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One- and two-dimensional standing pressure waves and one-dimensional travelling pulses using the US-NRC nuclear systems analysis code TRACE

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ABSTRACT

A variety of nuclear system transients can lead to rapid and large local pressure changes that propagate along the hydraulic system at the speed of sound, both in single phase and in two-phase fluids. Because of the relevance for safety issues, nuclear system codes like TRACE need to be assessed with respect to their capabilities to predict pressure wave behaviour. Therefore, we have analyzed the propagation of pressure waves in one-dimensional and two-dimensional configurations, i.e. a pipe and a slab, filled with liquid water. The pressure waves are driven by one-sided pressure boundary conditions, in the one-dimensional case of harmonic or Gaussian shape and in the two-dimensional case also of harmonic shape. The selected harmonic pressure boundary conditions lead to standing pressure waves, while using the Gaussian shape boundary conditions one-dimensional pressure pulses are injected and propagate through the pipe. The agreement of the TRACE results with the analytical solutions are, in general very good to good for the one-dimensional cases with respect to the pressure maxima and a small difference is only obtained in the wave speed.

At the resonance frequencies of the one-dimensional standing waves, the code is tested to the extreme and shows that enforcing small time step sizes is crucial for the performance of the code. Non-linear effects are observed in the code results for the large amplitudes encountered at the closest neighborhood of the resonances, where the analytical linear standing wave solution diverges and the linear approximation is outside of its validity range. Also for these non-linear standing waves TRACE yields qualitatively physically correct behaviour as the pressure amplitudes are limited and a plateau is reached.

For the one-dimensional pressure pulse of Gaussian shape the change of pulse amplitude and shape was analyzed in a longer system. The maximum amplitude of the pulse is slightly reduced as the pulse travels along the pipe. The effect of numerical diffusion on leading and trailing fronts is slightly asymmetric due to the donor-cell approach used in the numerical integration scheme of TRACE. The accuracy of the code is not negatively influenced by the reflections of the pulse at the boundaries of the pipe. As for the standing waves, the accuracy of the travelling pulse solution calculated by TRACE is negatively affected when the time steps are too large, while the effects of the spatial discretization are rather minor.

For the case of two-dimensional standing waves in a slab, a lowest spatial harmonic generated with one wave node in the direction parallel to the pressure driving boundary is considered. TRACE results show an overall good agreement with the *linear* analytical solution. This good agreement includes for low to medium excitation frequencies the damping properties of the skin effect perpendicular to the pressure boundary, which does not exist in one-dimensional pressure wave propagation, the transition to a harmonic shape of the wave also perpendicular to the pressure boundary and the frequency dependence of the resonance spectrum for further increased frequencies with the rapid changes of the wavelengths encountered. Effects of the model set-up and code limitations with respect to the two-dimensional TRACE model set-up using a TRACE VESSEL component in connection with pressure boundary conditions are discussed, in particular with respect to the underestimation of the damping in the skin effect frequency range and the numerical damping for higher frequencies. All in all, the TRACE code is able to calculate one- and two-dimensional pressure wave propagation in liquid water, when an appropriate spatio-temporal numerical discretization is chosen.

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1. Introduction

The propagation of pressure waves along nuclear systems is a matter of safety concern: (i) because of the immediate large loads that they can induce on the pressure boundaries and on their structural supports and (ii) because of the (indirect) effects through the fully coupled dynamics of a nuclear power plant during a system transient. A variety of transients can lead to rapid and large local pressure changes that propagate along the hydraulic system at the speed of sound. For instance, in boiling water reactors (BWRs) the fast closure of the turbine valve or of the main steam isolation valve can lead to a high pressure wave entering the vessel from the main steam line, which by collapsing the vapor bubbles, produces a surge of positive reactivity in the core resulting in a rapid increase of power (Ivanov et al., 2007 and references cited therein).

Another example is the expansion pressure wave that forms after a loss of coolant accident (LOCA), especially in case of large ones, and propagates from the break to the vessel, where it induces important loads on the vessel internals (e.g. Engel, 1994; Rapp and Tietsch, 2007). The propagation of pressure waves under hypothetical reactivity induced accident (RIA) conditions and the influence on BWR reactor internals against water hammer have also been considered (Azuma et al., 2003). In such cases multi-dimensional pressure wave propagation is important.

Pressure waves can also affect other parts of the nuclear system, especially pipes, where they appear and propagate as a result of water and cavitation hammers (e.g. Tijsseling and Lavooij, 1990; Bergant et al., 2006). During these types of transients, large pressure surges, which can affect the mechanical integrity of a system, are produced as a result of momentum changes in the fluid and of the formation of cavitation pockets of vapor at saturation pressure in the lines, which are rapidly collapsed as liquid flow rushes in to fill them (Dudlik et al., 2004; Prasser et al., 2003).

