DEVELOPING OF MODELING APPROACH OF THE STEAM GENERATOR CRACKING OF FLOATING NPP

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Abstract: In this work a problem of cracking of tubes of a steam generator (SG) of floating NPP (FNPP) is considered. Problem of the SG tubes cracking was experimentally investigated on similar to the FNPP reactors of nuclear icebreakers. It was concluded that main reason is in anomalously high hydrogenation of the titanium alloy of the SG tubing. For solution of this problem general mechanism of formation of gas bubbles on exit of the reactor and a transport them to problematic areas of the SG was proposed. To prove this hypothesis a multiscale, multi-physical modelling approach is developing. In application of this method to current problem a combination of 1D-3D codes is used. Features of each model and results of calculations are presented. Analysis of the calculation results allows concluding in feasibility of the proposed approach to cracking of the SG tubes.

Keywords: *Floating NPP, SG tubes cracking, multiscale, multi-physical modelling, CFD code*

1. INTRODUCTION

A floating NPP is a relative new type of NPP. Its main advantage is in mobility that gives possibility to transport such facility to required area to supply necessary power. After changing of necessity in power, the FNPP can be moved to other places and to continue their operation. Transport by sea can be not expensive. That gives possibility to FNPP be economical effective. Nevertheless, appropriate attention should be paid to a safety of the FNPP that could be even more then to stationary NPP because of nature of its mobility. In this work we are considering one potential problem of the FNPP which can be a cause for leak between primary and secondary systems.

A reactor of the FNPP has the same design as on nuclear icebreakers (NI) which are still in operation in Russian Federation where problem of the SG tubes cracking first appeared. Although the FNPP only is starting its operation in Russian Federation, it can be expected possibility of the same problem of the SG cracking in future.

Problem of cracking of the NI SGs appeared after operation time of 30 -70 thousand hours when leaks between first and secondary systems were detected. Experimental investigations has shown that the main reason is in the anomalously high hydrogenation of the titanium alloy of tubes reaching 0.1% by mass in the shell of the feedwater tubes. This value significantly exceeds the maximum expected hydrogenation of the SG tubes ~ 0.03-0.035% for predicted 150-175 thousand hours of SG operation.

This work was completed on the NPP department of NRU "MPEI".

2. THE MAIN PART OF REPORT

2.1. Research subjects and methodology

Two types of SGs are used on NIs of Russian Federation: PG-18T and PG-28, which are almost identical, designed to produce superheated steam. Fig. 1 shows the general view of the SG which consists of two main parts: the vessel of the SG and the internal structure (IS). The vessel is a cylindrical shell in which the IS is located. A flange from primary system is connected to the vessel. The main part of the IS consists of: a feedwater collector distributing water through tubes; steam generating tubing forming a steam generating surface; a steam collector and other internal equipment. After the feedwater collector the tubes come down and are separated from main tubing by a shell of feedwater tubes. Main parameters of the SG are following: primary system - pressure 12.75 MPa, inlet temperature 591.15K, outlet temperature 544.15K, mass flow – 180 kg/s.

