Design of Sleeve Valve Mechanism for Primary Sodium Pump of Future FBR

S.Aravindan[1], Bhagwana Ram Manda[1], K.V.Sreedharan[1], S.Athmalingam[1] & P.Puthiyavinayagam[1]

[1]Reactor Design Group, Indira Gandhi Centre for Atomic Research, Kalpakkam, India.

E-mail contact of main author: aravinds@igcar.gov.in

Abstract. Future FBRs in India with 600MWe capacity are designed with three Primary Sodium Pump (PSP). As the PSPs are operating in parallel, failure of one PSP will result in a significant reverse flow through it, thereby reducing the flow through the core. Minimizing or arresting the reverse flow will in turn increase the flow to the core and the power operation of reactor can be resumed with two pumps. Hence, an active system called sleeve valve mechanism is conceptualized in PSP, to facilitate the power operation of reactor in 2/3 mode. The mechanism contains a sleeve shell (outside the PSP shell) for closing the suction passage. It is designed to withstand the pressure surge by taking accidental closure into account, under all operating conditions. The sleeve shell will not perfectly seal the suction passage due to provision of gap for movement of sleeve shell outside the PSP shell, thereby leaving an annular gap resulting in a leakage. The leak flow rate and leak flow velocity are reduced by increasing the leak path resistance with a labyrinth, which is optimized to give the maximum possible pressure drop.

The sleeve shell can be raised or lowered using three tie-rods, which are designed with galling resistant screw threads for converting the rotary motion from drive motor to linear motion of sleeve shell. A universal coupling is provided in the tie-rods to accommodate the tilting of the PSP. The synchronous motion of the tie-rods is ensured by a planetary gear drive type arrangement provided above the roof slab. The drive arrangement is designed with manual and electric drives for diversity. Safety interlock systems are designed, which prevents any unwarranted operation of the mechanism. The primary cover gas is sealed with dedicated seal systems for each tie-rod, with provisions for monitoring inter seal argon. The tie-rods along with the sleeve shell are designed to be an integral part of pump, thus facilitating handling them as a single unit. It is planned to validate the design of the sleeve valve mechanism by experimental simulation and testing.

Key Words: Primary Sodium Pump; sleeve valve mechanism; arresting the reverse flow.

1. Introduction

Future Fast Breeder Reactors of 600MWe capacity are being designed in India, as a successor of Prototype Fast Breeder Reactor (PFBR) of 500MWe. The head and flow rate requirements of the primary sodium system are determined in order to assess the design rating and the number of Primary Sodium Pump (PSP) required for Future FBR. It is estimated that three PSP operating in parallel can satisfy the required head and flow while satisfying the constraints on size of the reactor assembly and the cost of the pump. The presence of three PSP offer various advantages over two PSP (as in PFBR) viz,

i. Since flow handled per pump is reduced compared to PFBR, Net Positive Suction Head Required ($NPSHR_{3\%}$) of each pump will reduce as the flow per pump decreases [1]. Thus, the overall diameter of PSP will be relatively less.
ii. Provide operational flexibility for the reactor during startup and if one out of three PSP is not available (2/3 mode), thereby enhancing plant availability.

iii. Since the number of primary pipe is increased from four to six, flow to the core will be significant even during higher category design basis event like primary pipe rupture.
iv. Also, the cost involved in technology development of large-sized components will be minimized.

2. Providing operational flexibility

The primary sodium pump has suction from the cold pool and delivers the sodium to two primary pipes. The primary pipes from three pumps were connected to a single plenum of grid plate. The flow from the grid plate gets heated up as it passes through the reactor core and enters the hot pool. It comes back to cold pool after rejecting heat to secondary sodium while passing through the intermediate heat exchanger as shown in FIG. 1.

