Dependence of Intermediate Heat Exchanger Life on Primary Sodium Heating Rate during Power Raising

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Abstract. The heating rate of primary sodium is an important consideration during start-up of the reactor. During cold shutdown condition of the reactor, the temperature of both hot pool and cold pool sodium is 453 K. During power raising, gradually the temperature of primary sodium will be increased at a specified rate. Traditionally, a slow heating rate of 20 K/h is considered. This requires about 20 hours to attain full power. Higher rate of sodium heating, which reduces the power raising duration, may cause creep and fatigue damages to the reactor components that are immersed in hot pool. In this study, the structural damage possible in the Intermediate Heat eXchanger (IHX) as a function of heating rate at a critical region has been determined and the dependence of IHX life on the heating rate is estimated. The fatigue damages caused due to power raising at the free level of sodium for heating rates 20 K/hr, 40 K/hr and 60 K/hr are 7.19E-17, 1.64E-08 and 4.95E-05 respectively and the corresponding creep damages are 1.3 E-02, 9.9 E-02 and 1.45 E-02 for 861 cycles. The number of allowable cycles determined by considering the creep and fatigue damage values at full power, along with the values at power raising are 2798, 2187 and 1958 cycles at heating rates 20 K/hr, 40 K/hr and 60 K/hr respectively. Hence, a primary sodium heating rate of 60 K/hr is acceptable during power raising in view of IHX life. This reduces the power raising duration from 20 hours to 6.6 hours.

Key Words: PFBR, IHX, power raising, start-up.

1. Introduction

During power raising, the sodium temperature is increased from 453 K to 820 K. The rate at which the power raising is to be done is a critical issue. As a safe practice, the power raising can be done slowly by increasing the sodium temperature at the rate of 5 K/hr to 20 K/hr. But this takes a long time for attaining full power, viz, 80 to 20 hours per cycle. On the other hand, to minimize this time, the power raising can be done at a higher rate, i.e, 40 K/hr to 100 K/hr or even higher. But higher heating rate causes creep and fatigue damages to the reactor components like Control Plug, Intermediate Heat eXchanger (IHX) and Inner Vessel, which are in contact with the hot primary sodium. Hence, a thermo-mechanical analysis has been carried out to optimize the heating rate during power raising, wherein the study focuses on IHX.

