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FLOW INDUCED VIBRATION ANALYSIS OF IHX TUBE BUNDLE IN PFBR

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1 INTRODUCTION

The Intermediate Heat Exchanger (IHX) of Prototype Fast Breeder Reactor (PFBR) consists of a tube bundle having 1782 straight tubes of 24 mm OD x 1 mm WT rolled and welded to tubesheets at both ends(Fig.1). The tubes are arranged in circular pitch in 18 concentric rows around central downcomer (radial/ circumferential pitch being 30/31.4 mm). The primary sodium enters radially on the shell side at the top of the bundle, flows vertically down and goes out radially to the cold pool at the bottom of the bundle. There is a vertical shell around the tube bundle with windows at the top and bottom. There is no shell at window locations and there are vertical strips welded to shells. The height of opening is 600 mm at each window. The ferrule and belt type of support for the bundle is envisaged. Based on preliminary design analysis, a design with 6 supports have been favoured so as to have the necessary margin against buckling also. The supports are equispaced with 1029 mm between each other. However the spans at extreme ends (distance between tubesheet and extreme support) where crossflow occurs are shorter (900 mm each). The major concern of flow induced vibration in IHX tube bundle is due to cross flow at inlet and outlet windows. Both vortex shedding and fluid-elastic instability analysis are carried out. Uniform cross flow distribution along the full window height of 600 mm at both inlet and outlet, perfectly normal to the tube axis have been assumed in the analysis.

2 ANALYSIS METHODS

To determine the adequacy of design, FIV analysis have been carried out following the procedure given in TEMA (1988) and the proposed Section III Appendix N (M.K.AU-Yang, 1991). It is noted that avoiding lock-in synchronisation as per the proposed Appendix N leads to unduly over conservation. Instead resonance response during lock-in is estimated for vortex shedding excitation. The critical velocity to initiate fluid elastic instability have also been determined. In all these procedures, one of the important input is information about natural modal behaviour. Towards estimating this, the tube has been assumed to be fixed at the tubesheet ends and simply supported at support. These assumptions are found to be realistic with experiment on a model (Prakash, 1988). The tube has been analysed using PAFEC and SAP-IV independently. The tube is modelled with Beam Elements (34100) in PAFEC and pipe elements in SAP-IV (Fig.3). The continuous tube natural frequencies of the first five modes are 36.5 Hz, 42.6 Hz, 51.2 Hz, 61.3 Hz and 71.4 Hz.

2.1 Excitation Due to Vortex Shedding

Tubes are in line in some locations and staggered in other as shown in layout (Fig.2).

Table 1: Strouhal Number from Various References

Tube Arrangement	Chen(1977)	Fitz-Hugh(1978)	TEMA(1988)
In-line	0.44	0.46	0.45
Staggered	0.39	0.35	0.25

Conservatively a value of 0.46 is used in the analysis. The mean gap velocity at the outermost row is 1.453 m/s and the vortex shedding frequency is 28 Hz. The proposed Appendix-N has given the potential for resonance by a bond of plus or minus 30 percent of this frequency. Fundamental natural frequency (36.5 Hz) is found to be 1.3 times the vortex shedding frequency. Hence a resonance excitation at first moe is postulated. The oscillating life coefficient for IHX tube configuration is expected to be < 0.1 based on reported values (Pettigrew, 1978, Chen.Y.N). However a conservative value of 1 as given in the proposed Appendix N is used for the analysis. The amplitude of lift force so computed is 13 N and is uniformly distributed over the window height and assumed to oscillate sinusoidally with a frequency corresponding to fundamental mode.

2.2 Response Analysis for Resonance with Vortex Shedding

The tube has been analysed by Response Analysis using SAP-IV (Pipe Element) and PAFEC (Beam Element). In SAP-IV direct step-by-step integration method is employed and in PAFEC, Newmark Beta Response Analysis is used. The stress history at each node is obtained. At the instance of occurrence of highest stress, the stress distribution is tabulated. Stresses are also computed from the displacement history obtained using Harmonic Analysis of PAFEC. The results obtained from SAP-IV and PAFEC are found to match closely. The maximum alternating stress intensity computed is 25 MPa. The endurance limit of SS 316 at 538 deg.C is 75 MPa (P.Marshall, 1981) after taking a factor of two on stress in accordance with ASME design rules.

