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Hydraulic Studies on Core Components of PFBR

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***Abstract*—**Detailed thermal hydraulic investigations are very essential for safe and reliable functioning of liquid metal cooled fast breeder reactors. These investigations are further more important for components with complex profile, since there is no direct correlation available in literature to evaluate the hydraulic characteristics of such components directly. In those cases available correlations for similar profile or geometries may lead to significant uncertainty in the outcome. Hence experimental approach can be adopted to evaluate these hydraulic characteristics more precisely for better prediction in reactor core components.

Prototype Fast Breeder Reactor (PFBR), a sodium cooled pool type reactor is under advanced stage of construction at Kalpakkam, India. Several components of this reactor core require hydraulic investigation before its usage in the reactor. These hydraulic investigations on full scale models, carried out by experimental approaches using water as simulant fluid are discussed in the paper.

***Keywords*—**Fast Breeder Reactor, Cavitation, pressure drop, Reactor components.

I. Introduction

THE Prototype Fast Breeder Reactor (PFBR), a sodium cooled pool type fast reactor is of two loop concept, each loop having one Primary Sodium Pump (PSP), One Secondary Sodium Pump (SSP) and two Intermediate Heat Exchangers (IHX). Heat is generated inside the reactor core due to nuclear fission reaction. This heat is transported by primary sodium to the secondary sodium in the Intermediate Heat Exchanger. Finally the secondary sodium exchanges heat to water in the steam generator leading to production of superheated steam to generate power [1]. Heat transport circuit of PFBR is presented in Fig. 1. The reactor core of PFBR consists of different regions viz., fuel, blanket, storage etc. The power spectrum across the core is not uniform. Each region is divided into number of zones based on the power produced and each zone consists of a number of subassemblies mounted vertically on the grid plate. These subassemblies have sleeves provided in the grid plate (GP) through which flow is distributed among the SA using common primary sodium pump. The discharge head of the pump depends on the resistances offered by the various components in the flow path of which subassembly contributes the maximum. Hence the hydraulic characteristics such as pressure drop offered by the subassemblies and cavitation performance should be evaluated accurately to overcome any uncertainty arising due to the usage of empirical correlations used for design calculations. Apart from this the geometrical details of each type of subassemblies are quite different from each other and determination of hydraulic characteristics for each type of subassembly is important.

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It is also very essential to have uniform temperature distribution at the core outlet to minimize thermal gradients across the core outlet and maximize mean mixed core outlet temperature. Higher mean mixed outlet temperature results in improved overall plant efficiency. Therefore, subassemblies are fed with a flow proportional to their individual power generation capability. This flow distribution are grouped into 15 flow zones and are achieved by employing various types of flow zoning devices which offers additional flow resistance inside the subassemblies.

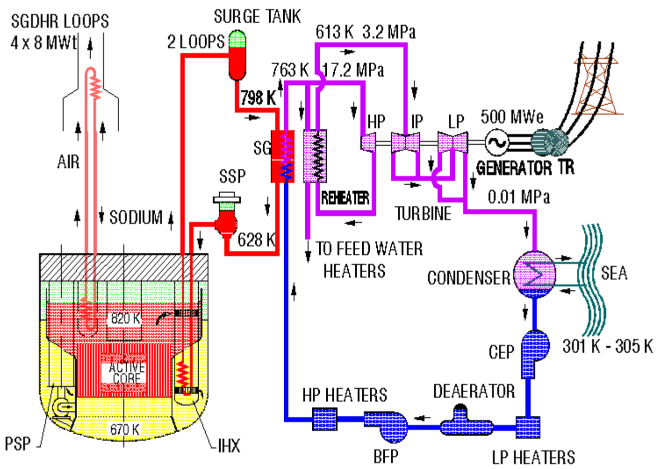


Fig. 1 Heat transport flow sheet of PFBR

The extent of pressure drop to be achieved for individual flow zones is dependent on pressure drop characteristics of the subassembly from respective flow zone. The flow zones in reactor core covers fuel, blanket, reflector, shielding, control rod, and storage subassemblies. Out of these, Zone1 which is the zone covering central subassemblies does not require any pressure drop devices as the flow required through the subassembly is maximum. The flow zoning devices are optimized based on the experiments carried out on 1:1 scale orifices of various kinds.

