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Application of simplified buckling analysis rules of RCC-MR (1993) for PFBR-IHX

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ABSTRACT: Buckling strength of straight tubes in an Intermediate Heat Exchanger (IHX) used in an FBR has strong influence on the basic tubesheet thickness. Hence accurate estimation of buckling strength with the sound design philosophy is very important. Towards this, the applicability of the simplified rules recommended in RCC-MR (1993) for the buckling design IHX tubes is investigated in this paper. Accuracy of buckling stress prediction as per RCC-MR is compared with the experimental data available in the literature. Finally, the minimum thickness of tubesheet for the IHX of a 500 MWe Prototype Fast Breeder Reactor (PFBR) arrived at based on the buckling strength computed as per the RCC-MR procedure is discussed with reference to the conventional method of estimating buckling strength.

1.0 INTRODUCTION

In the preliminary design of a 500 MWe Prototype Fast Breeder Reactor (PFBR), which was envisaged during 1985, there were 4 primary sodium loops with 8 IHXs and 4 primary sodium pumps (PSP) in the reactor assembly. Subsequently, this design was optimised during 1990's to arrive at an economic design with only 2 primary sodium loops involving 4 IHX and 2 PSP (refer fig 1). The structural mechanics analysis results for the IHX tubesheets including shape optimisation for the 4-loop concept were presented in the 10th SMiRT [1] and 13th SMiRT conferences [2]. The current paper is concerned with the studies done on the tubesheet of IHX for the 2-loop concept.

A schematic sketch of IHX for 2-loop concept is shown in fig 2. IHX is a shell and tube heat exchanger with primary sodium on shell side and secondary sodium on tube side, made up of austenitic stainless steel type SS316LN. The tube size selected is OD19 x 0.8 WT and the number of tubes per IHX is 3600. The tubes are rolled and welded to annular tubesheets at either end. Straight tube design without any expansion bend is selected considering simplicity and lower tubesheet thickness. The minimum unsupported span of tube bundle is 800 mm. The tubesheet thickness is to be finalised respecting the RCC-MR (1993) code stress limits taking into account the buckling risks of some of the tubes which are subjected to axial compressive stress under combined mechanical and thermal loads. It is seen that the buckling strength of tubes has significant effect on the minimum tubesheet thickness. Hence an accurate prediction of buckling strength is very important. It is planned to use RCC-MR (1993) simplified rules which account for plasticity and imperfection for establishing buckling strength of tubes. In order to have a confidence on the use of RCC-MR rules for the critical situations like this, a validation exercise of the methodology on the prediction of the buckling strength by RCC-MR is taken up. Towards this, a systematic experimental programme is being conducted at IGCAR Kalpakkam and tests are at the advanced stage of completion. While results will be available before the SMiRT-14 Conference proceedings, in the present paper preliminary validation studies performed with the experimental results available in the literature are included.

In the paper, the prediction of buckling strength of IHX tubes as per RCC-MR procedure, the effect of buckling strength of tubes on the tubesheet thickness, and the validation of the approach are given. The tubesheet analysis for PFBR IHX using these results is also highlighted.

2.0 BUCKLING STRENGTH OF PFBR-IHX TUBES

The main mechanical loads on the tubesheets are due to pressure (0.085 MPa) during steady state as well as transient conditions (maximum of 1.23 MPa during a large sodium water reaction). Under the pressure loadings, the top and bottom tubesheets deflect inward and as a consequence some of the tubes, particularly the tubes in the inner rows are under compression while the tubes in the outer rows are under tension. For the given geometry and loading, thicker tubesheets deflect less and results in lower compressive stresses in the tubes of inner rows. The thermal loading also adds compressive/tensile stresses in various rows. Hence, the total compressive stress in any particular tube shall be limited to a stress to avoid any risk of buckling.

