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SCIENCE DIRECT®
Nuclear Engineering and Design 235 (2005) 421–443
Nuclear Engineering and Design
www.elsevier.com/locate/nucengdes

Fluid mixing and flow distribution in the reactor circuit, measurement data base

U. Rohde[a,*], S. Kliem[a], T. Höhne[a], R. Karlsson[b], B. Hemström[b], J. Lillington[c], T. Toppila[d], J. Elter[e], Y. Bezrukov[f]

[a] *Forschungszentrum Rossendorf, Dresden, Germany*
[b] *Vattenfall Utveckling AB, Alvkarleby, Sweden*
[c] *Serco Assurance, Dorchester, Dorset, Great Britain*
[d] *Fortum Nuclear Services, Vantaa, Finland*
[e] *NPP Paks, Paks, Hungary*
[f] *FSUE EDO Gidropress, Podolsk, Russian Federation*

Received 6 August 2004; received in revised form 18 August 2004; accepted 31 August 2004

Abstract

Experimental investigations and computational fluid dynamics (CFD) calculations on coolant mixing in pressurised water reactors (PWR) have been performed within the EC project FLOMIX-R. The project aims at describing the mixing phenomena relevant for both safety analysis, particularly in steam line break and boron dilution scenarios, and mixing phenomena of interest for economical operation and the structural integrity. Measurement data from a set of mixing experiments have been gained by using advanced measurement techniques with enhanced resolution in time and space. Slug mixing tests simulating the start-up of the first main circulation pump are performed with two 1:5 scaled facilities: the Rossendorf Coolant Mixing model ROCOM and the Vattenfall test facility. Additional data on slug mixing in a VVER-1000 type reactor have been gained at a 1:5 scaled metal mock-up at EDO Gidropress. Experimental results on buoyancy driven mixing of fluids with density differences have been obtained at ROCOM and the Fortum PTS test facility.

Concerning mixing phenomena of interest for operational issues and thermal fatigue, flow distribution data available from commissioning tests at PWRs and VVER are used together with the data from the ROCOM facility as a basis for the flow distribution studies.

In the paper, the experiments performed are described, results of the mixing experiments are shown and discussed. Efforts on computational fluid dynamics codes validation on selected mixing tests applying Best Practice Guidelines in code validation will be reported about in a separate paper.

* Corresponding author. Tel.: +49 351 2 60 20 40; fax: +49 351 2 60 23 83.
E-mail address: u.rohde@fz-rossendorf.de (U. Rohde).

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doi:10.1016/j.nucengdes.2004.08.045

1. Introduction

The main objective of the investigations was to understand in sufficient detail, how water of different quality mixes in the cold leg and in the downcomer of a PWR before it enters the reactor core. These different quality might be different temperatures, different densities and/or different concentrations of additives. The most relevant additive to the primary coolant in PWR is boron acid used for the control of reactivity. In some cases, dependent on the scenario of the transient, both temperature and boron acid concentration might be different in the slug mixed with ambient water, in some cases density differences due to temperature gradients can be neglected with respect to mixing.

The mixing of lower borated slugs with water of higher boron concentration is the most mitigative mechanism against serious reactivity accidents in local boron dilution transients, and therefore, is one of the most important, nuclear safety related issues of mixing. Significant advantage in boron dilution transient analysis can be achieved, if realistic mixing data are used (Grundmann and Rohde, 1994 and Kliem et al., 2004).

Local or heterogeneous boron dilution refers to all events that could lead to formation of partially diluted or completely un-borated slugs in the primary system. In the FLOMIX-R project (Weiss et al., 2003), emphasis was put on heterogeneous dilution considering the transport and turbulent dispersion of a slug of lower borated water, which might be formed in the primary circuit by various mechanisms.

Lower borated slugs can be formed in the primary circuit of a PWR due to external or inherent boron dilution events. An external dilution refers to the cases where diluted or pure water slug is created by injection from outside of the primary circuit. Examples of such are an eventual injection of un-borated coolant or coolant of reduced boric acid concentration by the makeup system, and injection of un-borated pump sealing water to the primary system. Steam generators, chemical and volume control system, diluted accumulator or diluted re-fueling water storage tank and diluted containment sump are mentioned as potential sources of diluted water. Dilution may occur during power operation, shutdown or accident conditions. The sequence of events may vary significantly in different scenarios: pure water from the secondary side may flow to the primary circuit due to maintenance errors during shutdown, reactor coolant pumps (RCP) may stop during inadvertent dilution thus initiating slug formation or inadvertently diluted accumulators may leak to primary circuit during power operation or during accident conditions.

An inherent dilution mechanism is connected to a number of accident classes, where dilution could take place through an inherent phenomenon during an accident. Such an inherent phenomenon can be a boiling-condensing heat transfer mode occurring inside the primary system, or back flow from the secondary system in case of primary-to-secondary leakage accidents.

In VVER-440 reactors, because of the complex geometry of the primary loops and the main gates valves in both the hot and cold legs, there are various extra aspects of slug formation and transport. Particularly, main gate valves in VVER-440 can be closed during reactor operation to isolate single loops for maintenance. The water in these isolated loops might be under-borated due to failure of the water make-up system. The nuclear consequences of transients after re-start of an isolated loop in a VVER-440 type reactor have been studied in (Rohde et al., 1997).

The mixing of slugs of water of different quality is also very important for pressurised thermal shock (PTS) situations. In emergency core cooling (ECC) situations after a LOCA, cold ECC water is injected into the hot water in the cold leg and downcomer. Due to the large temperature differences, thermal shocks are induced at the RPV wall. Temperature distributions near the wall and temperature gradients in time are important to be known for the assessment of thermal stresses.

One of the important phenomena in connection with PTS is thermal stratification, a flow condition with a vertical temperature profile in a horizontal pipe. The fluid is in single-phase regime unlike in case when the upper part of the pipe is filled with steam, which is not elaborated within this context. Typically a stratified condition builds up, when a low-velocity cold fluid enters to a low-velocity warm fluid in a horizontal pipe. Stable stratification is not particularly dangerous for the pipe itself in structural integrity sense. However, in a real process, there are often disturbances that make the temperature boundary to move vertically. Velocity dif-