The subassemblies are mounted vertically on the grid plate without any mechanical fastening for fuel handling purpose. The foot of the SA is located inside the GP sleeve and a small radial gap exists between sleeve and foot. It is expected that there will be some leakage flow through this radial gap into hot and cold pools of PFBR. Any mismatch between the grid plate sleeve and the foot of the SA will lead to increased leakage flow rate. The leakage into the hot pool bypassing the SA's does not contribute to the heat removal from the core and hence it has to be minimized. However the leakage into the cold pool through the bottom direction is utilized for main vessel and control rods cooling system. Leakage flow rate in excess of the desired value would entail an additional load on the primary pump as well as affect the overall plant efficiency. The high leak flow rate also may cause cavitation which is undesirable. These types of labyrinth sealing devices are also developed through 1:1 scale water model studies.

Hydraulic tests are also performed on all these components to ensure cavitation free performance in the core for its safe and reliable operation. This paper presents the objectives of tests conducted on various components, their experimental methodology, instrumentation, results and discussion on results in detail.

II. Objective

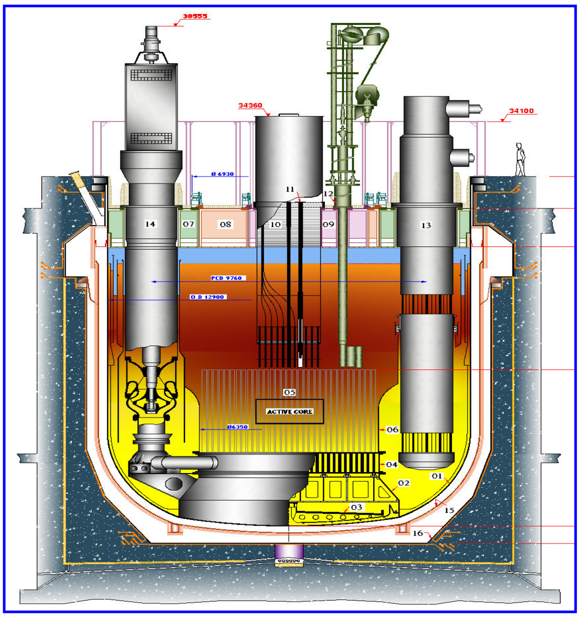
- To carryout hydraulic studies on core subassemblies for their pressure drop and cavitation performance.
- To find out the suitability of pressure drop devices utilized in the foot of the reactor core subassemblies.
- To study and evaluate the sealing performance of various labyrinth devices utilized at the foot of the subassembly.

III. Brief Description of Components

PFBR is a fast reactor utilizing mixed oxide fuel and liquid sodium as coolant. The reactor is a pool type reactor where all primary circuit components are accommodated in the pool. All major components of the primary circuit are shown in Fig. 2. The components are housed in a vessel called main vessel. The main vessel is surrounded by safety vessel which ensures safety of the reactor in the case of unlikely leak in the main vessel. The main vessel contains large quantity of sodium and argon is used as cover gas above the sodium surface [1].

The core subassemblies are supported on the grid plate which in turn is supported on main vessel through core support structure. The sodium flow in the subassemblies is fed by primary sodium pumps through the grid plate sleeves.

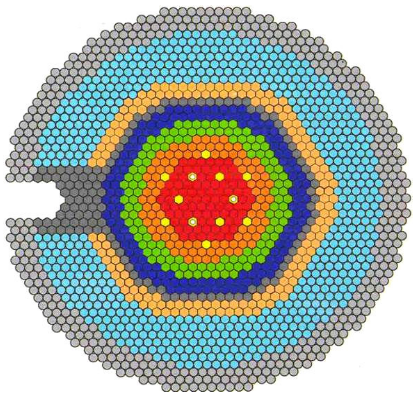
The reactor core which produces heat from the nuclear fission has design thermal power of 1250 MWt. The core plan for the reactor core of PFBR is shown in Fig. 3.



LEGEND

01. MAIN VESSEL
02. CORE SUPPORT STRUCURE
03. CORE CATCHER
04. GRID PLATE
05. CORE
06. INNER VESSEL
07. ROOF SLAB
08. LARGE ROTATABLE PLUG
09. SMALL ROTATABLE PLUG
10. CONTROL PLUG
11. CONTROL & SAFETY ROD MECHANISM
12. IN-VESSEL TRANSFER MACHINE
13. INTERMEDIATE HEAT EXCHANGER
14. PRIMARY SODIUM PUMP
15. SAFETY VESSEL
16. REACTOR VAULT

Fig. 2 Primary circuit components of PFBR



SYMBOL	TYPE OF SUBASSEMBLY
	FUEL (INNER)
	FUEL (OUTER)
	CONTROL AND SAFETY ROD
	DIVERSE SAFETY ROD
	BLANKET
	STEEL REFLECTOR
	B_4C SHIELDING (INNER)
	STORAGE LOCATION
	STEEL SHIELDING
	B_4C SHIELDING (OUTER)

Fig. 3 Plan view of Reactor Core

The reactor core is made of different type of subassemblies mainly fuel, blanket, reflector, shielding, safety rod assemblies etc. The central region of the core contains fuel subassemblies enveloped by blanket region subassemblies in the surrounding.

