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Piping System Response Induced by Thermal-Hydraulic Transient: a Review of Recent Analysis Methods and Experiments

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ABSTRACT

Complete thermal-hydraulic and structural dynamic response analysis of piping systems subjected to a thermal hydrodynamic transient, such as a safety/relief valve (S/RV) opening, is a complex multi-step process. The four links of this analysis chain are thermal-hydraulic analysis, mechanical loads calculation, structural dynamics analysis, and transient thermal stress analysis. This paper presents summaries of the individual analysis steps, guidelines for the performance of these analyses, and a review of recent experimental versus analytical prediction comparison studies. Finally, research needs are discussed.

1.0 INTRODUCTION

Prediction and evaluation of piping system dynamic and thermal stress response induced by a thermal-hydraulic transient are complex multidisciplinary processes. A complete and accurate evaluation contains four links of the analysis and evaluation chain: thermal-hydraulic analysis, mechanical load calculation, structural dynamics analysis, and transient thermal stress analysis. Each link of the chain contains uncertainties and potential errors due to inaccuracies of: (a) description of the physical system and initial conditions, (b) limitations of the representative governing equations, (c) generation of a consistent mathematical model, (d) algorithms and solution processes used, and (e) correct utilization or interpretation of results. In addition, due to the multidisciplinary nature of the task, potential communication problems may occur. Thus, complete and accurate analyses of the subject mechanical systems must be carefully planned, the important parameters thoroughly understood, and the solution process accurately performed.

The primary purpose of this presentation is to outline and briefly discuss those factors which are necessary for meaningful prediction and evaluation of piping system dynamic and thermal stress response induced by thermal-hydraulic transients, exclusive of water hammer (subcooled hydarulic transients). A particular example of this is safety and relief valve (S/RV) discharge induced piping response.

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2.0 THERMAL-HYDRAULIC ANALYSIS

The purpose of thermal-hydraulic analysis, for piping system design analysis, is the accurate prediction of those quantities necessary for realistic evaluation of the safety of the system. In particular, time dependent fluid temperatures and forces acting on the pressure boundary are required as input to additional analyses for the final design safety evaluation. The thermal-hydraulic evaluation of a piping system subjected to a transient, such as S/RV opening, is a complex process which requires extensive theoretical background and practical experience relating to two-phase thermo-hydrodynamic processes. The following paragraphs outline some of the more important topics that should be considered in thermal-hydraulic analyses of piping systems.

2.1 Computer Codes

A number of codes have been developed for general and special purpose thermal-hydraulic analysis. three of the more general and widely used code families are RELAP, TRAC, and DAPSY. Of these, the RELAP series is the most widely used for general two-phase thermo-hydrodynamic applications and will be used as a basis for further discussion. In particular, RELAP5/MOD1 appears to be most applicable to system analysis where transient initiation is similar to S/RV opening.

2.2 Application Guidelines

Since a comprehensive study of all factors involved in thermal-hydraulic analyses is outside the scope of this discussion, only those topics which are particularly important are presented herein. References 1, and 2 present thermal-hydraulic concerns as applied to S/RV systems. In addition, Reference 3 outlines those factors, relating to the use of RELAP5/MOD1 for S/RV system modeling, which were found to be important from many experimental versus analytical studies. This outline is summarized as follows:

1. System modeling: The piping system should be represented by straight segments between the midplanes of consecutive elbows. The path length should be maintained. Segments about two feet in length should have six to eight volume nodes. Segments from two to five feet in length need about ten nodes. Segments from five to ten feet need about twelve nodes. Longer pipes are unlikely but need no more than twelve nodes. Node segments should not be smaller than 0.25 feet.

2. Initial Conditions: Since downstream hydraulic forces are proportional to the initial downstream fluid density when piping heat transfer is not considered and, since leakage through the valve resulting in the downstream fluid being saturated steam is possible for non-loop-seal geometries, a reasonable initial quality should be assumed. Collection points for pools or slugs are possible and should be modeled as liquid-full unless drains are present. For loop seal geometries, since valve simmering prior to pop is likely if the loop-seal liquid is subcooled, liquid should be transported downstream assuming a constant enthalph process. Liquid should be distributed in the first few downstream cells with vapor assumed in remaining piping if sufficient vapor is generated based on the assumed process and upstream mass.