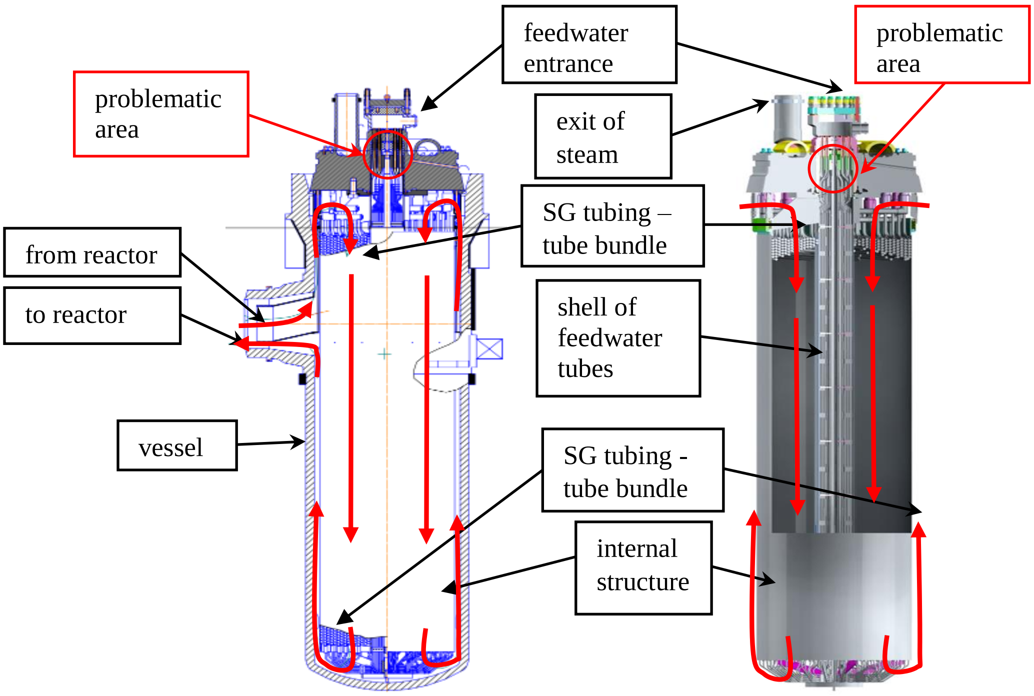
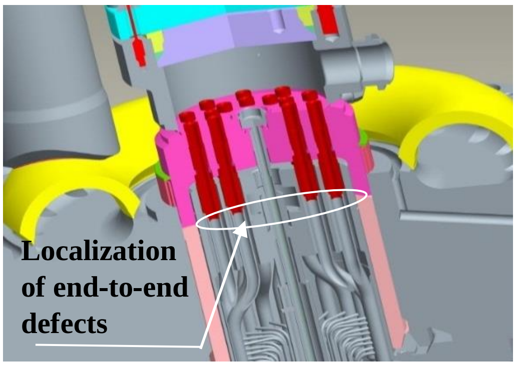


Figure 1. General view of SG → flow path of primary system

End-to-end defects in sections of the SG were discovered in experimental investigations at 2004 [1]. Leak regions were detected in area of welding of feed water collector to tubes – fig.2 (problematic area – fig.1). According to the research, a fatigue failure was initiated by the embrittlement of the material due to the intense accumulation of hydrogen in the local tube regions near the weld. The local hydrogen concentration in the damage region is almost an order of magnitude higher than the concentration of hydrogen in the remaining areas of the tubing.



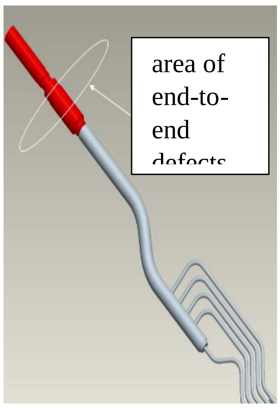


Figure 2. Localization of defects in the SG

In [2] data of materials science, studies and results of analysis of possible causes and mechanisms of failure of pipe systems of steam generators of nuclear vessels were presented:

- The transverse fracture was born on the outer surface of tube on the primary system, with no signs of corrosion damage in the development of the crack
- Structural features undoubtedly accelerated the fatigue failure, but it was initiated by the embrittlement of the material during the operation of the SG due to the intensive accumulation of hydrogen in the local areas of the tubes near the weld.

To solve of such problem we should take into account two main features of reactor design for the FNPP and the NI. First, for sake to make reactor more compact a gas type of pressurizer is used. Second, on exit of the core there is subcooled boiling. Therefore, we can consider following mechanism of hydrogen formation in the coolant of primary system. Because of subcooled boiling and of gas type of the pressurizer we have stable bubbles on exit of the core. Radiolysis in the steam produces oxygen accumulation in the bubbles, which passed through primary system back to the core can be a cause of nodular corrosion of Zr cladding and increase hydrogen in the primary system. As result on exit of the core we have stable bubbles containing steam+N_2+H_2. A transport of the bubbles to the problematic areas of the SG (fig.1-2) in particular to upper part of the shell of feedwater tubes and accumulation H_2 there can provide required cause of the high embrittlement.

The developing model of gas transport presented in this work bases on using of a multiscale, multi-physical approach. In this direction, in the general problem, the allocation of areas is made, where the optimal application of calculation codes of appropriate dimension (1D, 3D), physics and modeling accuracy is. In the problem under consideration, the main interest consists in a representing of the transport of the gas phase along the primary system, the possibility of getting it into the shell of the feedwater tubes, the accumulation of gas bubbles there, their rising and, further, the accumulation of the gas phase in problematic places.