2.1 RCC-MR Procedure

Appendix A7 of RCC-MR (1993) gives simplified buckling analysis rules taking into account plasticity and imperfection. The basic parameters needed for the estimation of buckling stress are classical Euler buckling stress (σ_E), material yield stress (σ_Y) and deviation of straightness in case of beam type of buckling (d). From these, two nondimensional parameters are defined as:

$$\xi = \sigma_E / \sigma_Y \quad \text{and} \quad \delta = d/D \quad \text{D is the outer diameter of the tube.}$$

In defining the deviation parameter for the present problem, the outer diameter D is taken as the normalisation parameter and the effect of ovality is considered to be negligible. In order to justify these assumptions, extensive validation studies are planned. One validation is presented in the subsequent paragraph. Knowing the values of ξ and δ, parameters X ($= \sigma_m/\sigma_E$) and Y ($=\sigma_m / \sigma_Y$) are determined from the curve as indicated in fig 3 schematically. The permissible axial compressive stress is the minimum of ($X.\sigma_E$ and $Y.\sigma_Y$).

2.2 Analysis for PFBR -IHX tube

The nominal dimensions of the tube are 19 mm outer diameter (OD=2R) and 0.8 mm wall thickness WT (h). The tolerance on OD including ovality is ±0.1 mm. The tolerance on WT is ±10% of nominal value. Including the corrosion allowance, dimensions assumed for the design calculations are 18.18 mm OD and 0.6 mm WT. An optimum span length (l) of 800 mm is chosen from buckling, flow induced vibrations and pressure drop considerations. The deviation from the straightness of the free tube as procured is around 0.7 mm for a span of 800 mm. For the case of as built heat exchangers (tubes rolled and welded to tubesheets at either end with intermediate supports placed at 800 mm span), a total deviation of 1.5 mm is taken as the design value for the analysis. The shape of the deviation of one span of the tube from true theoretical position is shown in fig 4. The yield stress is 114 MPa at the design temperature of 798 K. Euler buckling stress for the tube ($=\Pi^2 EI/l^2$/area of cross section) is estimated as 96.3 MPa.

Parameters $\delta = 1.5 / 19 = 0.08$ and $\xi = 96.3 / 114 = 0.845$.

Corresponding to the values, X = 0.47 and Y = 0.43 from the chart (Fig A7 2261.1 in RCC-MR) accordingly the acceptable compressive stress is 45.26 MPa, the lower of 45.26 and 49.02 MPa. After applying a factor of safety of 2.5 for level A loading, the allowable buckling stress is worked out as 18.1 Mpa. This value is taken as the reference value. The effect of any possible uncertainties on this value (±5MPa) on the tubesheet thickness is studied in the subsequent paragraph.

3. 0 EFFECT OF BUCKLING STRENGTH OF TUBES ON THE TUBESHEET THICKNESS

The top and bottom tubesheets, the inner shell, the various rows of tubes and the outlet header shells are all modelled using axisymmetric COQU elements of INCA as shown in fig 5. The input details are as follows:

Material data:

Youngs modulus for solid portions = 1.64×10^5 MPa
Youngs modulus for perforated portions = 0.49×10^5 MPa
Poisson's ratio for solid portions = 0.3
Poisson's ratio for perforated portions = 0.36

Loadings:

Differential pressure on tubesheets = 0.85 Mpa (level A loading)
= 1.23 Mpa (level C loading)

Thermal loadings:

For perforated portion of top tubesheet = 798 K
For perforated portion of bottom tubesheet = 628 K
Mean temperature for solid rim portion = 807 K for top tubesheet
ΔT for solid rim portion = 17 K for top tubesheet
Mean temperature for solid rim portion = 630 K for bottom tubesheet

ΔT for solid rim portion = 5 K for bottom tubesheet

mean temperatures for tubes K (25 rows) = 718,723,727,731,733,735,737,738, 739,740,741,742,743,744,745,745,746,746, 743, 733, 729, 727, 725, 724, 722.

Using this model, the stresses in the tubes under pressure loading as well as steady state thermal loading are extracted. The pressure stress, thermal stress and total stress for various rows of tubes are extracted for the given tubesheet thickness and the distribution of the same is given in fig.6 for 120 mm thick tubesheets. The tubesheet thickness as a function of buckling strength of tube is obtained by repeating the analysis with different tubesheet thickness so as to limit the compressive stress to avoid buckling. It is worth mentioning here that the tube stresses are deciding the tubesheet thickness in PFBR.