3.0 MECHANICAL LOADS DETERMINATION

Utilization of the thermal-hydraulics output for the determination of time-dependent mechanical loads is the link of the overall system analysis which is, at this time, the least systematized of the individual analysis processes. To circumvent this problem, the mechanical load determination process must be well planned, considering both thermal-hydraulics and structural response requirements, in advance of any calculational effort.

Two general formulations are used for mechanical loads determination: force balance and momentum balance. The first of these, the force balance method, equates resultant force transmitted from fluid to structural element as the sum of all pressure and frictional tractions acting on the wetted surface of the element. The momentum balance method equates resultant force on the element to the time rate of change of fluid momentum within a control volume. The following paragraphs briefly discuss these methods and present potential advantages of each method.

3.1 Force Balance Method

Many computer codes have been developed for force balance conversion of hydrodynamic output to time-dependent mechanical loads--one of which, designed for RELAP5/MOD1 output, is described in Reference 4. An advantage of the force balance method is that it is inherently stable due to the absence of time derivitives. In addition, it is relatively easily implemented due to its heavy dependence on pressure which is a principal variable of most hydrodynamic codes.

3.2 Momentum Balance Method

References 4 and 5 describe computer codes that have implemented the momentum balance procedure for determining mechanical loads acting on piping systems. Briefly, the momentum balance equation results in a three term expression representing force on a given control volume. One term is the time rate of change of mass acceleration within the control volume which has been termed the "wave" or "acceleration" force. The other two terms involve pressure and momentum flux integrated over the inlet and outlet surfaces of the control volume. The pressure contribution to these terms has been termed "blowdown force". An advantage of the momentum balance method is that all quantities required for computing force are usually contained in the hydrodynamic code output.

3.3 Modeling Guidelines

Due to dependence on system geometry, initial conditions, and codes used for piping system transient analyses, few general guidelines can be given. However, at locations where area or flow direction changes occur, obviously forces may be developed and the thermal-hydraulic model must be defined such that these forces may be accurately calculated. Particular attention must be paid at locations where the flow may become complicated such as at valves and tees. Another consideration, which may depend on the method of load calculation used, is convergence. In some cases, the load calculated may vary greatly depending on the time step chosen for the thermal-hydraulic analysis, even though the hydrodynamic results are stable.

4.0 STRUCTURAL RESPONSE ANALYSIS

Many computer codes may be used for the structural response prediction of piping systems subjected to hydrodynamic transient induced force histories. Among these are SAP IV, NUPIPE II, ADINA, and ANSYS. Utilization of most structural dynamics codes requires consideration of the following: (a) proper conditioning of input force data, (b) determination of the computational method to be used (direct integration of coupled equations of motion or modal superposition), (c) in the case of modal superposition, determination of the highest frequency to be considered, and (d) mathematical modeling considerations to ensure that forces are correctly applied and the model correctly includes boundary conditions and sufficient detail so that the highest frequencies of interest are accounted for. The following paragraphs briefly discuss some of the specific factors that must be considered in each of these areas.

4.1 Input Force Data Conditioning

Most thermal-hydraulics output histories and, hence, load histories are represented with unequal time steps. In fact, the time steps may vary from microseconds to milliseconds. Since many structural dynamics codes accept input loads defined at equal time intervals or at only a limited number of unequally defined time steps, it is often necessary to further process force histories to render them compatible with the structural response code utilized.