The best simulation of all these effects is possible on codes of computational fluid dynamics (CFD), but a calculation of the entire SG and the primary system will be a resource-demanding task. Therefore, in the model it is proposed to use the simulation of processes based on the 1D code Relap5 and 3D CFD code. At the first stage, a generalized 1-D model of the entire SG was developed the results of which determined the boundary conditions for models of the CFD code. In turn, based on the next analysis of CFD results, the 1D model were corrected.

From point of view of gas bubbles transport two main models should be used M3 and M4 – fig.3 based on boundary conditions on base of the Relap5 model. M3 was created to research the possibility of gas bubbles to get into the shell of the feedwater tubes where problem of cracking happened and this is main goal of current work. M4 is for modelling rise of gas bubbles in the shell and it will be created on next steps of development. Because of complex geometry of the SG and absence of 3D models for it models: M1 and M2 (fig.3) were first developed for modelling an entrance and an exit of the coolant of the primary system to the SG. These models play vital role in establishment of the boundary conditions for inlet and outlet of the M3 in particular distribution of mass flow that influences on movement of gas bubbles.

2.2. Results

The models M1 and M2 contain 4355000 and 7549000 elements respectively. Model of heat transfer did not used. SST model of turbulence was applied. CFD code ANSYS CFX version 14 has been used. Some results of calculations are presented on fig.4.

Main purpose of the M1 is to receive a flow distribution in the SG from primary system around tubing. As we can see on fig.4(a) there are forming of complex vortexes on top of the

SG. Then in flow down around tubing the vortexes have tendency to disappearing and mass flow reaches relative uniform distribution around tubing. On this basis Relap5 model of SG was corrected and in the model M3 flow distribution around tubing on inlet was chosen as uniform.

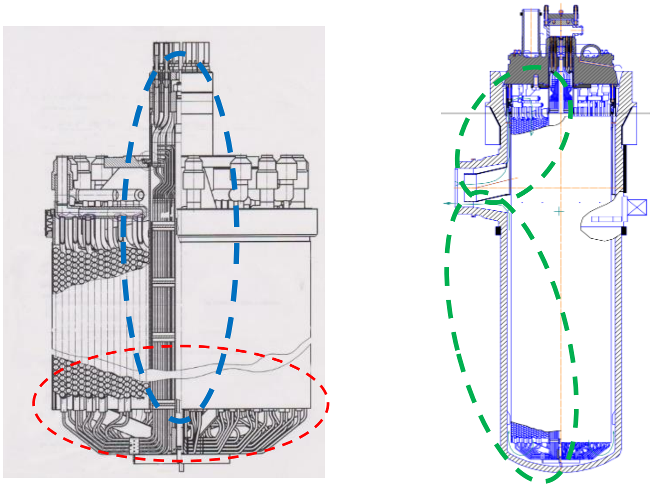


Figure 3. Areas of CFD models: - - - M3 with gases; - - - M4 rising of bubbles; - - macro models of entrance M1 and of exit M2

Main purpose of model M2 to give understanding how flow is distributed at bottom of the SG after exit from the tubing. Streamlines for this area presented on fig.4(b). Analysis has shown that in contrary to a priory beliefs flow is distributed rather uniform in circumference of the SG. However, it concentrates in enough narrow area on the height. In another area rather stagnation of flow exists fig.4 (b). This is important result as gas bubbles from bottom of SG can rise up because of buoyancy and go to the shell of feedwater tubes.

