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Gas entrainment issues in sodium cooled fast reactors

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HIGHLIGHTS

- Main sources of gas and related issues in SFR are presented.
- Various approaches of gas transport are briefly described.
- Previous experimental studies to reduce gas entrainment are reported.
- Present evaluation of free surface gas entrainment is presented.

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ABSTRACT

Sodium cooled fast reactors have been developed in France for nearly 50 years. The so-called Astrid technology demonstrator is currently designed in the frame of Generation IV deployment. Gas entrainment in the primary sodium circuit is a key issue as it can lead to safety problems in case of accumulation and transport of large quantity of gas through the core. The paper first introduces the main problems caused by the presence of gas in the primary sodium circuit, the various sources of gas and the main issues on gas transport. As sodium–argon free surface is potentially an important source of gas entrainment in the primary circuit, we present the main results obtained in past experimental studies on vortex type gas entrainment at free surface. Water tests were performed in a simple flow condition to study the physical process of vortex occurrence and gas entrainment. Other water tests were performed in representative hot pool models at different scales to analyze similarity criteria. Moreover, design improvements and local devices were tested to avoid gas entrainment at the free surface. Nowadays, numerical tools are progressively used to estimate the risk of gas entrainment at the free surface. We present the methodology in progress to define local criteria on vortex occurrence and gas entrainment, and to apply these criteria to global calculations of the whole pool. A Front-Tracking method coupled to a Large Eddy Simulation approach is implemented in TRIO_U code to compute free surface instabilities and vortex occurrence. Experimental data from the literature are used to validate the numerical approach and a new test facility called BANGA is in progress at CEA to complete the validation.

1. Introduction

Sodium cooled fast reactors (SFRs) have been developed in France for nearly 50 years with successively Rapsodie, Phenix and Superphenix plants. Moreover, the European Fast Reactor (EFR) project started in the late 1980s, in tight collaboration between France, England and Germany. After several years of design and safety studies, the EFR project was stopped in the mid-1990s (Lefevre et al., 1996). Nowadays, the so-called Astrid technology demonstrator is designed in the frame of Generation IV deployment. In SFRs, an inert argon cover gas is maintained above the sodium primary pool to avoid any contact with air and to limit the temperature of the slab. The entrainment of argon gas in the primary sodium circuit has always been a major issue as it may lead to safety problems in case of accumulation and transport of gas through the core. A positive reactivity effect should occur if a large quantity of gas is crossing the central region of the core. So, this scenario is not acceptable and it is needed to demonstrate that no large quantity of gas should accumulate and flows across the core.

For Phenix and Superphenix plants, the main source of gas in the primary circuit was the overflow of the vessel cooling system. In such pool-type reactor, a small by-pass flow is arranged

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at the core inlet to cool the lower plenum and the main vessel. This cold sodium is flowing upwards along the vessel and it overflows to return in the cold pool. As the cold pool free surface is lower than the weir level, the sodium jet crosses the free surface with sufficient momentum to induce gas entrainment. During the EFR project, a new source of gas appeared at the hot pool free surface, mainly due to the higher compactness compared to previous reactors (Tenchine, 2010). Hydraulic tests performed on water facilities showed that numerous vortices could be generated inducing bubbles entrainment in the main flow. Special devices were studied to avoid or at least to limit gas entrainment. Of course, the present design of Astrid project can take advantage of the past studies to prevent gas entrainment from the free surface.

Gas entrainment in the primary circuit is also a major issue of loop-type reactors (Kimura et al., 2008). The compactness of the reactor vessel and the high sodium velocity in the hot pool can induce gas entrainment at the free surface and transport of a large quantity of bubbles in the primary circuit (Eguchi et al., 1994a,b). For this reason, drastic solutions are proposed for the Japanese fast breeder reactor (JSFR) with large horizontal plates below the free surface to protect the free surface from high velocity and to limit gas entrainment in the hot legs. Hydraulic tests on water mock-ups of JSFR hot pool are performed to find the most efficient design. Nevertheless, the presence of mandatory gaps between the plates and the components are potential paths for bubbles transport into the hot legs. So, an extensive R&D programme including analytical (Yamaguchi et al., 2011), numerical (Sakai et al., 2008; Ito et al., 2010, 2011, 2013), experimental (Ezure et al., 2011) studies is going on to provide JSFR designer with reliable validated tools for the prediction of gas entrainment.

