論文の内容の要旨

論文題目　「Hydraulic Analysis of Liquid Droplet Impingement and Flow-Accelerated Corrosion in Nuclear Power Plants」
(原子力発電プラントにおける液滴衝撃エロージョンおよび流れ加速型腐食の流体解析)

氏名　　熊　進標

More than half of the operating nuclear power plants in Japan are the light water cooled reactor built in the 1970s and 1980s. After more than three decades of operation, the ageing components in these nuclear power plants starts to appear as a problem and the ageing issue is becoming one of the most important issues in the nuclear industry in Japan. The proper ageing management or maintenance is demanded to ensure the safety during operation and to avoid the unplanned outage of the plant. Ageing issues of nuclear power plants is not only appearing in Japan but also in other nuclear developed countries, such as the United States. The huge and complicated system of the nuclear power plant determines that the ageing issue has to be watched for many components. Among the components the piping consists of a large portion of the plant system and the incidents caused by piping degradation are frequently reported. Two accidents, i.e. the Surry-2 accident in the U. S. (in year 1986) and the Mihama-3 accident in Japan (in year 2004), were resulted from the rupture of degraded piping and caused fatal injuries. The observed piping degradation is regarded to be initiated or accelerated by the dynamic processes in the flow carried by the piping. The two processes studied in this thesis, liquid droplet impingement (LDI) and flow-accelerated corrosion (FAC), are among these processes.

In the nuclear power plant liquid droplet impingement (LDI) occurs in the piping carrying the high-quality two-phase flow where the steam entrains massive small droplets. When the flow is experiencing the abrupt change of velocity, the droplets do not exactly follow the change in the steam. Hence, the droplets can impact on the piping wall. The high-velocity droplet impact exerts significant mechanical loads on the piping inner surface. When the velocity is sufficiently high, damage can be resulted from a single impact. However, this is unusual in the piping system of nuclear power plants where the LDI damage is believed to be produced by massive impingement instead. Not all the impacts can produce damage. It is argued that there is virtually a threshold impact velocity only above which LDI damage is possible. The flow conditions that allow for the occurrence of LDI can usually be found in the piping from the low-pressure turbine to the condenser and the drain piping of the pre-heaters. The LDI damage is usually observed as local pitting or pinholes at the elbow, orifice or valve.

The evaluation of the mechanical load caused by LDI is an important step to understand the LDI damage mechanism and to predict the damage rate. A variation of the Moving Particle Semi-implicit (MPS) method, the MPS-AS method, is applied to simulate the single droplet impingement and to investigate the mechanical load induced by the droplet impingement. The simulation of the high-velocity impingement has been challenging because it involves both the simulation of free surface deformation and the shock generation and propagation. The MPS-AS method which inherits the capability of simulating the large deformation of free surface and holds the capability to capture the shock wave is utilized in this investigation. In the past, the evaluation of impingement pressure load has been based on the correlations. The different correlation may attempt to feature the different stage during the impingement. Beside the impingement phenomena, the numerical simulation also contributes to evaluate the major existing correlations for the impingement pressure load. The current correlations are only valid for simple impingement case. For even more complicated impingement scenario, the numerical simulation becomes the basis for the development of the new correlation. Compared with the prediction by the correlations, another advantage of the numerical simulation is that it enables the detailed study of the pressure load history which may also important to understand the damage process. The final interest of the investigation of LDI is the prediction of the damage rate caused by LDI. This investigation attempts to correlate the damage rate with the pressure load.

In the flow-accelerated corrosion, the corrosion or metal oxidation occurs on the interface between the base metal and the oxide layer. The oxidants have to diffuse through the oxide layer before they can oxide the metal. Thus the oxide layer normally protects the metal from oxidation by separating it from the oxidants. When the mass transfer between the corroded surface and the bulk flow is enhanced by the flowing stream, the concentration of metallic ion species near the surface may be reduced below its saturation value and the dissolution of the oxide layer starts. The oxide layer becomes thinner and less protective, and the corrosion rate increases. Eventually a steady state is reached where the corrosion and dissolution rates are equal and stable corrosion rates are maintained. FAC can occur in the piping carrying the single- (water) and two-phase (water/steam) flows.

In the hydraulic analysis for the flow-accelerated corrosion the turbulent mass transfer is the most important issue to be looked after. Currently, the mass transfer in the analysis of flow-accelerated corrosion is considered either with the empirical correlation or the models developed based on the empirical correlation. These models are always questionable on its physical foundation. This investigation attempts to provide the reliable and low-cost turbulence model which can be applied in the three-dimensional computation for the large-scale systems. The mass transfer in the flow-accelerated corrosion is characterized by the high Schmidt number due to which the apparent concentration variation is expected to appear in the vicinity of the wall. And the turbulence modeling at the wall has been a challenging task for a long time, especially when we need to handle the complex flows. With the aid of the DNS data, the development of the low Reynolds number models prosperous blossomed in the 1990s. Low Reynolds number models have been regarded to be advantageous in the turbulence modeling at the wall. There have been hundreds of variations of low Reynolds number model which are not possible to be tested for all. The models are selected based on the reported performance in the separated and reattaching flows, which is the important flow type leading to the mass transfer enhancement in the piping system of nuclear power plants. The low Reynolds number models demands the fine resolution near the wall, which can be a barrier preventing it from applying in the large-scale systems. Hence, the high Reynolds number models and wall functions are also surveyed and evaluated in this investigation. The evaluation is conducted in several flow geometries, the fully developed pipe flow, the backward-facing step flow and the flow through an orifice. The latter two are the typical flows with separation and reattachment. Especially, the flow through an orifice is the geometry leading to the Mihama-3 accident.

Above is the main content included in this thesis.