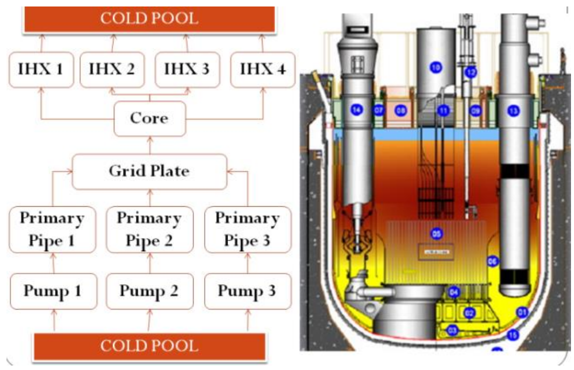

FIG. 1. Coolant flow network and reactor assembly of future FBR

The pumps are not provided with Non Return Valve (NRV) to arrest flow reversal in case of a pump trip. In the case of pool type reactor like future FBR, the absence of NRV provides various advantages like

a) Net Positive Suction Head Available (NPSHA) for the impeller increases in the absence of NRV due to increase in submergence, within the available height constraint. Thus, Net Positive Suction Head Required ($NPSHR_{3\%}$) can be increased, which results in a reduction of overall pump size. This may help in minimizing main vessel size, if the size of the pump governs the main vessel dimensions.

b) If NRV is provided, it will introduce additional flow resistance in the primary circuit, thereby increasing the total head to be developed by the pump (to deliver the same flow). Thus absence of NRV will help in minimizing the pump's power requirements. Minimizing pressure drop also helps in attaining better heat removal during natural convection.

c) The downtime due to operation and maintenance related issues of NRV are prevented [2] [3].

However, as the pumps are operating in parallel (as shown in FIG. 2a), one pump trip will result in significant flow bypass through the tripped PSP as shown in FIG. 2b. In the case of reactors having two PSP (like PFBR), operation of reactor with one PSP in operation (at reduced power levels) is a safety concern. Hence, the strategy adopted for PFBR in the event of a pump trip is to shutdown the reactor, perform required repair or replacement activities and restart the reactor. Nevertheless, for the reactors with more than two pumps operating in parallel, two available options are either to go for replacement of the tripped pump (which involves a significant downtime), or to continue the reduced reactor power generation at reduced level. The repair can be done parallelly, if the system permits (or) the repair/replacement can be synchronized with fuel campaign. The selection of the option is based on various factors like fuel campaign duration, the month of the pump trip in the fuel campaign, power generation with (n-1) pump available, etc.,

For future FBR, with designed fuel campaign duration of 8 months and pump maintenance time and refuelling time taken as 1 month, it is found that the operation of the reactor at reduced power levels is not economically beneficial, if the reduced power generation is less than 50%. If the pump trip happens 2 months before the upcoming fuel campaign and if the reduced power generation can be increased to 66%, then continuing the reactor with reduced power generation is economically beneficial. Hence, to increase the power generation at reduced level, the reverse flow through the tripped pump has to be arrested or minimized. Thus, the approach is to make the reverse flow path through the tripped PSP as highly resistant path, without increasing the resistance when the pump is normally operating as shown in FIG. 2c. Hence, a reverse flow blockage device called sleeve valve is conceptualized. Such a flow blocking/resisting arrangement can also provide the flexibility during reactor start up.

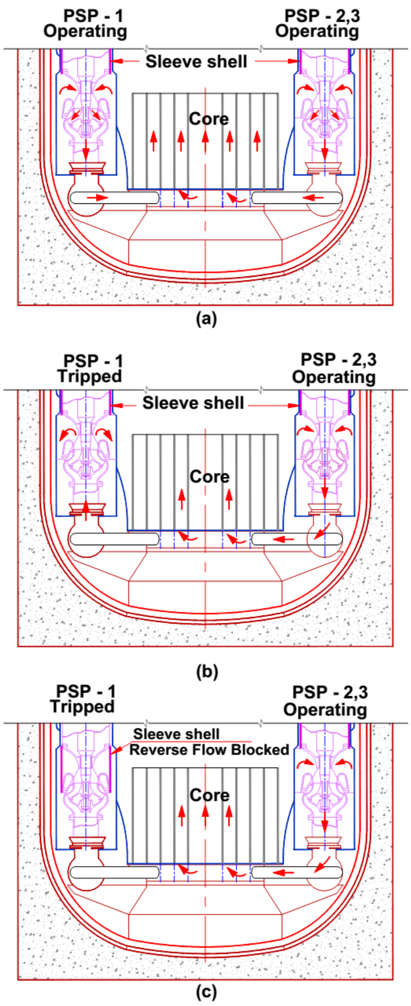

FIG. 2. Flow pattern in the reactor when (a) All PSPs are operating normally (b) After a PSP trip (c) After the closure of tripped pump's suction

