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Occurrence of thermal stratification in sodium cooled fast reactor piping

D. Tenchine[a,*], P. Gauthé[b]

[a] CEA, DEN, DM2S/STMF, F-38054 Grenoble, France
[b] CEA, DEN, DER/SESI, F-13108 Saint-Paul-lez-Durance, France

HIGHLIGHTS

- Specific governing parameters of thermal stratification in piping are proposed.
- Occurrence and amplitude of stratification based on water tests are reported.
- Thermal stratification test performed in Phenix reactor is described.
- Water and sodium results are compared on the basis of proposed parameters.

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ABSTRACT

Sodium cooled fast reactors (SFRs) are operating in a wide range of temperature. For some off-normal conditions, the flow rate is drastically reduced and large temperature variation occurs. In such transient situations, buoyancy influence can be very important and thermal stratification can appear in the horizontal portions of the piping, particularly in secondary circuits. From the viewpoint of thermal stress analysis in the piping, the occurrence of thermal stratification must be predicted to prevent any crack or damage leading to a sodium leak.

The paper first introduces a qualitative description of the influence of the buoyancy forces on the flow behaviour in piping, depending on the piping geometry. Then, dimensionless parameters which play a role in the occurrence, the amplitude and the duration of thermal stratification are recalled. Past experimental results obtained in a long horizontal pipe using water as a simulant fluid are presented and new dimensionless parameters are proposed. Measurement of thermal stratification in one secondary circuit of Phenix reactor during the ultimate tests performed in 2009 is described.

The water and sodium results are compared on the basis of the proposed dimensionless parameters. A prediction of the risk of thermal stratification in piping based on these parameters seems possible. Nevertheless, it is shown that the influence of piping geometry and specific boundary conditions can play a significant role in the stratification amplitude.

1. Introduction

Sodium cooled fast reactors (SFRs) are operating in a large range of temperature. Typically, the temperature difference between the core inlet and the core outlet is around 150 K. The difference of temperature between the steam generator outlet and the core outlet can reach 200 K. Under normal steady-state operating conditions at full flow, buoyancy forces have generally no significant influence except in some particular regions were the velocity is low. For certain off-normal conditions, the flow rate is reduced and large temperature variation occurs. In such transient situations, buoyancy influence can be very important and it can modify the global thermal hydraulic behaviour. In the vessel, thermal stratification may be induced in the hot pool and the cold pool. In the secondary circuit, thermal stratification may also appear in the horizontal portions of the piping. The occurrence of thermal stratification in SFRs piping has two main consequences described hereafter.

From the viewpoint of the reactor system analysis, the influence of buoyancy forces and especially thermal stratification in horizontal pipes will change the global system behaviour. One dimensional plant dynamic codes are commonly used to predict the system response to a transient situation. So, a particular attention

* Corresponding author. Tel.: +33 4 38 78 30 85; fax: +33 4 38 78 57 28.
E-mail address: denis.tenchine@cea.fr (D. Tenchine).

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must be paid to take into account the possible influence of thermal stratification on the system behaviour. The transition from normal operation to a decay heat removal condition at low flow rate is one important issue in which thermal stratification must be carefully estimated. The problem is increased in case of natural convection strategy for decay heat removal as there is no more imposed flow rate in the circuit.

From the viewpoint of thermal stress analysis on the piping, the occurrence of thermal stratification must be predicted to prevent any crack or damage leading to a sodium leak. Effectively, due to thermal stratification, the temperature difference between the upper and lower regions of a horizontal pipe produces bending moments and local stresses. These stresses must be added to existing mechanical and thermal stresses. So, one needs to predict not only the occurrence of thermal stratification but also the amplitude of the temperature difference between the upper and lower regions in horizontal pipes.

Several studies on thermal stratification in horizontal pipes for transient conditions have been reported in the literature. Some papers are concerned with water cooled reactors and others deals with sodium cooled reactors.

