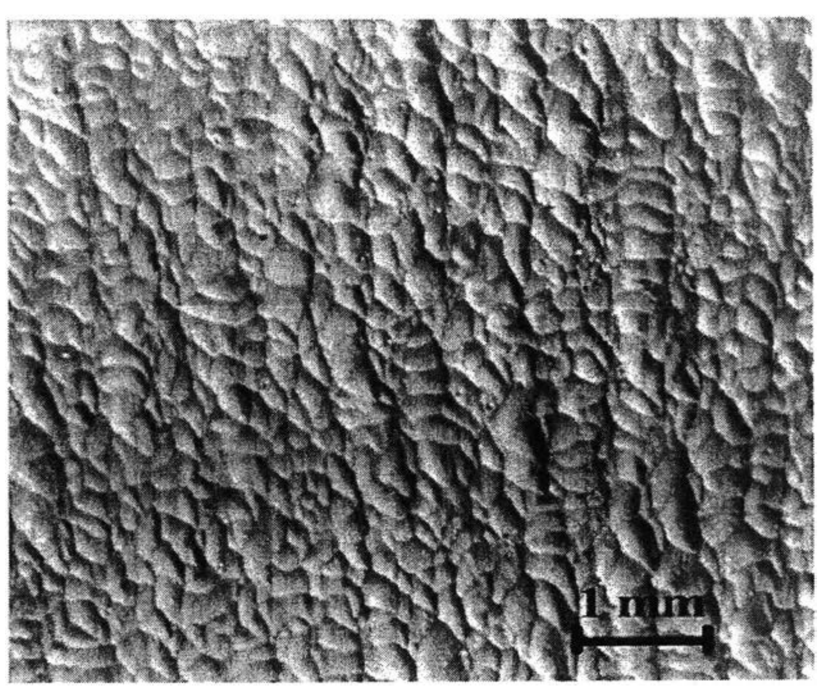

Figure 2.2 Scalloping on the inner surface of a carbon steel feeder pipe (Villien, 2001)

2.2 Scalloping Phenomena

2.2.1 Scallops

Surface scalloping is typical of the attack by FAC of carbon steel. It is also found in the sculpting of clay, mud or rock river beds by fast flowing streams (Allen, 1971). In general, the crest-to-crest spacing is eight times longer than the peak-to-valley height of scallops.

The investigation of the S08 feeder of PLGS at the intrados of the first bend, which was attacked by FAC ,showed that the scallop size are roughly 0.5-0.75 mm across and appear to be in an overlapping pattern that follows the principal direction of the fluid flow. This type of scallop may be initiated by oxide spalling, which is occurring randomly over the surface in small patches. As the corrosion process proceeds, the oxide film is progressively weaker even though the thickness is increased with time. Eventually when fluid shear force overcomes the cohesive force, the spalling occurs. This type of attack can give rise to a scalloped surface. (Lister, 1997)

Villien at el. (2001) found that the individual scallops are initiated at surface defects. They begin upstream and progressively form downstream with characteristics that depend on the flow. The number of scallops increases with the flow rate whereas the average size of a scallop decreases with flow rate. Some defects are erased from the surface after a certain period of time. Only the scallops that are larger than the critical size set by the flow condition remain at the surface. Another important finding is that the rate of dissolution of plaster in a laboratory experiment was found to be proportional to the water flow rate.

Burrill (1998) compared the characteristics of scallops formed on corroded metal with those formed on plaster of Paris. Due to the similar profile, he concluded that the scalloping is the result of hydrodynamic phenomena with little influence from the property of the solid. However, recent research found that different metal compositions may lead to different features of the scallops. More investigation is needed to verify this. (Lister, 2006, private communication)

2.2.2 <u>Geological Study</u>

Since scalloped surface is also observed in the nature such as ice, mud and limestone, some geological studies have been done.

A flute is a two-dimensional (2D), stable periodic dissolution profile resulting from interactions between adjacent turbulences, as shown in Figure 2.3. It is much easier to study the transport properties from a flute rather than from 3D scallop directly.