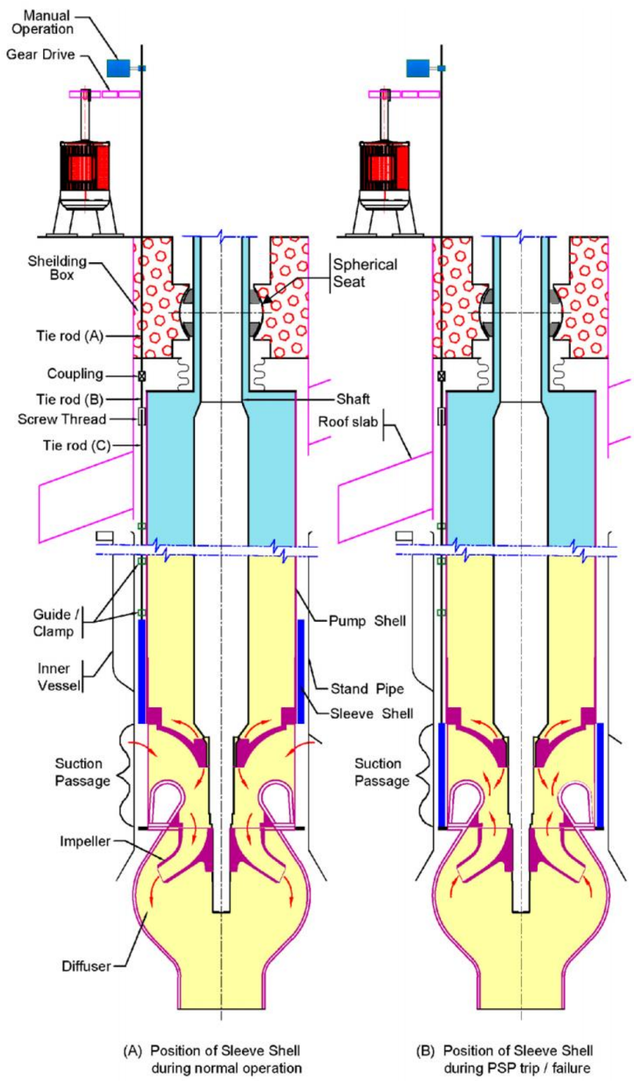

FIG. 3. Schematic on operation of sleeve valve

3. Conceptual Design of Sleeve Valve Mechanism

A cylindrical shell (called sleeve shell) is designed to close the suction passage of the tripped PSP, thereby making the path highly resistant to reverse flow. Sleeve shell is located outside the pump shell as shown in FIG. 3a. When all three PSP are operating, the sleeve shell will be located just above the suction passage as shown in FIG. 2a and FIG. 3a. Thus, it will not contribute to additional pressure drop in an operating PSP. When one of the PSP is not available, the sleeve valve of the tripped PSP is lowered to close the suction passage as shown in FIG. 2.c and FIG. 3.b. The movement of pump supports (with respect to core axis) due to thermal expansion are different, resulting in tilting of the pump, which is accommodated in Spherical Seat (SS). Hence, the sleeve valve mechanism should also undergo tilting along with the pump.

Raising or lowering the sleeve shell is done with the help of three tie-rods located at 120° apart, where each tie rod has three components namely tie-rod (A), (B) and (C) and a drive arrangement as shown in FIG. 3 and FIG. 4. The concept is devised such that various constraints are addressed namely,

- The sleeve shell has to move in a synchronous manner.
- The requirement of bellow for sealing shall be prevented or minimized.
- The tilting of the pump has to be accommodated in the mechanism.
- Flexibility in operating the mechanism shall be envisaged.
- Spurious operation of the valve shall be prevented.
- The valve shall remain as a part of pump, even if it fails.