2.3 Analysis for Fluid Elastic Instability

F.L. Eisinger(1980) gives the critical flow velocity to initiate fluid elastic vibration for a multispan tube with spanwise variation of flow velocity, fluid density and tube mass. Using the equivalent velocity concept (recommended formula in proposed Appendix-N), a computer programme 'CRITICAL' has been written to evaluate the ratio of critical velocity distribution to the actual velocity distribution. The damping constant for various modes (logarithmic decrement) is given as a function of natural frequency and other parameters in TEMA. The instability constants are given as a function of parameter. X(=m / D) and P/D in TEMA for various tube patterns. The outermost three rows of IHX tube bundle are shown in Fig.2. If the flow is perfectly radial, tube layout at some locations is equivalent to 30 deg. triangular pattern and some other locations square tube layout could be seen. However the tube pattern in between these two locations does not fall in any category specified in TEMA and are also staggered. The programme calculates the instability constants on a conservative basis. [In case of IHX rotated square (45 deg.) gives minimum critical velocity as per TEMA]. The proposed Appendix-N has recommended the instability constant C=3.3 (3.4 is for square) and is not varying with P/D as in TEMA. Further C=3.1 (obtained as per TEMA) is lower and hence used in the present analysis. The natural frequencies along with the modeshapes and the actual velocity distribution are the required input. A unique ratio is printed for each mode upto 30 modes. If the ratio is less than or equal to 1 (the critical velocity less than the actual velocity), the instability is observed. If the ratio is more than one, the tube is safe with respect to instability. The minimum critical velocity is found to occur at the sixth mode. This is explained by the shape of the sixth mode which is largest in the end spans where crossflow occurs (Fig.4). This is also in line with the result of process heat exchanger tube reported where 8th mode was found to govern (Pettigrew, 1978).

2.4 Analysis for Parallel Flow Induced Vibration

Parrallel flow vibration amplitudes have been computed as per Burgreen and Paidoussis (recommended in the proposed Appendix N) correlations. Paidoussis correlation gave the higher value of 23 microns (compared to 3 microns of Burgreen) for the longest intermediate spans. The associated bending stress is found to be negligible.

3 EXPERIMENTAL VERIFICATION

Experiments were carried out in water on a sixty degree sector model. Vibration levels measured were low in general. The highest amplitude of vibration was 180 microns and is measured at 120% of the nominal flow required from modelling criteria. (Prabhakar.R., 1990). The heat exchanger is safe based on experimental results as the stress induced is lower than the endurance limit.

4 CONCLUSION

The integrity of the tube bundle of IHX against flow induced vibration risks has been assessed using various procedures available in open literature including the one proposed for the inclusion in ASME Appendix-N and accordingly relative conservatism in the above procedures are brought out. From the analysis, it is noted that the maximum alternating stress intensity computed for resonance response under FIV is about 25 MPa even using a conservative value of CL equal to 1 as recommended in the proposed Appendix-N (endurance limit of SS 316 at 538 deg.C is 75 MPa). This indicates that criteria for avoiding lock-in-synchronization proposed in Appendix-N is highly conservative. Further the minimum critical velocity for avoiding fluid elastic instability is found to be more than the velocity for full load operations by 70%. The tube bundle is thus found to be safe against vortex shedding and fluid-elastic instability mechanisms. The analysis for random excitation and the analysis with more realistic variation of flow velocity at inlet/outlet are areas of future work.

Table 2. Variation of Peak Stress

Node No	Time at Peak Stress	Peak Stress (MPa)
31	0.090	4.0
32	1.713	5.6
33	1.947	12.0
34	1.879	17.4
35	1.961	20.8
36	1.88	25.0
37	1.934	20.8
38	1.934	17.4
39	1.934	12.2
40	1.77	5.4

Table 3. Stress Distribution at t = 1.88 S

Node No	Time at Peak Stress	Peak Stress (MPa)
31	2.6	2.2
32	4.8	5.6
33	11.6	13.0
34	17.0	18.8
35	20.6	22.4
36	25.0	24.6
37	20.6	22.6
38	17.2	18.4
39	11.8	12.8
40	5.2	5.4

Table 4. Critical velocity for various modes

Mode No.	Freq. (Hz)	Log Decrement	Critical Vel. m/s
1	36.5	0.09	13.19
2	42.6	0.08	7.41
3	51.2	0.07	5.80
4	61.3	0.05	5.35
5	71.4	0.05	6.08
6	88.6	0.04	2.48
7	89.2	0.04	2.55
8	141.8	0.02	18.07
9	154.7	0.02	12.73
10	170.8	0.02	11.91