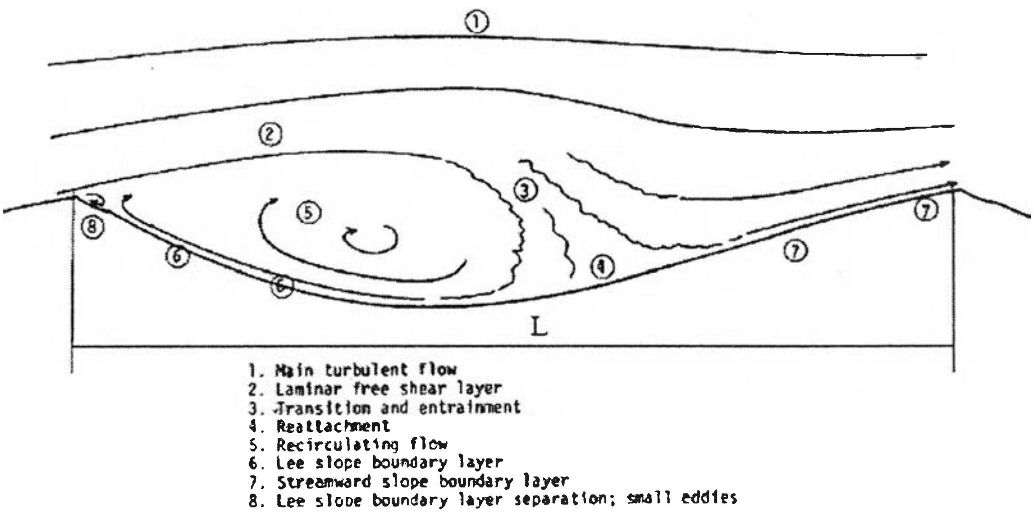

Figure 2.3 Flute hydrodynamics (Blumberg, 1970)

Blumberg (1970) studied the hydrodynamic factors affecting the origin and propagation of a flute. He tried to obtain a stable fluted surface and found that by using a knife to create a series of grooves perpendicular to the flow direction, the stable dissolution profile flute can be created.

When the flow enter the scalloped surface, flow is separated and the recirculation zone is created due to the existant of lamina free shear layer. At a certain distance determined by the flow hydrodynamics, the lamina free shear start to be weak and finally disappear. Since there is no lamina shear layer, the flow then impinge on to the surface at reattachment zone which has the highest corrosion rate. The distance of impingement can determine the size and shape of the scallop.

In 1971, Allen found that flute is generated from the defect on the surface that exceed a certain critical dimension set by flow conditions. The defect then grows larger and become a flute. Figure 2.4 shows its steps of development.