Considering the above constraints, motion transfer from the drive motor to sleeve shell is conceptualized as explained below.

At the top of the roof slab, a drive motor is mounted with a driver gear as shown in FIG. 3. An annular gear (Girth gear) is rested on bearings around the motor support stool, and it has external as well as internal gears. The external Girth gear will be driven by the driver gear, and the internal Girth gear will drive three gears that are in contact as shown in FIG. 5. The above three driven gears are mounted on tie-rods, which are 120° apart. Each tie-rod has three elements, say tie-rod(A), tie-rod(B) and tie-rod(C) which transfers motion from the driven gear to the sleeve valve as shown in FIG. 4. Tie-rod (A) has the driven gears, which is supported with bearings at the top. The rotation in tie-rod(A) is transferred to tie-rod(B) through a universal coupling. Universal coupling will accommodate the tilting of PSP, and it is located near Spherical Seat (SS). The rotation of tie-rod(B) is converted to linear motion to raise or lower the sleeve valve using a screw, which connects tie-rod(B) with tie-rod(C). Another end of tie-rod(C) is screwed and welded with sleeve valve, and thus there is no relative motion between them. Thus, the rotation of driver gear is transferred and converted as a linear motion of sleeve valve.

The sleeve shell is designed to withstand the pressure surge which could occur in the event of instantaneous failure of sleeve valve mechanism [4]. The thickness of the sleeve shell is estimated to be 15mm, based on pressure surge estimated using Joukowsky's fundamental equation of water hammer [5]. The maximum flow rate which could give the maximum pressure surge is taken for the estimation.

4. Power Screw Design

The power screw is a mechanical device meant for converting rotary to linear motion and for transmitting power. As mentioned in previous section, tie-rod(B) and tie-rod(C) are connected by a screw, thereby converting the rotary motion of tie-rod (B) to linear motion of tie-rod(C). Tie-rod (C) is screwed and welded with the sleeve shell. Two common forms of threads are,

- Square threads
- Trapezoidal (or) ACME threads

Though square threads have lesser core diameter than trapezoidal threads, the former is used in typical load carrying applications like screw jack. The primary reasons are, square threads are more efficient than trapezoidal threads and the radial forces on nuts are negligible when square threads are used. In the design of sleeve valve, any unbalance in radial forces on the nut will cause the entire tie-rods to oscillate, which is undesirable. Hence, square thread is chosen for this application.

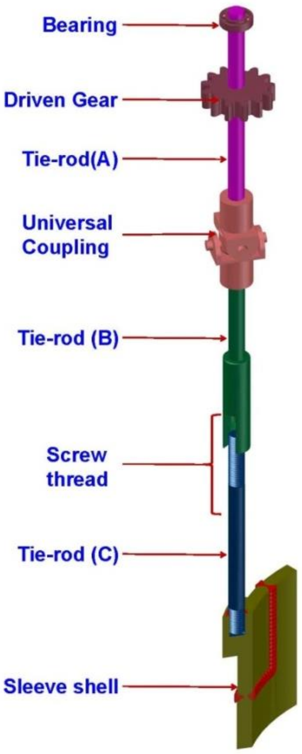

FIG. 4. Components of a typical Tie-rod for operating the sleeve shell

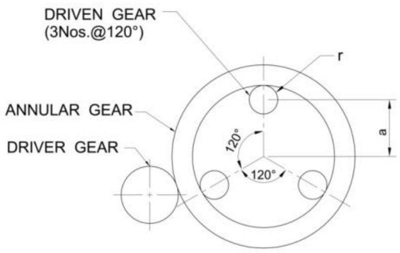

FIG. 5. Drive arrangement of gears for motion transfer from drive motor to tie-rods