Table 1: Effect of buckling strength of tubes on tubesheet thickness

Buckling strength of tube (MPa)	Tubesheet thickness (mm)
13	200
18	120
23	80

4.0 VALIDATION OF RCC-MR SIMPLIFIED APPROACH

It is necessary to ensure the applicability of RCC-MR procedure for the analysis of IHX tubes wherein there exists ovality, out of straightness and the uncertainty on the boundary conditions at the intermediate supports offered by ferrules.

Autrusson et.al. [4] have validated simplified analysis of RCC-MR against buckling by more than 60 experimental results on various models. Out of them, 12 tests are carried out on thin tubes under axial compression. The imperfections were neither measured nor used in their theoretical prediction using the charts. However Hamid and Wardle [5] in their investigation on buckling of fast reactor heat exchanger tubes have shown that the critical buckling load is very sensitive to initial geometric imperfections present in the tube. The buckling loads have been presented for wider range of imperfections (0.1 mm to 5.0 mm) on 25 mm OD and 1 mm WT tubes. For the same problem and with the same cases of imperfections, the buckling strength have been computed as per RCC-MR approach.

The RCC-MR procedure normalises the imperfection with respect to wall thickness. While it is appropriate to normalise the imperfections of ovality type with respect to wall thickness, the imperfections such as straightness is to be normalised with respect to OD of the tubes. The buckling strength for various cases of imperfections have been computed using RCC-MR charts, by two approaches namely normalising with wall thickness and normalising with OD of the tube. Both the results are plotted along with the reported values in fig 7. It may be seen that normalising with respect to wall thickness gives very conservative buckling load for larger imperfections while normalising with respect to OD gives reasonable comparison. Hence the approach followed for the assessment of buckling strength of PFBR-IHX tubes have been justified.

5.0 CONCLUSION

The effect of buckling strength of tube computed as per the simplified approach of RCC-MR A7 (1993), on tubesheet thickness of IHX has been studied in detail. The minimum tubesheet thicknesses required are 200, 120 and 80 mm respectively for the buckling strength of 13, 18 and 23 MPa. Further it is justified that 120 mm tubesheet thickness is adequate for PFBR-IHX. The applicability of RCC-MR approach for the heat exchanger tube buckling studies is validated by using the published experimental results. Towards validating further for the direct relevant cases, tests on PFBR-IHX tubes are being done and results would be presented in the conference.

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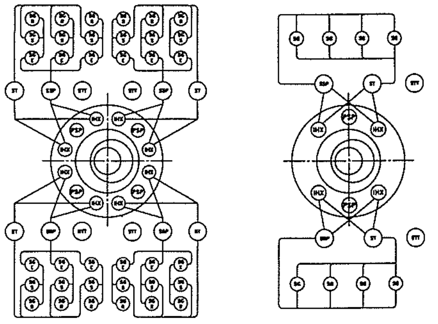