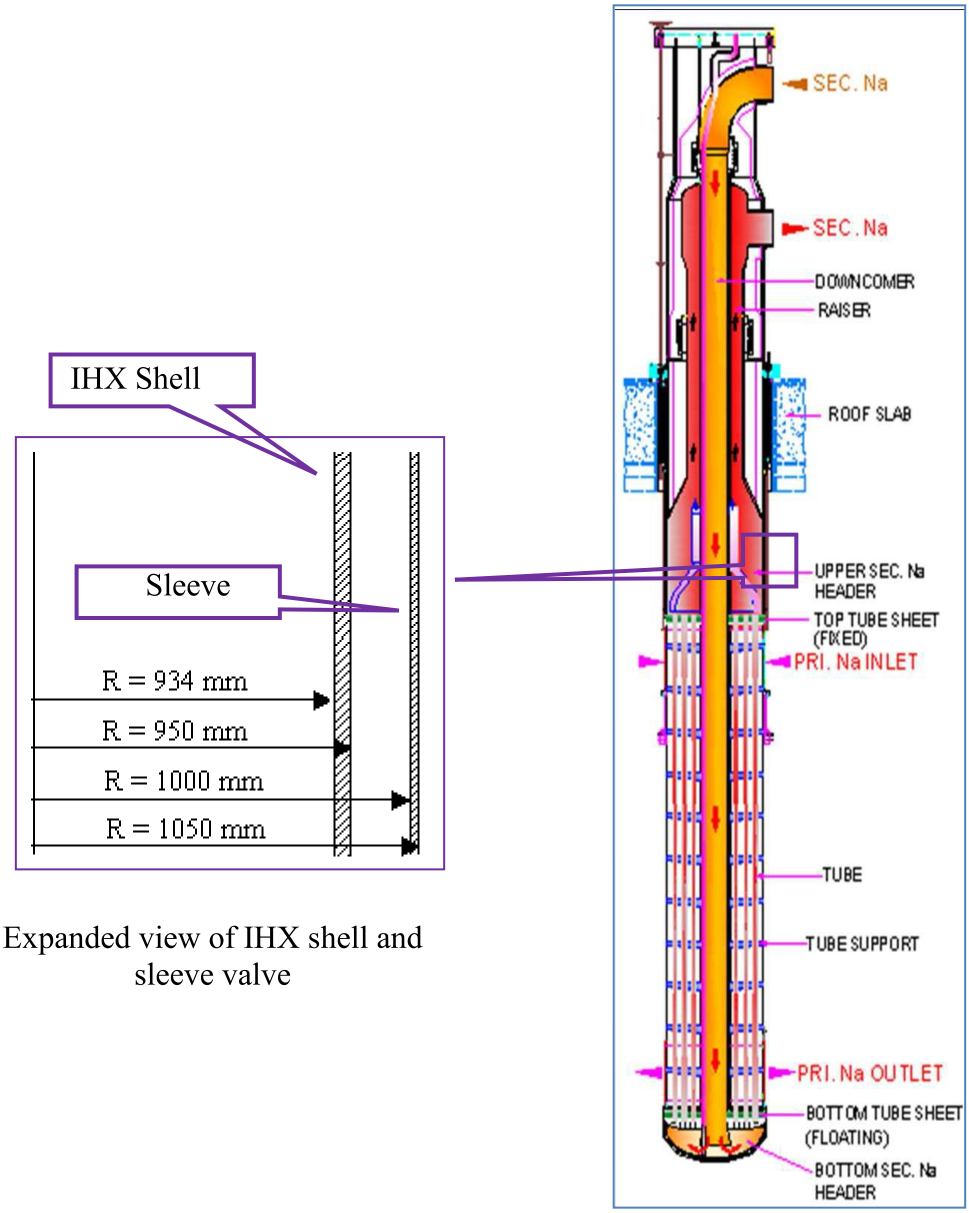
2. Functions and Geometrical Details of IHX

The function of IHX is to transfer thermal power from the radioactive primary sodium to the non-radioactive secondary sodium [1]. It also takes part in the decay heat removal and provides a leak tight barrier between primary and secondary sodium. It protects the core against the effects of sodium water reaction taking place in steam generator. The geometrical details of IHX are given in Fig.1 [2].

It is a vertical counter-current, shell and tube heat exchanger. The tube bundle consists of 3600 straight tubes of outer diameter 19 mm and 0.8 mm thickness. The tubes are rolled and welded to the top and bottom tube sheets. The secondary sodium enters through the down comer and flows upwards on the tube side, whereas the primary sodium enters through the window and travels from top to bottom on the shell side. Manually operated sleeve valve is provided to close the primary sodium inlet windows to permit operation of reactor with one secondary loop.

The tube sheets are the critical parts among other parts of IHX. During power raising, the sodium temperature is gradually increased. This, along with the raise in sodium free level causes damage to the component. Hence, the region at the sodium free level is considered for the present analysis.

The free level of sodium as indicated in Fig.1, is at the upper secondary sodium header. It consists of two concentric cylinders, the inner one being the IHX outer shell and the outer cylinder being the sleeve valve as depicted in the inset of Fig.1.



Expanded view of IHX shell and sleeve valve

Fig.1. Geometrical details of IHX

3. Loading Conditions in IHX

The level of hot pool sodium (at 453 K) at the start of power raising is ~ 26700. Upon reaching full power (820 K), the hot pool sodium level reaches 27400. The maximum sodium temperature is taken as 833 K. Thus, the sodium travels a height of 700 mm while gaining 380 K temperature rise on an average.

The evolution of sodium temperature at various locations namely, IHX Shell inside (secondary sodium outlet), IHX shell out, IHX sleeve inside and IHX sleeve out (primary sodium inlet) for heating rate 20 K/hr is shown in Fig.2.