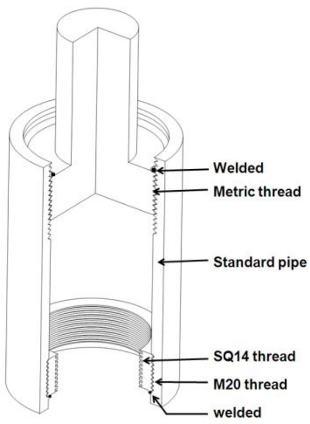

FIG. 6. A schematic of sectional view of screw thread arrangement in tie-rod(B)

The total travel length of sleeve shell is ~1500mm. Cutting external thread of 1500mm is feasible. But, an internal thread of this dimension is not commercially possible in industry. Hence, screw thread in tie-rod (B) which has internal thread is modified as shown in FIG. 6. A standard pipe is tapped with internal metric threads (M20) on both ends. A ring with M20 on its OD and square thread (SQ14) on its ID is inserted from the bottom of standard pipe and welded. Similarly, a connecting rod with external metric thread (M20) is inserted from the top of the standard pipe’s thread and welded. Thus, tie-rod (B) is still a single component, which provides square thread for support and allows the threaded portion from tie-rod(C) to pass through the gap in the standard pipe.

4.1.Galling of screw threads

Since the screw is present in sodium environment (above the pump free level), galling (or) self-welding is possible. Various causes of galling are studied and preventive measure taken to address the causes are given in Table I.

TABLE I PREVENTIVE MEASURE TO MINIMIZE/ELIMINATE THE OCCURRENCE OF GALLING

S.No	Causes	Preventive measures
1.	Use of similar metals	A fastener made from 400-series stainless steel has less tendency to gall with 300-series fasteners because the alloys work-harden at different rates. Hence, the combination of 400 series and 300 series is chosen. Hence, SS304LN and ASTM A412/A479 (carpenter alloy 22Cr-13Ni-5Mn) material combination can be used for screw and nut [6].
2.	Higher frictional heat	Frictional heat can be reduced by reducing the load or speed. Since the load cannot be reduced due to design constraints, the speed of raising/lowering sleeve shell will be kept as low as possible.
3.	Fastener misalign ments	The misalignment will be held minimal as the universal coupling will accommodate angular tilting in PSP. Stringent assembly and handling procedures shall be followed to minimize the misalignment.
4.	Surface finish of threads	Literature reveals that higher and lower surface roughness of threads are more prone to galling. Hence, an optimal roughness has to be maintained (preferably between 0.254 and 1.778 microns) [6]. It was also observed in the fastener industries that internal threads were mostly responsible for galling, as they are cut, whereas the external threads were rolled [7]. Hence, reputed manufacturers were recommended and the same manufacturer for nut and bolt.

Hence, a combination of SS304LN and A412/A479 will be used for bolt and nut. During detailed phase, the material for screw/nut will be finalized.

4.2. Self locking screw threads

The self-weight of sleeve shell and tie-rods contributes to the load faced by the screw threads. Hydraulic thrust due to reverse flow in PSP is not expected to act on the sleeve shell in the axial direction because the direction of sodium flow at suction passage is perpendicular to sleeve shell's movement. Hence, only self-weights of the components are considered for calculation of load to be handled by a screw. A single tie rod is designed to hold the entire weight of the sleeve valve, in the case of failure of other two tie-rods. Hence, for screw thread design, only one tie-rod is considered. Thus, it is estimated that, the core diameter of the rod must be above 12mm. Hence, a square thread of SQ14x2 is shortlisted.

To ensure self locking of the mechanism, the friction angle has to be greater than the helix angle. Thus, in order to minimize the helix angle, single thread screw is selected, which results in a helix angle of 2.4°. The screw threads are not lubricated as it is present in the argon gas above sodium. For non-lubricated surfaces, the coefficient of dynamic friction varies from 0.3 to 0.6, which results in a friction angle of 16.7° and 30.9° respectively. Argon gas may contain sodium aerosol, which may provide some lubrication. During any unprecedented event, even if sodium makes contact with the screw thread, it can be assumed that it is equivalent to lubricated surface (even though sodium has low viscosity). For steel to steel under lubricated conditions, the coefficient of friction is as low as 0.15, for which the friction angle works out to be 8.5°. Hence, it is ensured that the friction angle is greater than the helix angle even under lubricated conditions.