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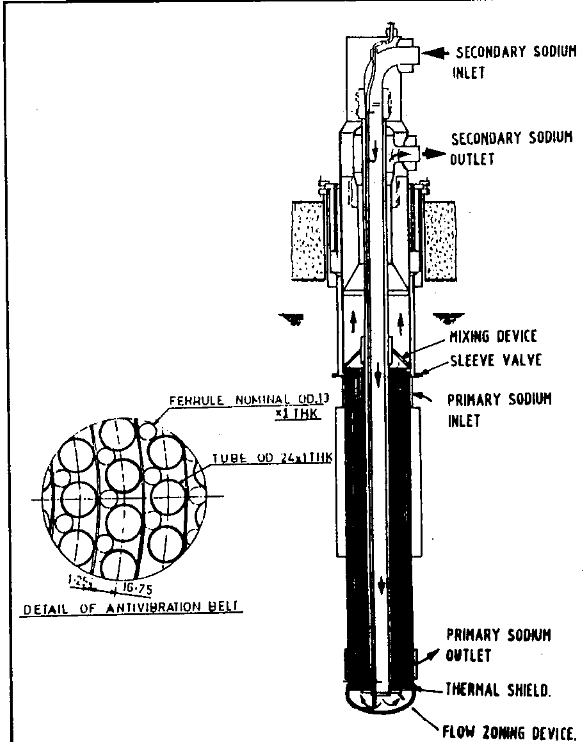
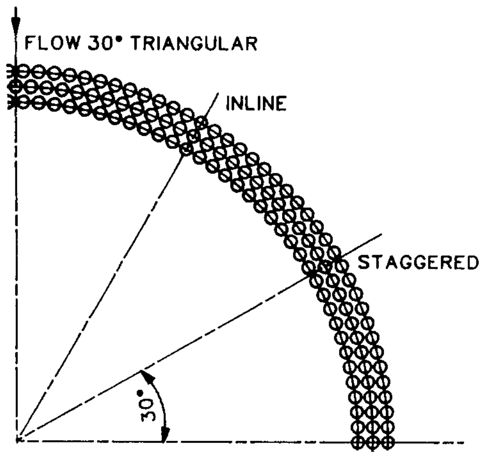
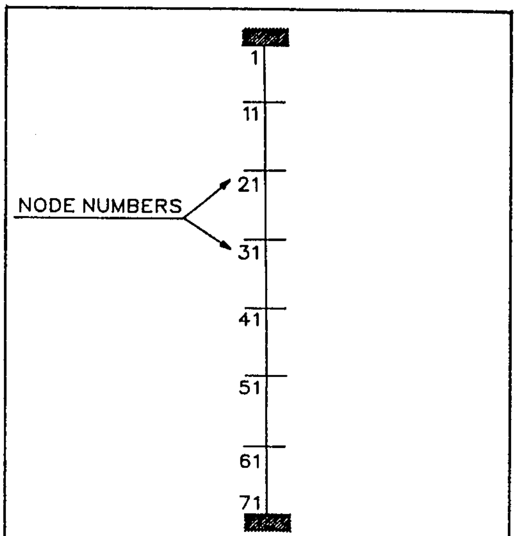


FIG.1 PFBR-IHX

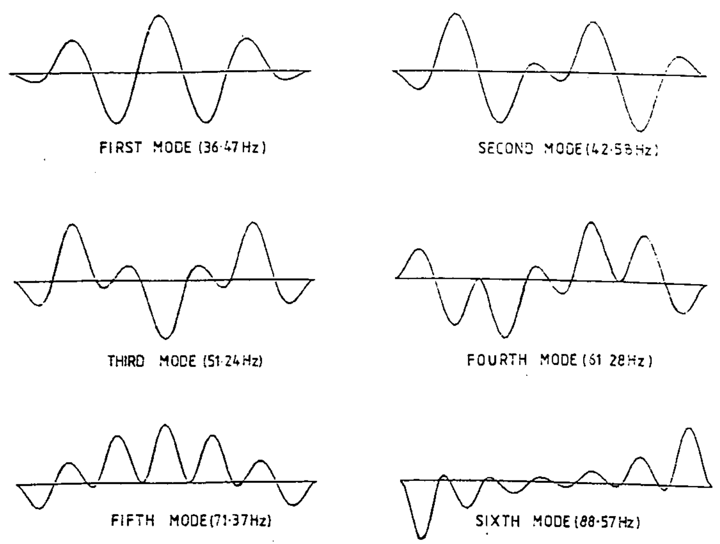


TUBE LAYOUT OF
LAST THREE ROWS
FIG. 2



FEM MODEL 2 – BEAM ELEMENTS (PAFEC)
PIPE ELEMENTS (SAP IV)

FIG. 3



MODE SHAPES FOR PFBR IHX. TUBE
FIG. 4