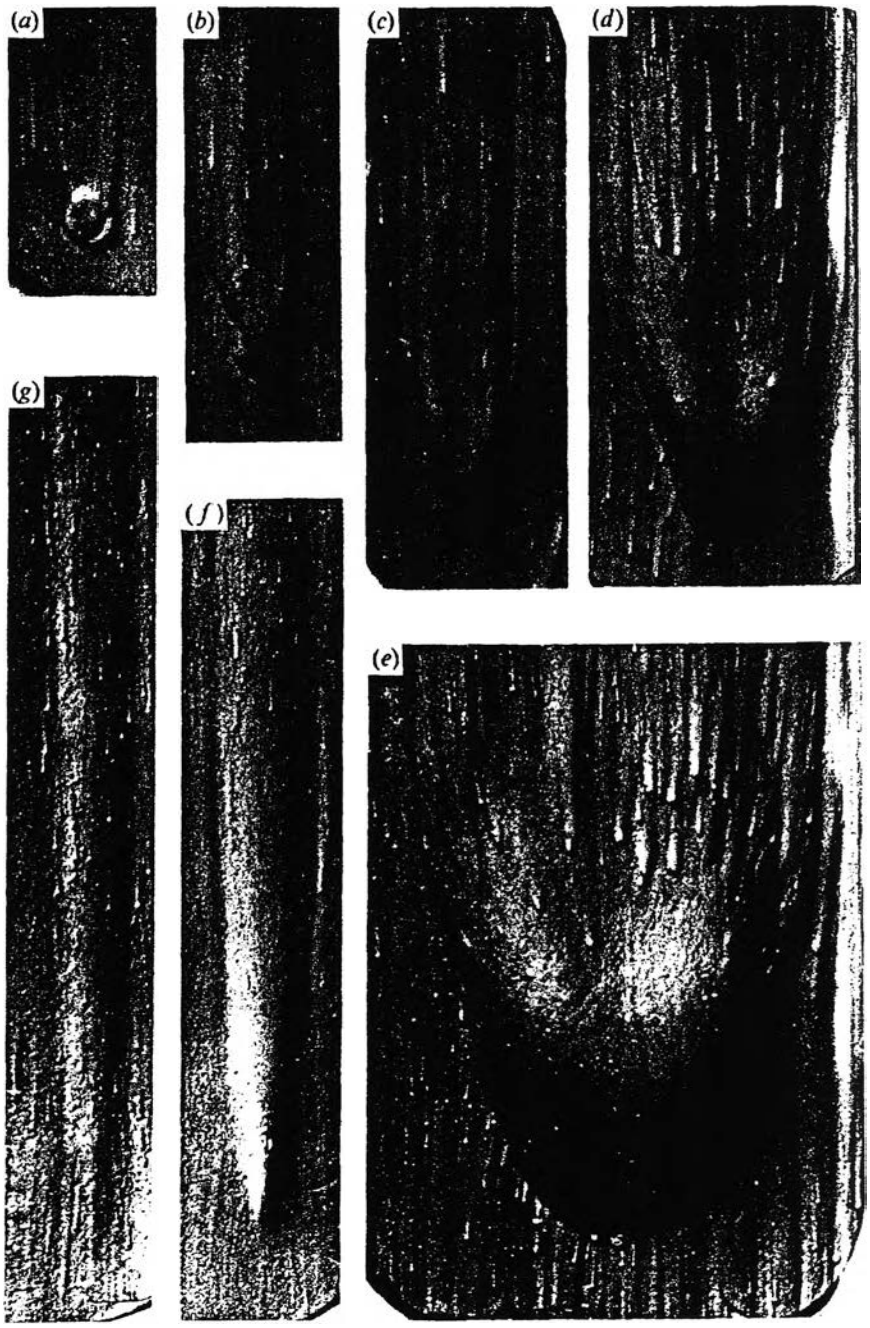

Figure 2.4 Stages in the delopment of experimental Flutes (a-e) and grooves (f), (g) from defects introduced into Plaster of Paris beds Flow from bottom to top. (e) is 10 cm wide. (Allen, 1971)

Flute continue growing and eventually the overlap pattern of flute will give rise to scallop surface. For the defect that doesn't exceed the critical size, it grow initially in length and width to give a long narrow groove lying parallel to the flow but finally be removed from the bed after a sufficient time. The skin frintion of flute is shown in Figure 2.5 (Allen, 1971)