5. Contact between Tie-rod and sleeve shell

Tie-rod (C) shown in FIG. 4 is to be connected with the sleeve shell within the space available. The tie-rod is 14 mm in diameter, and the sleeve shell is of 15mm thick. Hence, the thickness of the upper region of sleeve shell has to be increased to bolt or weld the tie-rod (C) with sleeve shell. The increase in thickness will result in an increase in weight of sleeve shell and hence, the load on tie-rods and drive motor will increase. Since the additional thickness is required only at three tie-rod locations around the perimeter of sleeve shell, localized increase in sleeve shell thickness can provide support for tie-rod, with a marginal rise in the weight of the sleeve shell. The locations of the sleeve shell where tie-rod is present is cut and removed. In that location, rolled plates of 30mm thick are welded to the sleeve shell. This results in a fillet welding between 30mm and 15mm thick plate. However, fillet welding cannot be subjected to 100% radiography. So, in order to provide the butt welding, the support plates are machined to 15mm thick locally to facilitate butt welding as shown in FIG. 7.

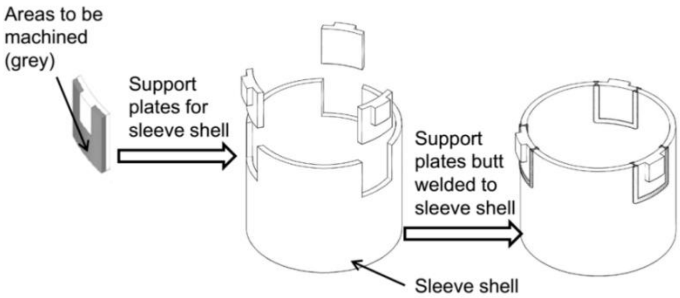

FIG. 7. Machined support plates welded with the sleeve shell

The support plate is provided with an internal metric thread (M14) and the tie-rod (C)'s lower end is provided with external M14 thread. Square threads are not chosen to avoid the possibility of inverted assembly of tie-rod (C). It is then screwed into the support plate's square thread and then tag welding is done to arrest the rotation of tie-rod(C) and to prevent sodium entry in the gaps between the threads.

6. Seals and bearings

Tie-rod (A) was envisaged to be a single rod with bearing at top, supported from motor support stand and it is connected to the tie-rod (B) at the bottom through a universal coupling. During handling of PSP, the motor support stand is removed and the pump flange is used for lifting the pump using handling flask. Thus, this would demand removal of tie-rod mechanism, which is practically not possible. Hence, from the handling point of view, the design of the tie-rod (A) has to be modified. Tie-rod (A) is divided into two halves namely upper tie-rod (A) and lower tie-rod (A), which are connected by means of a flange as shown in FIG. 8a. The lower tie-rod (A) is supported with a main thrust bearing in the pump flange and the upper tie-rod (A) is supported with a support thrust bearing from motor support stool. Thus, during removal of pump, the stool can be removed along with upper tie-rod (A) and the associated drive system. The lower-tie-rod (A) along with sleeve shell will remain as integral part of the pump, even during handling as shown in FIG. 8b.

The lower tie-rod (A) below the pump flange is present in argon atmosphere. Thus, the argon is sealed using elastomeric lip seals. Two stage sealing is proposed to be adopted with the space between the two seals is provided with an inter seal argon at a slightly higher pressure than the primary argon and atmosphere which will be monitored continuously.