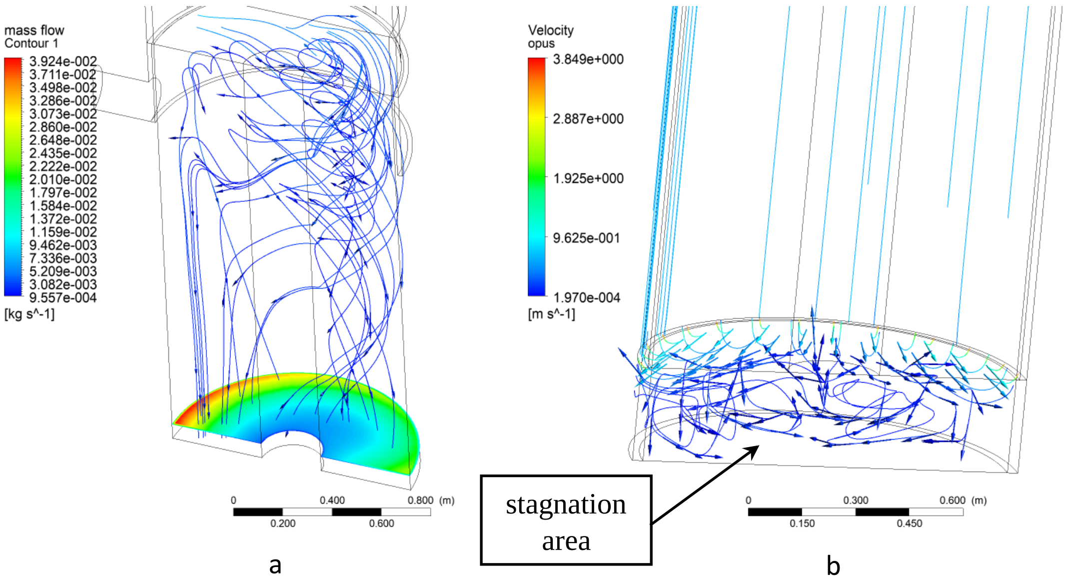


Figure 4. Mass flow and velocity streamlines for the M1 (a) and velocity streamlines for the M2 (b)

Because of a buoyance mechanism plays important role in considering problem, on first stage a validation of the CFD code on base of enough simple model was completed. Several parameters such as bubble diameter, interphase drag model etc. were varied and calculated velocity of bubble rise in the water versus its theoretical value were compared. Results of dependence of rise velocity from bubble diameter variation are presented on fig.5. There is enough small difference in velocity between calculated and theoretical values. In increasing bubble diameter the CFD code predicts less velocity but in considering problem this deviation is conservative and acceptable. Results of calculations allow concluding that CFD code can be used in the modelling of gas transport.

On final stage the M3 was used to research problem of transport gas to shell of feedwater tubes. In model only lower part of the SG tubing, an area between tubing and bottom of the SG vessel and lower part of the shell were modeled. Because in more details spreading of bubbles in the shell will be implemented in the M4 then in the M3 the shell was simplified via representing as top-closed cylinder. Main interest in simulation was in determination of a gas appearance in area of the bottom of cylinder. Mesh of the model contains 1276000 elements and is not uniform with refining toward most interesting for analysis areas: walls and bottom of the shell. Analysis of processes in the core estimates that on exit of the reactor we have approximately volume fraction of gas 0.02. This value was used as boundary for model inlet. In Relap5 model it was found that coolant temperature in the shell is sufficient lower than in the main part of the SG and in average it is about 398.2K and this value was used for initialization of the shell. Temperature 575K on inlet of the tubing was used from Relap5 model. Interphase mass transfer did not taken into account. Because we have complex dynamic of gas bubbles in the coolant, where breakup or coalescence can occur therefore multiple size group (MUSIG) model of CFX was used. A uniform distribution of the bubbles on diameters diapason from 0 to 0.5 mm on inlet of the SG was setup. As in M1 and M2 the SST model of turbulence was used. Exit from model was setup on base of velocity distribution from M2. Transient type of calculation was used with time interval 60s. Some results are presented on fig.6.

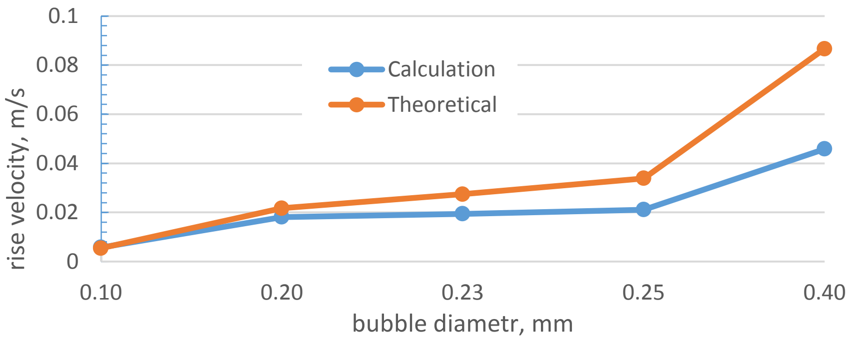


Figure.5. Dependence of rise velocity of bubble from its diameter for calculation model and theoretical values

As earlier in the M2, it was found that in lower part of the SG after exit from the tubing a stagnation area exists. The gas bubbles because of buoyancy there can rise and go into the shell of the feedwater tubes. As well because of difference in density of the coolant in tubing and in the shell some naturel convection exists. In this case the gas bubbles can be moved by coolant to the shell. In operation of the FNPP and of the icebreakers the gas volume fraction on exit of the reactor can change. For its researching set of variants of the M3 with variation of inlet volume fraction from 0.005 to 0.02 were calculated. As resultant parameter the volume fraction of gas on the inlet of the shell averaged on 20s of problem time was used and its dependence is presented on fig. 7. In additional average mass flow of the gas on inlet of the shell also is there. As we can see these two parameters have the same tendency. Slight difference is because mass flow of gas can change in time its sign. As well, even with the volume fraction 0.005 we have the gas accumulation on the inlet of the shell.