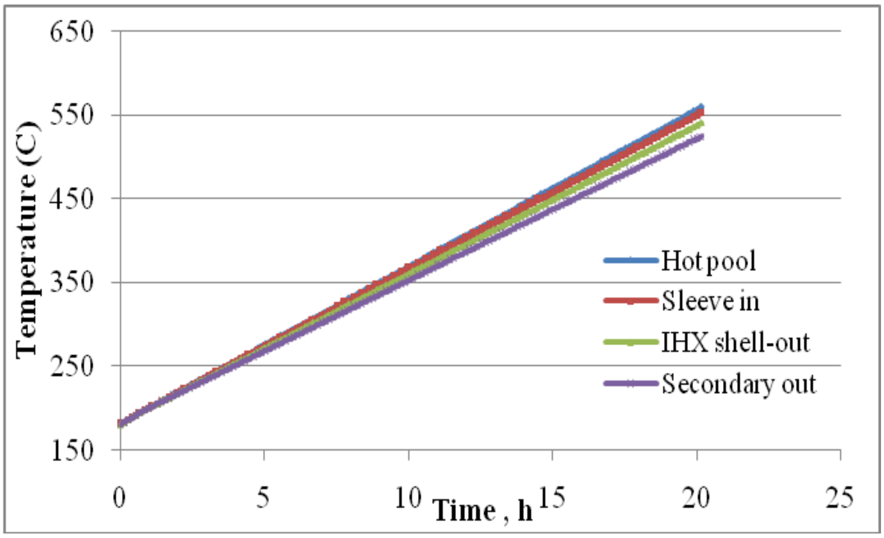


Fig.2: Evolution of sodium temperature at IHX

The inner side of IHX shell is washed by secondary sodium whereas the outer side of the IHX shell is surrounded by primary sodium at the bottom and argon cover gas at the top. The sleeve is surrounded by primary sodium at the bottom and argon cover gas at the top (both inside and outside). The argon gas temperature is the same for all the three top regions. The argon gas temperature is calculated using the expression given below and is updated at each iteration.

$$T_{Ar} = (((393.0 + T_{Nas}) / 2.0) + T_{Nas}) / 2.0$$

Where T_{Na} is primary sodium temperature (K) and T_{Ar} is argon gas temperature (K).

The time taken to heat the primary sodium and the raise in sodium level at three heating rates considered are given in Table-1.

Table-1: Input parameters used in the analysis

Heating Rate	Heating Time	Raise in Sodium level in 1 hour
20 K/hr	20 hours	35 mm
40 K/hr	10 hours	70 mm
60 K/hr	6.6 hours	105 mm

4. Flow chart for developing the FE program

In order to simulate the complex loading conditions at the free surface, a numerical model has been developed using CASTEM code. The generalized approach followed to determine the stress and temperature at every iteration is shown in Fig.3.