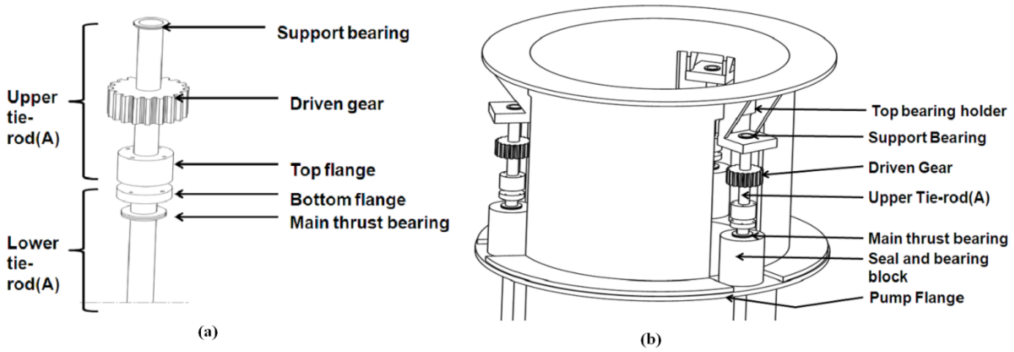

FIG. 8. (a) Tie-rod (A) with modified design from handling perspective (b) A Schematic of motor support stand with its components assembled on top of pump flange

7. Sleeve shell rest:

The sleeve shell has to be supported at the bottom, to ensure that it remains an integral part of pump due to any unanticipated event. Thus, the suction passage of the pump is designed with support flange for resting the sleeve shell. But, when PSP is to be removed from reactor for repair/maintenance, there is possibility of sodium hold up at the support flange. Necessary slope/holes are to be provided as shown in FIG. 9, so that sodium will not get stagnated while removing PSP.

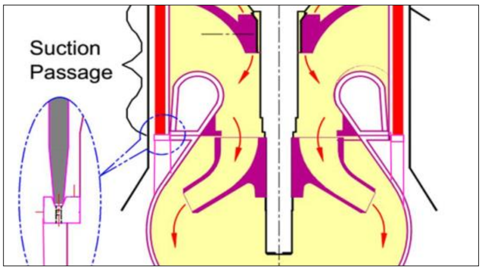

FIG. 9 Sleeve shell rest with holes for sodium drain

8. Manual Operation

Manual operation of the mechanism will be used to override the electric motor, in case when the motor used for raising and lowering the valve got tripped. Requirements of the manual operating drive are,

- It should not prevent or give obstruction when the operation via motor is in progress.
- It should be able to engage and run the gear train when the motor is tripped.
- It should move all 3 rods synchronously.

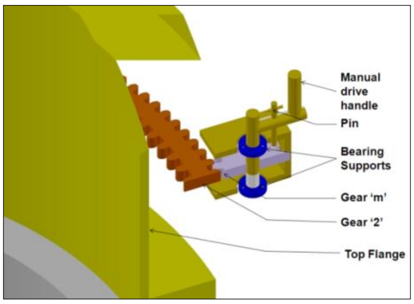

FIG. 10. Manual drive and interlock systems

The drive motor of sleeve valve mechanism is located above the roof slab (i.e., in the accessible region). Hence, in the event of the motor failure, the motor has to be removed or disengaged from the gear train. The same gear train (except driver gear) can be used for manual operation. Since the annular gear will synchronize the movement of tie-rods, the issue of synchronization during manual operation can be taken care, if annular gear was rotated using another gear (say Gear 'm'). The gear 'm' will be supported in the housing with the help of bearings as shown in FIG. 10. Handles were provided for manually rotating the gear.

9. Safety Interlock

The mechanism of sleeve valve is designed with a single motorized drive to bring synchronization among the tie-rod movements. Hence, any spurious signal to motor may result in closing suction passage when the pump is operating. Instantaneous closure of suction side when the pump is running will lead to drastic fall in NPSHA. Such a condition is called suction throttling, which results in severe cavitation. Hence, closure during operation should be completely avoided. An interlock is conceptualized to be present along with the manual drive system for the convenience of handling them together as a module.

Since the Gear 2 is linked to driving the tie-rods irrespective of manual or power mode, providing interlock at gear 2 will arrest motion in both modes. Since gear 'm' will rotate even when the mechanism is rotated by driver gear, gear 'm' can be used to provide an interlock. A shear pin is designed as safety lock as shown in FIG. 10.