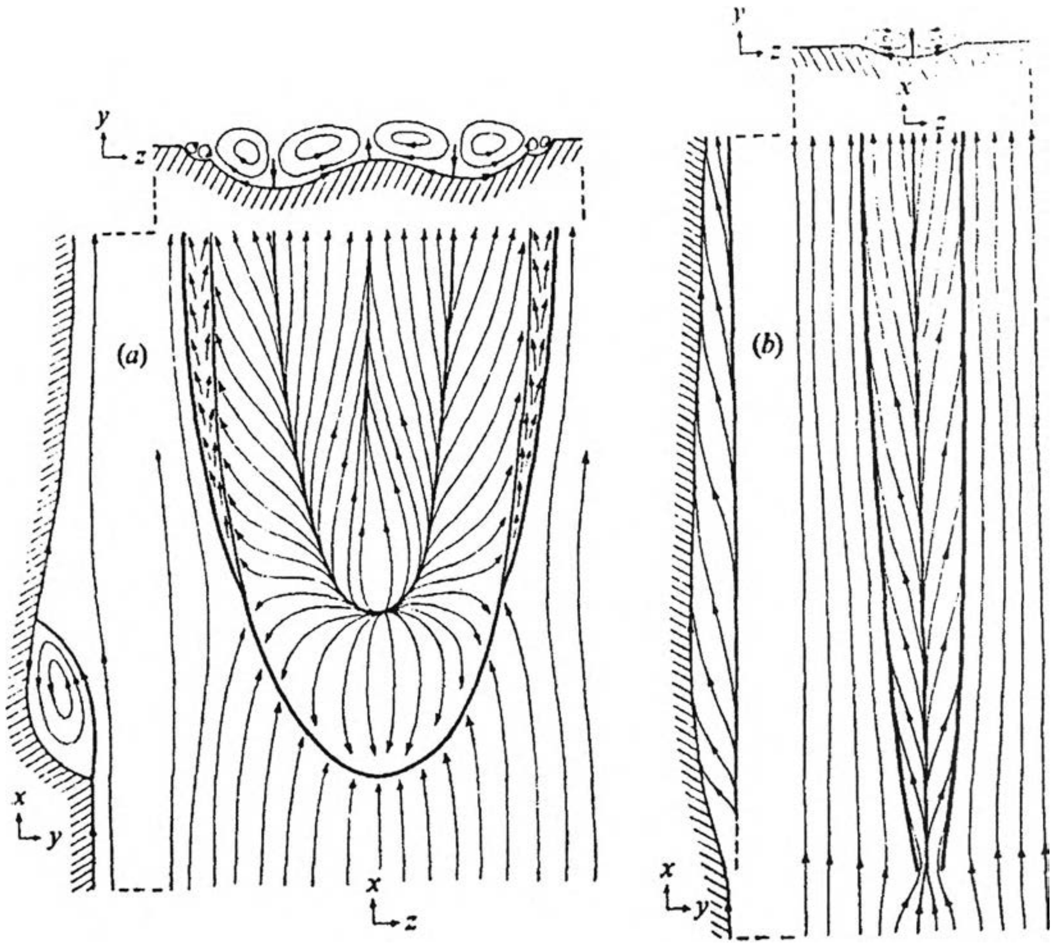

Figure 2.5 Schematic flow fields (skin-friction lines and streamlines associated with (a) mature flutes and (b) mature grooves)

He suggested that separation of flow may be a phenomenon necessary for maintain of scalloping and in the case of flute, perhaps also for their origin.

Blumberg and Curl (1974) found that there is a stability wavelength Reynolds number for flute stability, which is about 23000 (Blumberg and Curl, 1974), which agrees with the value obtained from ice and limestone. They suggested that the number 23000 could be a universal Reynolds number for an equilibrium erosional surface. Such a Reynolds number means that the type of surface material and the dissolution rate will not affect the scalloped surface characteristics. Recently, a further study showed that the idea of universal wavelength Reynolds number doesn't apply to a metal corroding surface. (Private Communication , Lister, 2006)

2.3 Roughness and Pressure Drop

Yong Shao (2006) studied the effects of scalloping on pressure drop. The result is shown in Figure 2.4.