Measurements on a real plant have been done by Yu et al. (1997) on the YGN-3 pressurized water reactor in South Korea. Temperatures and displacements measurements were recorded on the surge line connecting the pressurizer to a cold leg. This line has a long horizontal branch which can be subjected to thermal stratification during pressurizer in-surge or out-surge. Several thermocouples were circumferentially located in nine sectional positions along the pipe. Important thermal stratification could be measured and large vertical displacements were also recorded. Computational fluid dynamics analysis of surge line connecting the pressurizer to a cold leg was performed by Kang and Jo (2007) using the CFX commercial code. Thermal stratification was computed for transient conditions taking into account heat transfer at the pipe wall. Thermal stratification in safety injection system or shutdown cooling system of pressurized water reactor has been studied by Kim et al. (2005) on a 1/10 reduced scale facility. Buoyancy forces are induced in these isolated branches by heat transfer or leak through the isolation valve. Thermocouples were located along the branches to measure the temperature field and the stratification. Various flow conditions were tested to be able to estimate the amplitude of the stratification as a function of dimensionless parameters. Another facility was used by Kim et al. (2007) to measure thermal stratification in the horizontal inlet nozzle of steam generator for pressurized water reactors. This branch pipe was subjected to cracks in several power plants due to thermal fatigue during auxiliary feed-water injection. For VVER-440 reactor, Boros and Aszodi (2008) used the CFX commercial code to estimate thermal stratification in the pressurizer surge line during transient conditions. Computational results were compared with measurement data obtained in the Paks plant and the agreement was rather good.

For sodium cooled fast reactors, several experimental facilities were used to find criteria for thermal stratification occurrence in horizontal pipes. Firstly, sodium tests were performed by Tenchine and Martin (1980) on a sodium rig to get preliminary sodium experimental data on thermal stratification. A long horizontal pipe with water was used by Tenchine and Toly (1981) to measure the temperature gradient induced by thermal stratification during transient conditions. A study of governing parameters was associated to these tests. A significant work on thermal stratification in piping systems was performed in Argonne National Laboratory in the early 1980s. Kasza and Bobis (1980) reported briefly on first stratification measurements in a water facility. Then, more detailed test measurements were presented by Kasza et al. (1981a) for transient conditions. A one dimensional pipe flow model is proposed by Kasza et al. (1981b) to take into account thermal stratification in a simple way. Other tests are reported by Kasza and Kuzay (1982) with the influence of an elbow on the amplitude of the stratification. Later, sodium tests were performed by Toly (1984) in the piping located at the outlet of a mixing tee for transient conditions. Numerical results based on a curvilinear 2-D modelling are also reported for the same flow condition. Taking the opportunity of tests focused on the onset of natural convection in a sodium loop, Toly (1987) reported thermal stratification occurrence in horizontal portions of the piping and he measured the temperature gradients. A few authors have tried to develop analytical modelling for the prediction of thermal stratification. A 1-D model is proposed by Dhir et al. (1988a, 1988b) for the prediction of stratification in horizontal pipes subjected to fluid temperature transient at the inlet.

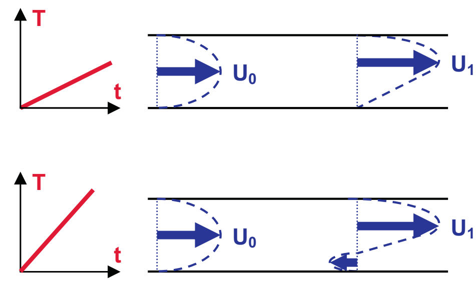

Fig. 1. Buoyancy influence in a horizontal pipe.

Available experimental data correspond to different geometrical situations and different boundary conditions. As the piping geometry plays an important role in the stratification behaviour, the prediction of the occurrence and the amplitude of the stratification is a real challenge. Nevertheless, the availability of simple criteria to predict thermal stratification is important for design and safety analysis of nuclear reactors piping systems. The present paper will successively introduce:

- A qualitative description of the influence of the buoyancy forces on the flow behaviour in piping, depending on the piping geometry.
- Non dimensional parameters which can play a role in the occurrence, the amplitude and the duration of thermal stratification.
- Experimental data obtained in a long horizontal pipe using a water facility.
- Phenix reactor data obtained during the ultimate tests performed in 2009, before the reactor was definitively stopped (Tenchine and Gauthe, 2013).

2. Qualitative analysis

The development of thermal stratification in horizontal pipes is one typical effect of buoyancy forces influence. For steady-state condition, buoyancy can affect the flow behaviour if the flow rate is sufficiently low and the inlet temperature gradient sufficiently high. This situation can occur at a tee junction or at the outlet of some component where an important temperature difference is present. For transient situations, buoyancy can affect the flow behaviour if the flow rate becomes sufficiently low and the inlet temperature variation sufficiently important. The present paper is focused on thermal stratification in horizontal pipes during transient situations at low flow rate.

First of all, we can describe qualitatively the effect of buoyancy forces in piping system. Let us consider an increase of temperature at low flow rate condition, at the inlet of a horizontal pipe as shown in Fig. 1. Buoyancy forces will induce an acceleration of the flow in the upper part of the pipe where the lighter hot fluid will concentrate. For momentum conservation reason, the heavier cold fluid remaining in the lower part of the pipe will decelerate. In the case