4.2 Solution Algorithm Determination

Two methods of solution of the governing structural equations of motion are available: direct integration of the coupled equations and modal superposition method. In the case of direct integration, little more need be said at this time. Use of the modal method offers significant computational time savings for some analyses. However, as outlined in Reference 6, utilization of the modal superposition solution method for systems subjected to hydrodynamic loads requires caution. One must assure that the frequencies of the modes included in the analysis envelope the frequency content of the input loads. The upper limit of significant input frequency content is normally about 100 Hz. It has also been demonstrated in Reference 6 that a pseudostatic high frequency response component must also be included in the modal superposition solution to avoid significant errors in the total response. The integration time step should be chosen, for either direct coupled equation integration or modal superposition, so that integration errors for the highest frequency of interest are acceptably small. The theoretical largest integration time step is 0.5/(highest frequency of interest). However, it is common practice to limit the time step to be equal to or less than 0.1/(highest frequency of interest). This results in acceptable integration errors for the higher frequencies and correspondingly lower errors for the lower frequencies.

4.3 Modeling Considerations

One of the most important considerations in modeling the structure is that boundary conditions (piping supports and associated structures in the case of piping systems) be correctly represented. Supports present the most significant nonlinearities in a piping system. If significant nonlinearities are present (gaps, hysteresis, etc.), then a more accurate nonlinear solution must be utilized or the conservatism of a linear analysis must be demonstrated. Model nodes capable of transmission of the external forces to the structure must be present at area changes, elbows, and tees. Some codes, such as NUPIPE II, allow for the definition of both structural connectivity nodes and mass point nodes. In this case, it is important that it is realized that some types of node points (structural connectivity only) do not allow for the input of external forces. Finally, the length of piping elements, specified between adjacent nodes, must be small enough to ensure that the structural response frequencies are greater than the input force significant frequency content. A common recommendation is to place the mass points no more than 1/4 wavelength apart at the highest frequency of interest. This length may be computed by assuming the pipe to behave as a simple beam with a standing wave of the limiting frequency.

5.0 EXPERIMENTAL STUDIES

The Three Mile Island-2 (TMI-2) incident provided reasons for an increased emphasis within the nuclear power industry for more detailed standards and experimental programs relating to S/RV discharge thermal-hydraulic transients and resulting attached piping system response. Within this section, some of the more pertinent experimental programs are reviewed.

The TMI-2 incident prompted issuance of a series of U.S. Nuclear Regulatory Commission Regulatory Reports which required the nuclear power industry to experimentally demonstrate operability of power operated relief and safety valves. The Electric Power Research Institute (EPRI) instituted a research program which resulted in a large number of valve tests and, in addition, approximately 116 tests of pressurized water reactor S/RV systems (with and without loop-seals, steam, steam-water, and water). These system tests were conducted at the Combustion Engineering test facility. Results of some of the tests have been analyzed and/or compared with corresponding analysis predictions.

A series of 29 relief valve discharge tests was conducted at the Kuosheng BWR-6/ Mark III Nuclear Station where the reactor was operating at 60% power. The test series consisted of single, consecutive, multiple, and extended valve actuations. Partial results and selected analysis comparisons concerning these tests may be obtained in Reference 8 and 9.

The Federal Republic of Germany conducted a series of tests at the decommissioned Heissdampfreaktor (HDR) facility termed "German Standard Problem No. 4". This system consisted of pressure vessel, primary piping, check valve, and rupture device. Although the tested system is not a conventional S/RV system, the thermal-hydraulic transient is analogous to a typical S/RV system transient. Results of analytical versus experimental thermal-hydraulic and structural response comparisons are given in References 10 and 11, respectively.

6.0 SUMMARY

Summaries of those factors which are believed to be important for accurate thermal-hydraulic transient induced piping system response analyses have been presented. It has been shown that a complete system analysis is a complex multidisciplinary process involving several distinct analysis and evaluation steps. Perhaps the weakest link in the analysis chain is the utilization of hydrodynamic results for the prediction of mechanical load histories for subsequent input to structural dynamic response analysis.

A brief summary of recent experimental and analytical studies relating to S/RV system thermal-hydraulic and structural response has been given. A relatively large number of experimental results are available with relatively few corresponding analytical comparisons. The comparisons that have been cited are, generally, not in "good" agreement with tests. Additional indicated research is that a comprehensive evaluation of these comparisons be undertaken so that a unified and more quantitative understanding of the ability to adequately perform piping system analyses is obtained.

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