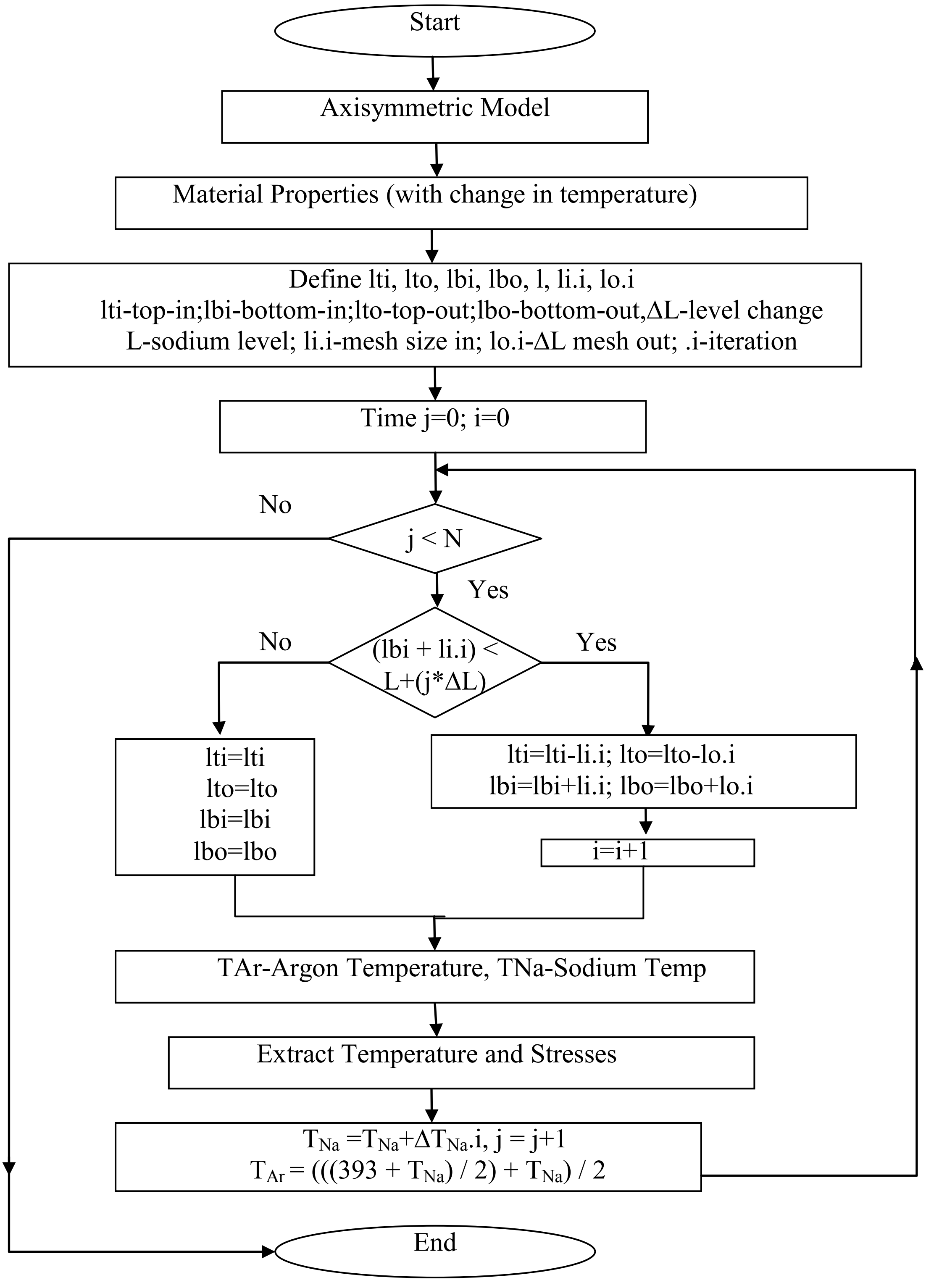


Fig. 3: Flow chart for finite element program to simulate the change in length and temperature of primary sodium

5. Material Data

The material for the construction of IHX is SS 316 LN. Density has been conservatively taken at 423 K and all the other material properties have been conservatively taken at 823 K. Important material properties used for the analysis are given below. These material properties are taken from RCC MR Appendix A3 [3].

- Density, ρ = 7879 kg/m^3
- Young's Modulus, E = 1.8E11 Pa
- Poisson's Ratio, ν = 0.3
- Expansion coefficient (α) = 16.9 x 10^{-6} /K
- Conductivity (K) = 17.74 W/mK
- Specific Heat (C) = 540 J/kgK

6. Finite Element Formulation

An axi-symmetric model of the IHX outer shell and sleeve has been employed for the finite element analysis. The IHX is supported at the roof slab. Thus, as the IHX is hanging from the top, the axial displacement has been arrested for simulating the boundary conditions. The finite element mesh of the IHX is shown in Fig.4.

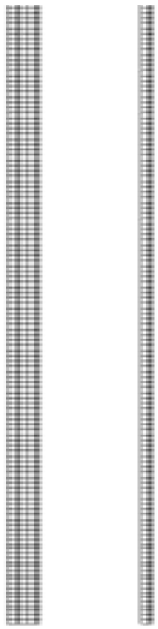


Fig.4: FEM mesh of IHX

7. Results and Discussion

Transient analysis of the IHX with the above mentioned loading and boundary conditions has been carried out considering a heating rate of 20 K/hr. The evolution of temperature of the shell and sleeve of the IHX and the corresponding stress distribution are shown in Figs .5-8. It is observed that, as the temperature increases from 456 K to 755 K, the stress increases from 2.6 MPa to 70.3 MPa. Thereafter, the stress decreases to 52.3 MPa when it reaches the maximum temperature.