2.3. Discussion

Calculations have proved that there exists mechanism of transport gas bubbles in the SG to bottom entrance of the shell of the feedwater tubes. This can happen even in the case of enough low gas volume fraction on the inlet of the SG. In future developments additional refinement of models are planned. In particular, effects of temperature variation along tubing and shell should be taken into account. The precise model M4 of the shell for research of dynamic of the bubbles rise will be created and a more complex model on base of coupling various calculation codes to accurate modelling of relevant dynamic processes is planned.

3. CONCLUSION

Modelling of the SG tubes cracking can help to understand main processes and to develop appropriate design or operational measures for its preventing what in turn should increase FNPP safety and efficiency.

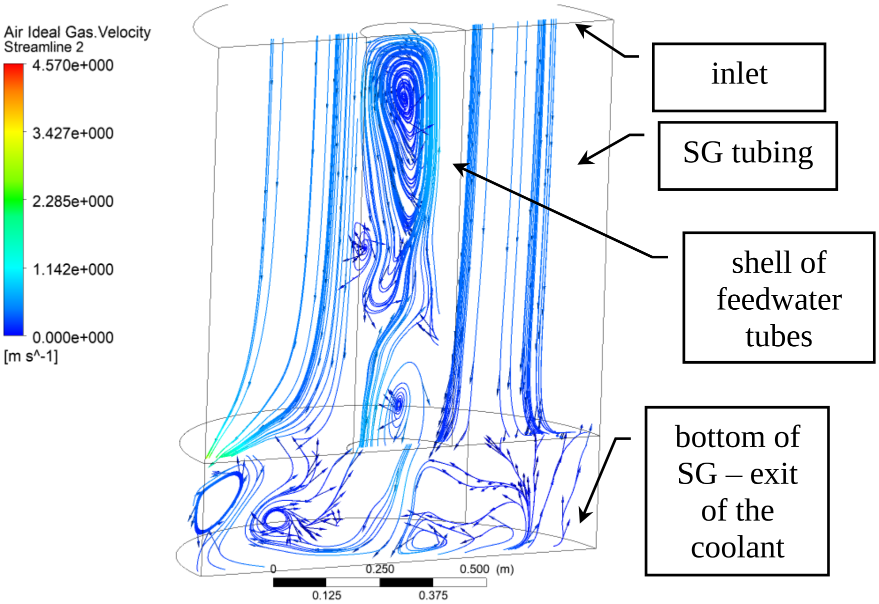


Figure.6. Model M3 and streamlines of gas velocity

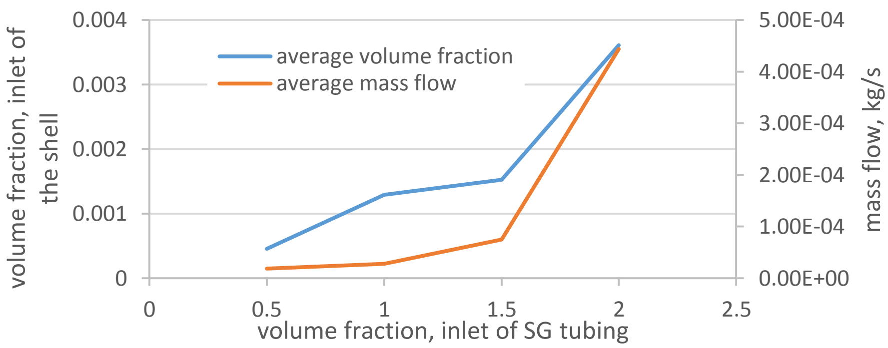


Figure.7. Dependence of volume fraction and mass flow of gas on inlet of the shell of feedwater tubes from gas volume fraction variation on inlet of the SG tubing

This work has been carried out using computing resources of the federal collective usage center Complex for Simulation and Data Processing for Mega-science Facilities at NRC “Kurchatov Institute” (ministry subvention under agreement RFMEFI62117X0016), http://ckp.nrcki.ru/.

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