Fig.1 PFBR component layout

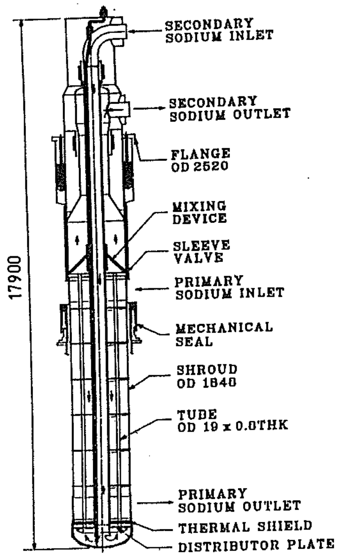

Fig.2 Intermediate Heat Exchanger

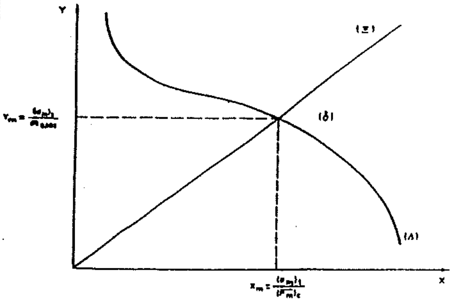

Fig.3 Schematic RCC-MR diagram for X and Y

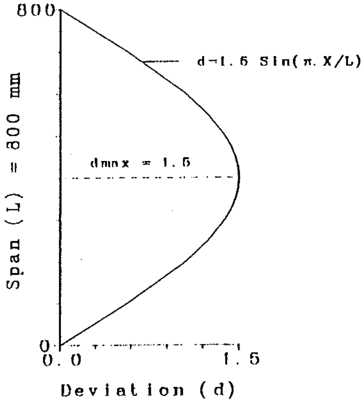

Fig.4 Imperfection of tube span

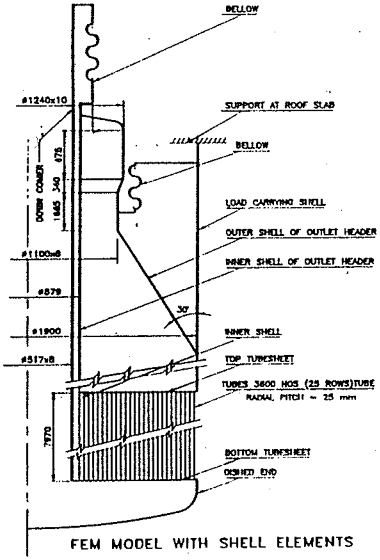

Fig.5 FEM model with shell elements

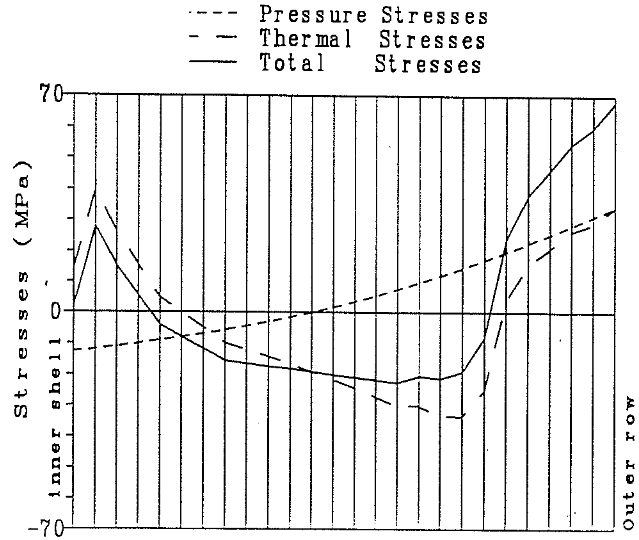

Fig.6 Stress distribution in tube bundle
ΔP = 0.85 MPa (Level A)

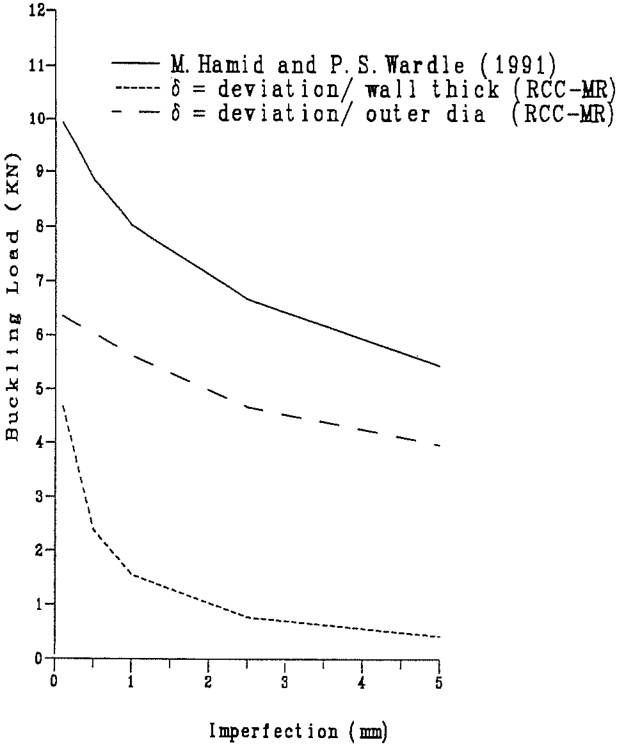

Fig.7 Effect of imperfection on buckling load