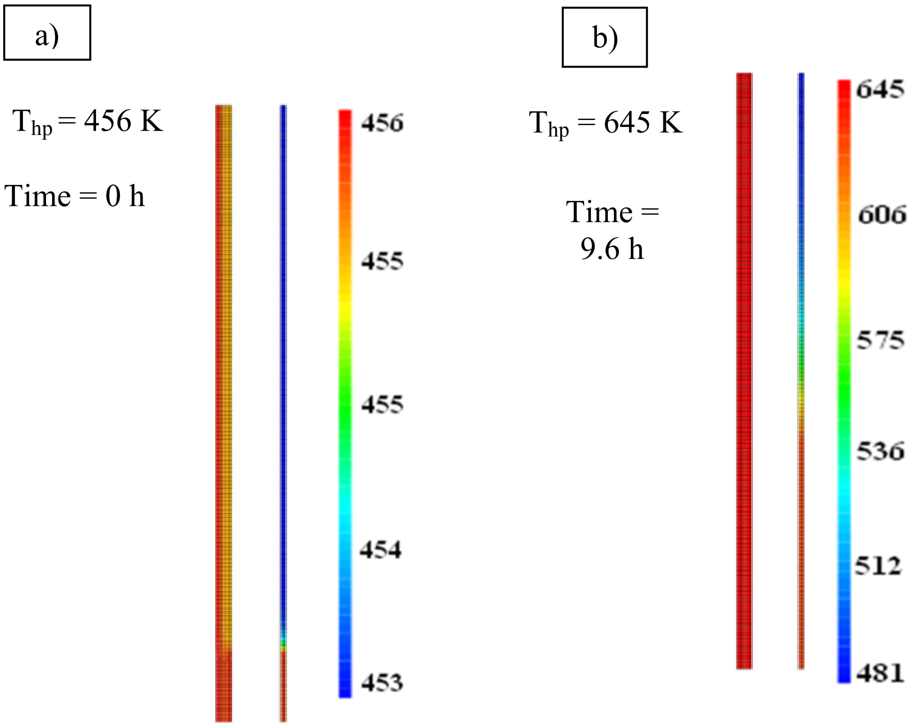


Fig.5: Temperature field (K) at 0 h and 9.6 h for 20 K/hr

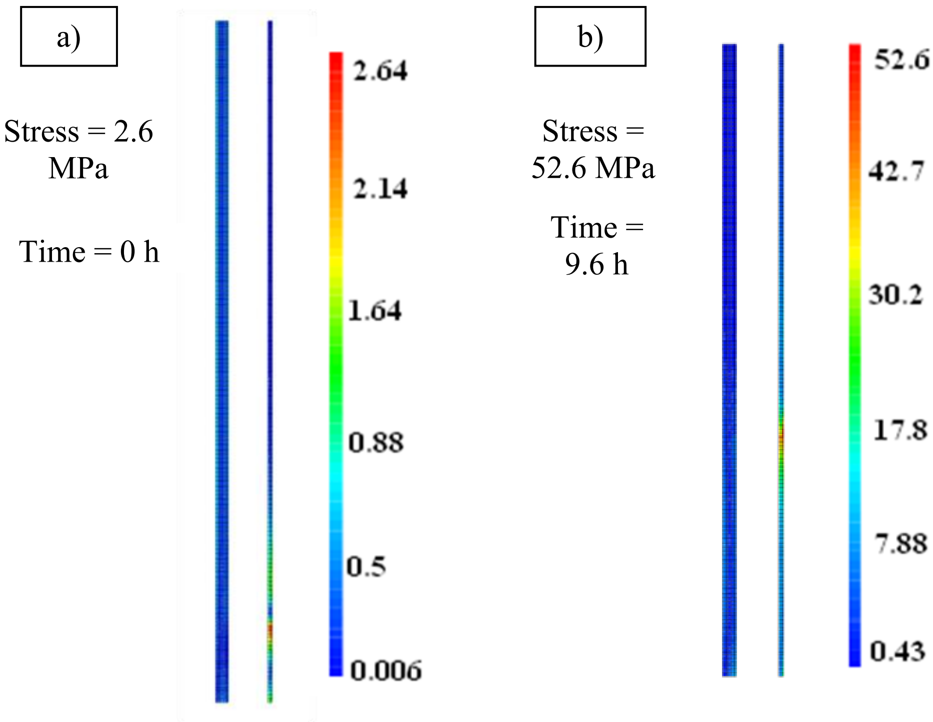


Fig.6: Stress distribution at 0 h and 9.6 h for 20 K/hr

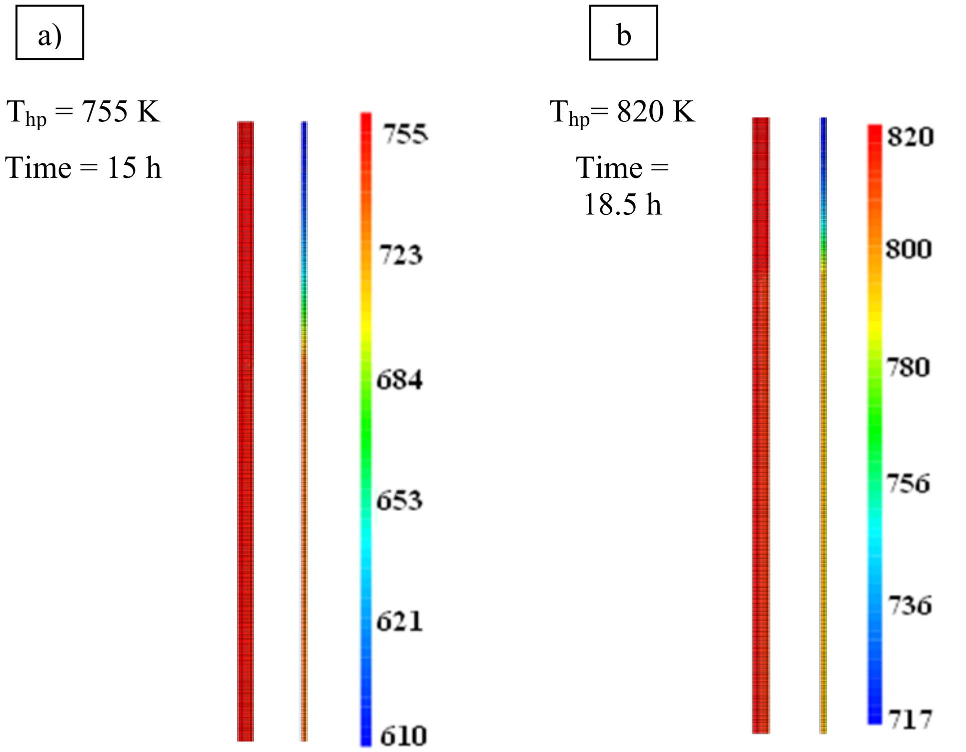


Fig. 7: Temperature field (K) at 15 h and 18.5 h for 20 K/hr

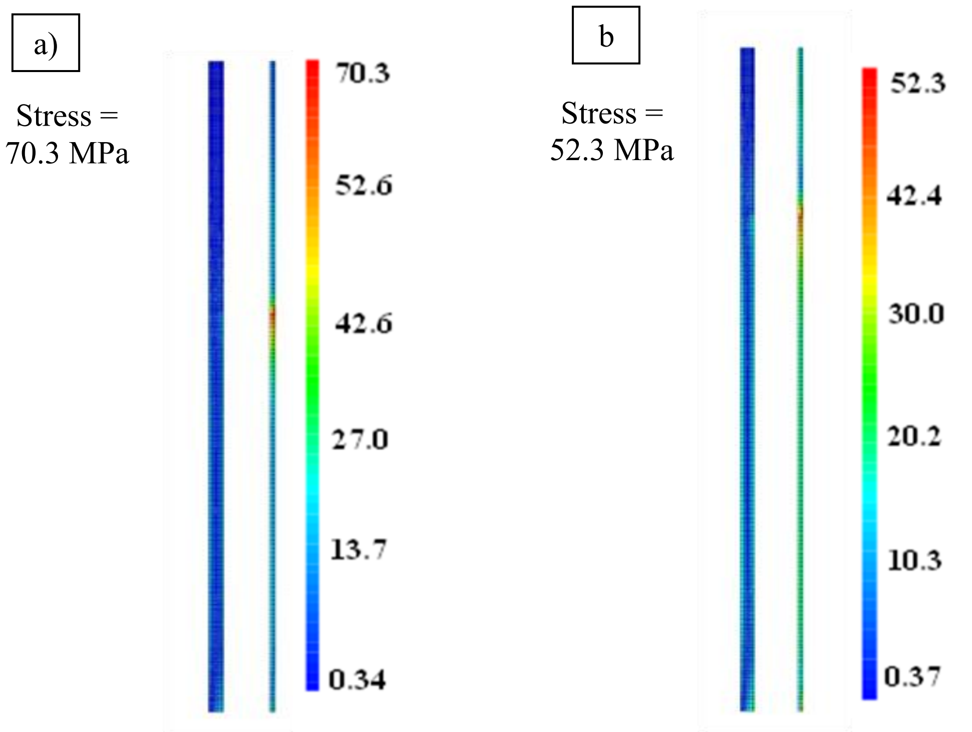


Fig. 8: Stress distribution (MPa) at 15 h and 18.5 h for 20 K/hr

Transient analysis of the IHX with the loading conditions mentioned in section 3 has been carried out with primary sodium heating rate at 40 K/h. The maximum stress at the sleeve was found to be 131 MPa at 802 K temperature.

A similar analysis with the loading conditions at 60K/hr has also been carried out. The maximum stress at the sleeve valve was found to be 182 MPa at 801 K at 8.7 hrs.

8. Design Check for Secondary Loading

8.1 Assessment of Progressive Deformation