10. Leakage through sleeve shell

The sleeve shell will not be able to perfectly close the suction passage of the PSP, as the relative movement of sleeve shell is required. Thus, sodium will leak back to cold pool through this path. Though the leak flow rate was lesser with annular passage, leak flow velocities are higher. Thus, the path resistance is increased by using a labyrinth and final leak flow rate was brought down to 2% of the pumped flow, with leak flow velocities within the acceptable limits [4].

11. Power generation with 2/3 mode

The maximum power generation during 2/3 mode is possible, if the pumps could provide more flow rate. However, the flow rate through the pumps are limited by various factors namely, permissible limiting velocities, acceptable cavitation margin, etc. Based on these factors, it is estimated in ref. [8] that

- The operating speed of the two available PSPs after a PSP trip is to be maintained at most 65% of nominal speed.
- After the closure of suction passage of tripped PSP with sleeve valve, the operating speed can be increased up to 80% of nominal speed.
- Continued reactor power generation at 66% power level can be achieved.

12. Conclusion

Future Indian Fast Breeder Reactors are being designed with three primary sodium pumps operating in parallel. In order to take the advantage of three pumps, in terms of operational flexibility and part load operation during non-availability of one pump, a reverse flow blockage device called sleeve valve mechanism is conceptualized and designed. The sleeve valve mechanism addresses the requirement of a non-return valve, without having the demerits of it.

The design of the sleeve valve mechanism is envisaged with various provisions to prevent accidental closure like self-locking screw threads, interlock pin to avoid a spurious operation, etc. The design also ensures that, even during an unwarranted closure, the entire mechanism will remain as part of the pump and its structural integrity is maintained. The seals and bearing for the tie-rod mechanism are designed such that the sleeve valve mechanism remains part of the pump, even during handling. The operation of the mechanism will facilitate in operating the reactor in 2/3 mode with reduced power generation of 66%. It will also provide flexibility during initial start up of the reactor. An experimental setup to validate the design and operability of the mechanism is being pursued.

REFERENCES

[1] IGOR J. KARASSIK, Centrifugal Pump Clinic - 2nd edition, CRC Press, Florida (1989).

[2] DUFFY, J.G., WAGNER, H.A., "Operating Experience With Major components at the Enrico Fermi Atomic Plant", Performance of Nuclear Power Reactor Components 1969 (Proc. IAEA symposium, Prague, 1969.) IAEA-SM-127/40, pp. 635-646.

[3] TROYANOV, M.F., RINEISKY, A.A., "Status of Fast Reactor Activities in the USSR," 24th Annual meeting of IWGFR, Japan, 1991.

[4] ARAVINDAN, S., et al., "Design of Reverse Flow Blockage Device for Reactor Coolant Pumps", Applied Mechanics and Materials **852** (2016) 489.

[5] GHIDAOUI, M.S., et al., "A Review of Water Hammer Theory and Practice", Applied Mechanics Reviews **58** (2005) 49.

[6] COMMITTEE OF STAINLESS STEEL PRODUCERS, "Review of wear and galling characteristics in stainless steel", American Iron and Steel Institute, Designers Handbook Series, Washington DC (1978).

[7] PENCOM PENINSULA COMPONENTS, Galling of stainless steel fasteners (2015), http://www.pencomsf.com

[8] ARAVINDAN, S., et al, "A Study on Limiting Speed of Pumps during 2/3 mode in CBR", Fluid Mechanics and Fluid Power (Proc. of 4th Int. conf. Allahabad, 2016), Paper No - 349.

[9] RAJ, Baldev., et al., Sodium Fast Reactors with closed fuel cycle - 1st edition, CRC Press, Florida (2015).

[10] ARAVINDAN, S., et al., "Conceptual Design of Isolation Valve (Sleeve Valve)," Internal Report.

[11] PSG COLLEGE OF TECHNOLOGY. PSG Design Data (2015), http://www.psgdesigndata.org

[12] BHANDARI, V.B., Design of Machine Elements - 3rd edition, Tata McGraw-Hill Education, Uttar Pradesh (2010).

[13] MEGYESY, E.F., BUTHOD, Paul., Pressure vessel Handbook - 10th ed, Pressure vessel publishing Inc. Oklahoma (2001).