The Prototype Fast Breeder Reactor (PFBR) is also submitted to a risk of gas entrainment in the primary circuit (Velusamy et al., 2010). PFBR is a pool-type reactor and the gas entrainment issues are similar to EFR ones. Numerical studies are performed on a representative hot pool configuration to get the sodium flow field. As the free surface velocity seems too high, baffles are added in particular positions and new calculations are performed to optimize the efficiency of the baffles in reducing the free surface velocity. A hot pool reduced scale water model is used to validate the previous calculations. Moreover, experimental investigations have been carried out on a spillway weir crest for the main vessel cooling circuit to assess no gas entrainment at the overflow. A volume of fluid (VOF) computational approach is developed (Satpathy et al., 2010) to provide local criteria on gas entrainment at a free surface. Other fundamental studies on various types of gas entrainment are also in progress (Patwardhan et al., 2012) to get local criteria based on experimental data.

The paper will first introduce the main problems caused by the presence of gas in the primary sodium circuit, the various sources of gas and the possible sinks for gas bubbles. As sodium–argon free surface play a major role in the gas entrainment process, we present the main results obtained at CEA in past experimental studies on vortex type gas entrainment. Water tests were performed in a simple geometry to study the generic conditions of vortex occurrence and gas entrainment. Other tests were performed in reactor hot pool water models at different scales to analyze similarity criteria. Moreover, design improvements and local devices were tested on these facilities to avoid gas entrainment at the free surface. Nowadays, numerical tools are progressively used to estimate the risk of gas entrainment at the free surface. We present the methodology in progress at CEA to define local criteria on vortex occurrence and gas entrainment and to apply these criteria to global calculations of the whole pool. A Front-Tracking method coupled to a Large Eddy Simulation approach is implemented in TRIO_U code to compute free surface instabilities and vortex occurrence. Experimental data from the literature are used to validate the numerical approach and a new test facility called BANGA is in progress to complete the validation.

2. Main issues and main sources of gas

Gas entrainment in the primary circuit of sodium cooled fast reactors may lead to safety problems in case of accumulation and transport of large pockets of gas through the core (Tenchine, 2010). A positive void reactivity effect could occur if a large quantity of gas is crossing the central part of the core. Moreover, the heat transfer efficiency of liquid sodium will be drastically reduced in subassemblies if the void fraction is significantly increased, leading to possible clad melting of fuel pins. So, this scenario is not acceptable and it is needed to demonstrate that no large quantity of gas can accumulate upstream to the core and cross the central part of the core. In the frame of the Astrid project, efforts are made on the core design to reduce the positive void reactivity effect in case of sudden increase of the void fraction in the core. An indirect consequence of argon gas passage through the core is the argon activation because of the high neutrons flux in the reactor core region. The cover gas plenum activation could prevent the prompt detection of fission products leakage from failed fuel pins (Cristofano et al., 2012). Other issues are concerned with the presence of gas bubbles in the primary circuit. The presence of gas bubbles in the sodium flow can disturb electro-magnetic sensors used for shutdown systems. The reliability of such device could be altered by the bubbles in the sodium flow. The use of acoustic or ultrasonic instrumentation for continuous monitoring in operation, to detect boiling occurrence, presence of undesired obstacles or to potentially measure the core outlet temperatures could also be limited by the presence of gas bubbles in the sodium flow. Bubbles can modify the sound celerity, attenuate the signal and disturb the propagation of ultrasonic waves (Gobillot et al., 2009). Another potential problem induced by gas bubbles in the primary sodium circuit is the inception of cavitation in primary pumps, with consequences on the pump efficiency, on occurrence of vibration and on possible deterioration of pump blades by mechanical erosion.

Various potential sources of gas are present in SFR as free surfaces, overflows, nucleation, leakage of gas seal, as illustrated in Fig. 1.

Gas entrainment at the free surface is one important potential source of gas. As the reactor compactness remains an economical objective, the volume/power ratio is generally designed as small as possible. For this reason, the upper plenum velocities are increased and the free surface can be disturbed. As for Phenix and Superphenix reactors, the volume/power ratio was rather large and the free surface was smooth. A disturbed free surface was expected in the European Fast Reactor (EFR) project with higher compactness than previous reactors. The main source of gas entrainment at EFR hot pool free surface was the presence of vortices, according to reduced scale water models. Such vortices were induced by concomitant local vorticity and downward flow. The phenomenon appeared as an unsteady complicated process with creation, transport and vanishing of vortices, with or without bubble entrainment in the flow. The shape of the vortices and the occurrence of small or large bubbles are depending on the local velocity field and turbulence characteristics, as shown in Fig. 2. In parallel to a necessary physical understanding and modelling of this complicated process, design adaptations must be studied to avoid (or at least to reduce) bubble entrainment. The numerical and experimental researches on gas entrainment by vortices at free surface are presented later in the paper. Other physical processes can lead to gas entrainment at the free surface. Of course, gas diffusion and dissolution in the liquid sodium occur, but it is limited by the saturation level which depends on the temperature. A notable point is the increasing