In high temperature structural design, it is very important to prevent progressive deformation in the points of functional requirements and structural integrity. When there is significant creep, the progressive deformation designates the increase in deformation due to loads caused by imposed cyclic deformation such as thermal deformation.

The secondary ratio (SR_1) in relation to the primary membrane stress intensity (P_m) and the secondary ratio (SR_3) in relation to the sum of the primary stress intensities ($P_L + \Phi\ P_b$) are determined and the efficiency indicies (ν_1 & ν_3) are obtained from the efficiency diagram. Using these values, the effective stress intensities (P1 and P3) are calculated. The values of P_m and $P_m + P_b$ are at the tube sheet location (taken conservatively) which are extracted from [5].

The primary creep strain is given by $\varepsilon_c\,(\%) = C_1\ T_H^{C2}\ (\sigma)^{n1}$, where $\sigma = 1.25\ P_1$ as well as $1.25\ P_3$ have been used for the above mentioned two cases. The hold time (T_H) is taken as 20, 10 and 6.6 hours respectively for 20 K/hr, 40 K/hr and 60 K/hr. The plastic strain is calculated from the equation $\sigma = C_o * (R^t_{p,0.2})_{moy} * (\varepsilon_p)^{n0}$ (for $\sigma = 1.25\ P_1$ as well as $1.25\ P_3$) [A3.1S.451 in RCC MR]. These values are provided in Table – 2 and are found to be within the allowable limits.

Table – 2: Effective Primary Stress Intensities and Total Strain

Cases	20 K/hr	40 K/hr	60 K/hr	Allowable
P_1 (MPa)	34.7	47.2	53.1	124 [1.3*S_m]
P_3 (MPa)	62.4	79	91.15	187 [1.3*1.5*S_m]
$\varepsilon_p + \varepsilon_c$ (for 1.25 P_1) (%)	0.013	0.03	0.04	1
$\varepsilon_p + \varepsilon_c$ (for 1.25 P_3) (%)	0.128	0.25	0.39	1*

* Conservatively allowable values of weld are used, anticipating the presence of weld at peak stress location.

8.2 Assessment of Creep Fatigue Damage

The creep and fatigue damage calculations have been done as per RCC-MR RB [4] for 20 K/hr, 40 K/hr and 60 K/hr and the values are given in Table-3. The $\bar{P}_{max}$ value is calculated from the values of P_m and $P_m + P_b$ extracted from [5]. The creep and fatigue damages are added to those obtained from the plant design life [6].

