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ASSESSMENT OF THERMAL FATIGUE IN MIXING TEE BY FSI ANALYSIS

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Thermal fatigue is a significant long-term degradation mechanism in nuclear power plants. In particular, as operating plants become older and life time extension activities are initiated, operators and regulators need screening criteria to exclude risks of thermal fatigue and methods to determine significant fatigue relevance. In general, the common thermal fatigue issues are well understood and controlled by plant instrumentation at fatigue susceptible locations. However, incidents indicate that certain piping system Tee connections are susceptible to turbulent temperature mixing effects that cannot be adequately monitored by common thermocouple instrumentations. Therefore, in this study thermal fatigue evaluation of piping system Tee-connections is performed using the fluid-structure interaction (FSI) analysis. From the thermal hydraulic analysis, the temperature distributions are determined and their results are applied to the structural model of the piping system to determine the thermal stress. Using the rain-flow method the fatigue analysis is performed to generate fatigue usage factors. The procedure for improved load thermal fatigue assessment using FSI analysis shown in this study will supply valuable information for establishing a methodology on thermal fatigue.

KEYWORDS : FSI(Fluid-Structure Interaction) Analysis, Mixing Tee, Thermal Fatigue, Thermal-hydraulic Analysis, Piping System, Turbulent Flow

1. INTRODUCTION

One important aspect on ageing management of nuclear power plants (NPP) is the monitoring and assessment of thermal fatigue [1]. The strong linkage of the long-term degradation mechanism to actual plant conditions, rather than to design assumptions, reveals that its evaluation is a key issue of on-going safety assessments. Thermal fatigue damage and fatigue usage factors need to be carefully monitored and evaluated to ensure continuous safe and economical operation of ageing components and structures.

However, the Civaux 1 failure and comparable incidents reveal that certain piping system Tee connections are exposed to thermal fatigue arising from low- and high-cycle temperature turbulences. Inservice experiences show that thermal fatigue cracks may occur arbitrarily in different locations, e.g. welds, base material, straight pipes, elbows, and under rather different loading conditions. These cracks are usually explained by thermal stratification and temperature mixing effects caused by different mass flows in “run” and “branch” pipes at the Tee-connection.

Potential consequences are surface stresses, crack initiation, stresses in the wall or crack propagation. Even though this problem is well known, high cyclic phenomena may not be properly detected by common thermocouple instrumentation and, thus, integrity evaluations rely on estimations and boundary conditions. These approximations may not cover the entire loading conditions and material behavior and, therefore, lead to either too conservative or to not conservative results. Both ways are not acceptable for applications on NPPs, i.e. current fatigue assessment methods have to be adjusted to cover this specific thermal fatigue issue. In particular, the determination of lower not fatigue relevant threshold values in terms of temperature differences, is important for practical plant related applications.

The European Commission funded the international project “thermal fatigue evaluation of piping system Tee-connections” which was launched as a 3-year project with the main objectives to advance the accuracy and reliability of thermal fatigue load determination in engineering tools and to formulate research oriented approaches to outline a science based practical methodology in managing thermal fatigue risks [2].

Therefore, in this study the thermal fatigue evaluation of piping system Tee-connections is performed using fluid-structure interaction (FSI) analysis, addressing the present demand on optimized and verified application procedures for assessing the integrity and safety of Tee-configurations in safety relevant NPP-systems sustained to significant turbulent thermal stratification and temperature mixing effects. The results will supply valuable information for plant operations and ageing management by improving the confidence in integrity assessments of relevant components, leading to advanced system surveillance with a consequent reduction of operator dose and to an improved cost effectiveness of the NPP.

2. THERMAL LOADING

2.1 Turbulent Loads

Turbulent mixing of hot and cold water is characterized by rapid and highly irregular fluid motions. These fluctuations will increase the transfer of energy and momentum as well as the heat convection transfer rate. Turbulence is associated with random fluctuations and the fluid motion occurs on several length scales. Generally, this makes the fluid motion extremely difficult to describe in detail. In the context of turbulent or mixing the description of eddies are used. Eddies are small portions of fluid in irregular motion that exists for a short time before losing its identity. The temperature fluctuations near the pipe wall can be of the order of up to several Hz.

In turbulence the inertia forces are high in comparison to the viscous forces in the fluid. A common measure for this relation is the dimensionless Reynolds number. High Reynolds numbers will indicate higher levels of turbulence in comparison to organized laminar flow. The Reynolds number can be seen as a measure of the ratio between inertial forces and viscous forces. As a rule of thumb, $Re > 2000$ can be used as a criterion for the onset of turbulent flow in a pipe.

2.2 Damage Cases

Several recent studies have considered damage due to thermal fatigue in light water reactor components, with a particular focus on those cases resulting in leakage. The NESC failure database could be employed to examine the parameters governing thermal fatigue in nuclear components [3].

The failure cases examined essentially fall into two groups, as observed in other thermal fatigue studies [4]. In the first group the loading is characterized by turbulent mixing (or striping), with or without stratification. Typical components affected by this process are tees without internal mixers. It is noted that none of the through wall cracking cases can be attributed to turbulence alone. However, the observed damage is not just superficial, and cracks penetrating to more than 50% of the wall thickness were observed in a few cases. In the second group the thermal loading is predominantly stratification. Damage caused by stratification appears much more likely to cause leakage, and almost all the cases of through-wall cracking referred to in the present report are associated with this phenomenon. The damage occurs at much lower flow rates than in the turbulent case. The combination of a low flow rate in at least one of the fluids and a high temperature difference controls the damage evolution. It is clear that different forms of stratification exist, the most harmful being the case with a moving interface between a stratified and a non-stratified state.

No case of component rupture was found and any crack growth seems to have been stable up to the point it was detected.

2.3 Problem Definition

A shutdown cooling system is connected to the reactor coolant system in parallel to eliminate the decay heat during plant shutdown, taking coolant in the hot leg and circulating it into the cold leg. This system for Ulchin 3 and 4 starts to operate when the coolant temperature is 177ºC and its pressure is 3 MPa until the temperature becomes 60ºC with a cooling rate of 41.7 ~ 16.7ºC/hr.

The area to be analyzed in this study is the mixing tee area where the main pipe conveying high temperature coolant meets the branch line pipe carrying low temperature coolant passing through the heat exchanger (Figure 1). In this area, the thermal fluctuation and/or stratification appears due to the high-low temperature mixing flow, which causes thermal fatigue.

The dimensions and operating conditions considered in this study are summarized in Table 1.

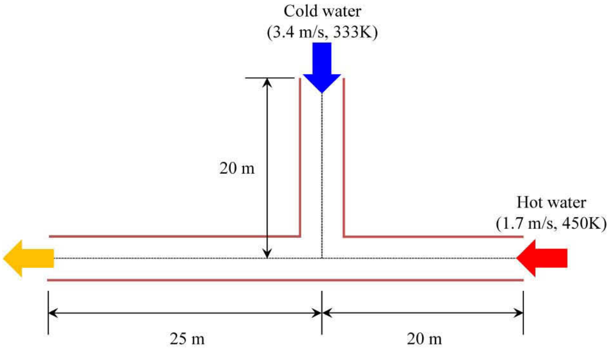

Fig. 1. Layout of System for Analysis

Table 1. Dimensions and Operating Conditions

	Outside diameter (mm)	Inside diameter (mm)	Coolant temp. (K)	Flow velocity (m/s)
Main pipe (Hot water)	273.05	242.926	450	1.7
Branch line pipe (Cold water)	273.05	242.926	333	3.4