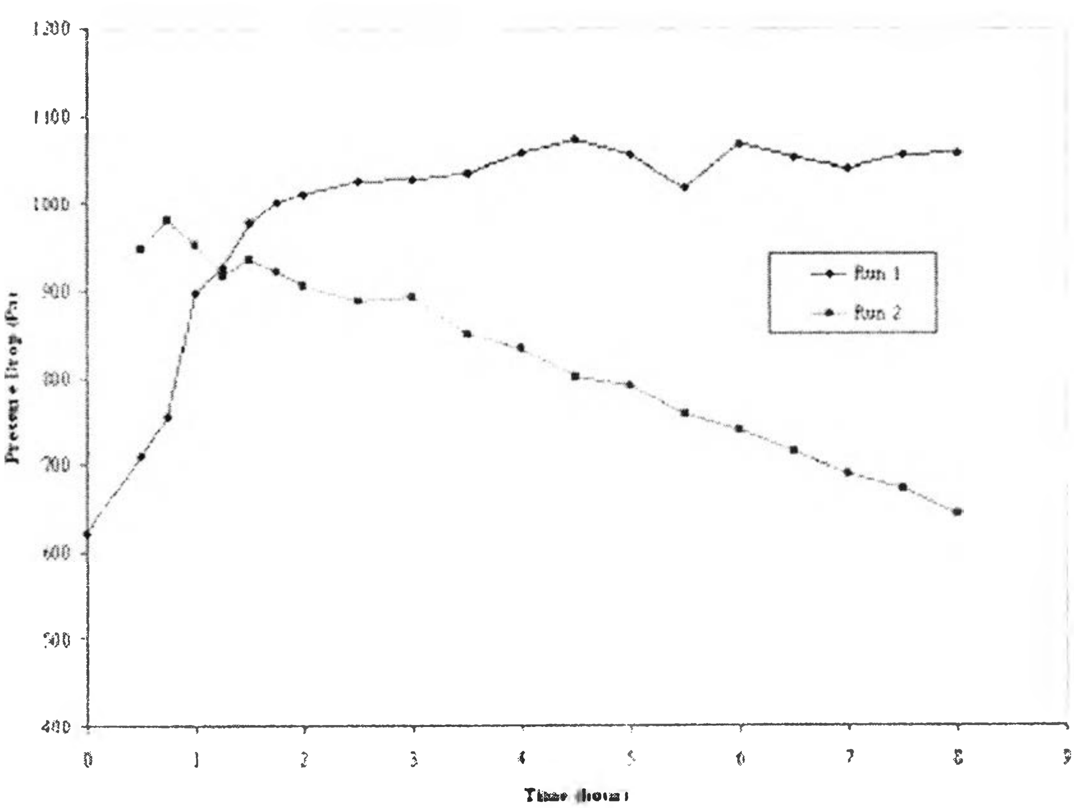

Figure 2.6 The pressure drop vs. time (Yong 2006)

These two runs used the same operating conditions with different types of surface material. Run 1 used pure plaster of Paris as a surface while Run 2 used commercial plaster of Paris containing many impurities such as sand.

When scalloping was developing, the surface of Run 1 seemed to be stable but the surface seemed to be smoother in Run 2. Further experiments are needed to obtain a more comprehensive understanding of the surface behavior.

Yong Shao (2006) also proposed that if the scalloping can make the surface smoother, a scalloped surface could be the best candidate to give the highest ratio of k/f (mass transfer coefficient to friction factor) for a given roughness height. This highest ratio can make the scalloped surface a potential choice for industry that desires a high mass transfer with a low pressure drop.

2.5 Computational Fluid Dynamics (CFD) and Viscous Model

The CFD software used in this study is FLUENT 6.0. FLUENT is a world-wide provider of commercial computational fluid dynamics (CFD) software and services. The software is capable of modelling fluid flow in complex geometries. It provides complete mesh flexibility to maximize the efficiency of creating complex geometry.

2.3.1 Simulation Procedure

The simulation consists of six main steps:

1. Define the modelling goals.
2. Create the model geometry and grid.
3. Set up the solver and physical models.
4. Compute and monitor the solution.
5. Examine and save the results.
6. Consider revisions to the numerical or physical model parameters.

These steps can be divided into three parts. Steps 1 and 2 are in pre-processing part. In this part, the purpose of the simulation should be properly defined. The grid of any geometry that we study is meshed in this step and made ready to be read into the solver. GAMBIT software which comes with the FLUENT package is used for grid processing.

The solver part, consisting of steps 3 and steps 4, is about solving, computing and monitoring the solution. The Solving parameters can be defined in this part. The number of iterations can be specified and the convergence of the computation can be monitored.

The last part is post-processing, steps 5 and 6. In this part, the result will be displayed graphically by many tools. That grid and model can be adapted to improve the quality and accuracy of the results. Since every step is important to the accuracy and reliability of the results, a good understanding of the problem and the program are beneficial.

2.3.2 Turbulence Viscous Model

Turbulence is characterized by fluctuating velocity fields. Viscous models are used to decrease the computational expensive by removing small fluctuation using time-averaged, ensemble-averaged, or otherwise manipulated to remove the scales. In some situation, the choice of viscous model can significantly change the solution. It is benefit to use the appropriate model for specific type of problem.

Since, there is no universal turbulence viscous model, the capability and limitation of the model need to be understood. The turbulence models are listed below.

- Spalart-Allmaras model
- k-ω models
    - Standard k- ω model
    - Shear-stress transport (SST) k-ω model
- k-ε Models
    - Standard k- ε model
    - Realizable k- ε model
    - Renormalization-group (RNG - k-ε Model)
- v^2 - f model
- Reynolds Stress Model (RSM) model
- Detached eddy simulation (DES) model
- Large eddy simulation (LES) model

Due to their high computational cost but no guaranteed for better results, RSM, DES and LES are not used in this work. Spalart-Allmaras model and V^2 – f model are normally used for quick and rough simulation in specific type of problem. Since high accuracy is needed, these two models are not used. Standard model of k- ε and k-ω model are proved to be less superior to the modified one. The models to be tested in this work consist of 3 models below.

1) Shear-stress transport (SST) k-ω model
2) Realizable k- ε model
3) RNG - k-ε Model

The results are proposed in chapter 4.