Table – 3: Creep and Fatigue Damage Calculations for IHX Free level of Sodium

Cases	20 K/hr	40 K/hr	60 K/hr
$\Delta\sigma_{Tot}$ (MPa)	70.3	131	182
$(\overline{\Delta\varepsilon})_{el+pl}$ (%)	0.04	0.076	0.11
$\bar{P}_{max}$ (MPa)	42	42	42
$\overline{\Delta S}^* = \overline{\Delta\sigma}^* - \overline{\Delta P}$ (MPa)	70.3	131	182
K_s	1	0.88	0.72
σ_k (MPa) = $\bar{P}_{max} + K_s\ \overline{\Delta S}^*$	112.3	157.4	173.3
$(\overline{\Delta\varepsilon})_{cr}$ (%)	0.0052	0.014	0.017
$(\overline{\Delta\varepsilon})$ (%) = $(\overline{\Delta\varepsilon})_{el+pl} + (\overline{\Delta\varepsilon})_{cr}$	0.04	0.09	0.13
No. of cycles allowable (N_d)	1.2 E+19	5.2 E+10	1.7 E+07
Fatigue Damage *[861 cycles]*	7.2 E-17	1.6 E-08	4.9 E-05
$S_r = \sigma_k / 0.9$ (MPa)	124.7	174.9	192.6
t_r (hours)	1.3 E+06	8.7 E+04	3.9 E+04
Creep Damage *[861cycles]*	0.013	0.099	0.145
Fatigue Damage (from [6])	0.002	0.002	0.002
Creep Damage (from [6])	0.29	0.29	0.29
Total Fatigue Damage	0.002	0.002	0.002
Total Creep Damage	0.303	0.389	0.435
D_{eff}	0.3	0.39	0.44
No. of cycles	2798	2187	1958

The above results show that the creep fatigue damage caused due to heating rate up to 60 K/hr is acceptable.

9. Conclusion

Detailed structural analysis has been carried out to investigate the possible damage caused to IHX, due to the heating rate of primary sodium during power raising. The fatigue damages caused due to power raising at the free level of sodium for heating rates 20 K/hr, 40 K/hr and 60 K/hr are 7.19 E-17, 1.64 E-08 and 4.95 E-05 respectively and the corresponding creep damages are 1.3 E-02, 9.9 E-02 and 1.45 E-02 for 861 cycles. The number of allowable cycles determined by considering the creep and fatigue damage values at full power, along with the values at power raising are 2798, 2187 and 1958 cycles at heating rates 20 K/hr, 40 K/hr and 60 K/hr respectively. It may be noted that these results are based on elastic route, and the permissible number of cycles are expected to increase if an inelastic analysis is performed. Hence, a sodium heating rate of 60 K/hr is acceptable during power raising in view of IHX life. This reduces the power raising duration from 20 hours to 6.6 hours. However, the other components which are immersed in hot pool sodium i.e., inner vessel is being analyzed for the final recommendation of the sodium heating rate during power raising.

References

[1] Srinivasan R. et. al., "Conceptual Design of Intermediate Heat Exchanger", IGCAR Design note: PFBR/32130/DN/1005/R-C.

[2] Athmalingam S. et. al., "Intermediate Heat Exchanger for PFBR and Future FBR", Technical Meeting on Innovative Heat Exchanger and Steam Generator Designs for Fast Reactors, 21-22 December 2011 at IAEA Headquarters.

[3] RCC-MR Section I, Subsection Z, "Technical Appendix A3", 2010.

[4] RCC-MR Section I, Subsection B, "Design and construction rules for class-1 components of FBR nuclear islands", 2010.

[5] Suman Gupta and Chellapandi P, "Application of RCC-MR for the structural design of tubesheet of Intermediate Heat Exchanger for a sodium cooled fast reactor", Nuclear Engineering and Design, 280 (2014) 181-200.

[6] Chellapandi P., et. al. "Plant Design Life", IGCAR Design Note: PFBR / 30000 / DN / 1016 /R-0 (2001).