The use of simplified approximations for pressure wave propagation dynamics, spatially distributed and time-dependent pressure induced structural loads, as well as mechanical stability and performance, might need to be re-assessed. These questions will become ever more relevant for ageing plants (40+ years), since the mechanical properties of the pressure boundary structures may change under the strains of operation and neutron fluence. Such changes could potentially diminish the safety limits of allowed stresses with respect to those established at the design time, even to the point at which once allowable dynamic forces might lead to structural failure.

In order to estimate the effects of pressure waves and also the involved loads in nuclear safety related questions, knowing the full spatio-temporal behaviour of the pressure and flow field is important, including the timing of the pressure wave and the non-homogeneous pressure distribution. The types of effects in nuclear power plants described above are often analyzed by specialized codes, CFD and structural analysis codes, which, however, might lack to a large extent important systems analysis capabilities and, in particular, the specific correlations for heat transfer, two-phase flow and component behaviour implemented in state-of-the-art best estimate nuclear system analysis codes such as TRACE, RELAP5, CATHARE, ATHLET, etc., used by the nuclear industry and regulatory authorities in the context of nuclear safety applications. Therefore, from this perspective, it is very beneficial when the capabilities of nuclear system codes to model accurately rapid pressure propagation phenomena can be assessed in order to determine the quality of nuclear system code's predictions of the pressure field in system transients.

For this purpose, we have recently analyzed (Barten et al., 2006, in press, 2008) the capability of two of the currently most used system codes for nuclear applications, namely TRACE and RELAP5, with two experimental data sets from two-phase water hammer experiments performed in the context of the EURATOM WAHALoads Programme (Giot et al., 2002) at the Pilot Plant Pipework (PPP) test loop located in the Fraunhofer Institut UMSICHT, Germany (Dudlik and Müller, 2004), which had been provided for a water hammer benchmark workshop held during the NURETH-11 conference (Giot, 2005). Cavitation water hammer experiments were performed in the PPP test loop based on the fast closure of a valve in a pipe of about 160 m length and ~0.1 m diameter containing two bridges.

This assessment study showed that both codes were able to model the flow behaviour and the generation and collapse of vapor bubbles just downstream of the valve and at the first bridge; although code improvements were needed for this purpose (Barten et al., in press, 2008). Also the width and magnitude of the first pressure increase, just after the closing valve, was well captured by both codes. Moreover, the modeling of the collapse and flashing of the vapor bubble, generated just downstream the valve, demonstrated the flexibility and, in particular, the usefulness of the two-phase modeling capabilities of system codes. The validation of the fast pressure wave propagation with the speed of sound along the pipe, could only be performed in a semi-quantitative manner, because the uncertainties of modeling important two-phase effects, e.g. interfacial mass and heat transfer, as well as important fluid–structure interaction (FSI) phenomena (Neuhaus and Dudlik, 2005; Barten et al., 2008) arising from the interaction of the travelling pressure wave in the flow with the vibrations of the piping structure were not considered in the purely thermal-hydraulic modeling approach used. Thus, improvements of these modeling issues and more accurate measurements for comparison, e.g. interfacial phenomena, are needed in order to evaluate the code capabilities for pressure wave propagation. As the TRACE code was not developed originally for the detailed modeling of fast pressure wave propagation effects and as the donor-cell spatial differencing together with the stability-enhancing two-step method (SETS) used in TRACE for the time integration of the balance equations both generate artificial numerical damping (Hirt, 1968; Harlow and Amsden, 1971; Mahaffy, 1993), we consider here cases without friction and for which an analytical solution is available for comparison.

To this aim, we concentrate in this paper on the **assessment** of the TRACE code for pressure wave propagation in one- and two-dimensional cavities filled with *liquid* water, i.e. flow in a straight horizontal pipe and a rectangular horizontal slab, in situations where analytical solutions are available for comparison. The insights provided by the one-dimensional single phase results can help determine whether TRACE can deal with pressure wave propagation also in multi-dimensional geometries, and are a prerequisite if an extension of its application to two-phase flows is envisaged, in which the damping and collapsing effects on the pressure field observed in the studies mentioned above, will also play an important role. In the cases considered in the paper the pressure waves in the cavities are driven with one-sided pressure boundary conditions and impervious conditions are set at the other boundaries.

The structure of the paper is as follows. One-dimensional standing waves in a pipe are considered in Section 2. Travelling pressure pulses of Gaussian shape are analyzed in Section 3. Section 4 considers two-dimensional standing waves in a slab. Finally, Section 5 summarizes the conclusions drawn from the analyses presented in previous sections.

2. One-dimensional standing waves

In order to analyze the capabilities of the TRACE code (Spore et al., 2000; Odar et al., 2004) for pressure wave propagation in liquid