The major components which are discussed in this paper are different core subassemblies, flow zoning devices for various zones and sealing devices between grid plate sleeve and SA foot.

The fuel subassemblies in the core produce about 90% of the power generated in the core. The schematic of the fuel subassembly for PFBR is shown in Fig. 4.

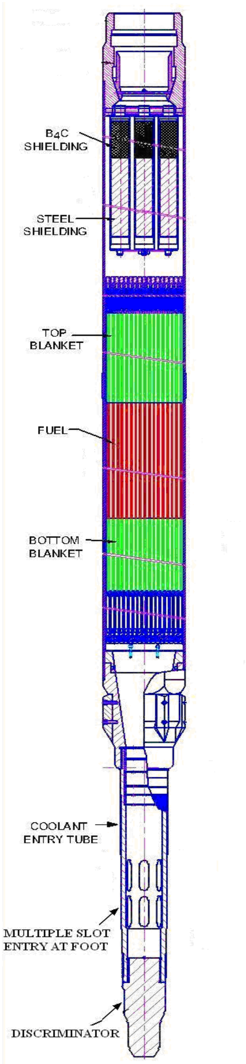


Fig. 4 Fuel Subassembly

Each fuel SA consists of a foot, a handling head, central hexagonal sheath housing fuel pins in triangular pitch arrangement. The fuel subassemblies are distributed in seven zones in the central region of the core as per their power levels. The coolant enters through multiple slots provided in the foot through the holes in the grid plate sleeve.

The blanket subassembly generates rest of the thermal power (after fuel SA) and is geometrically similar to the fuel SA externally. This too consists of a foot, a handling head, central hexagonal sheath housing fuel pins in triangular pitch arrangement. But the pin configuration in the buddle is quite different from fuel SA. These Subassemblies are distributed over three different zones.

The subassemblies like reflector and shielding subassemblies are located in the outer ring of the core. Since the heat generated from these subassemblies is quite less, coolants flows through them are also less.

The flow through these respective zones is adjusted according to their power level which is called flow zoning. These flow zoning is achieved by using suitable pressure drop devices of various types. Fig. 5 shows the location of different devices in the foot of a subassembly.

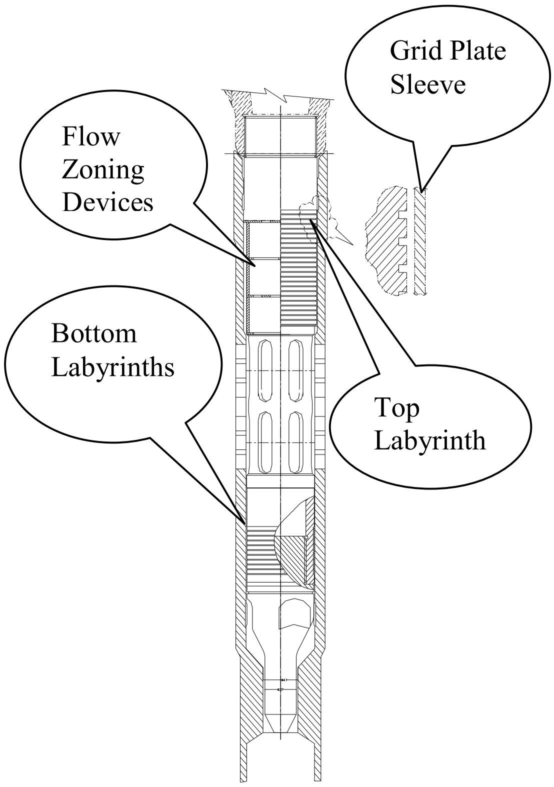


Fig. 5 Location of Devices in the foot of the SA

Development of such devices from pressure drop considerations is relatively easier than qualifying it for cavitation performance under given operating conditions. Hence the selection of a suitable geometry becomes far more important. Machined orifices with simplest geometry (concentric single hole) are normally used as pressure drop devices due to ease of manufacturing as well as availability of suitable design correlations [2]. However multi hole orifice plate offers several advantages over single hole design. Honeycomb structured orifices which have complex geometries are utilized for fuel zones of reactor core where flow is high. Whereas multi hole multi plate orifices are utilized for blanket subassemblies where flow is less.

The leakage between grid plate sleeve and foot is restricted by using labyrinth type seals on foots. The design of labyrinth type sealing devices offering very high pressure drop without cavitation is very challenging due to limited space on the foot.

IV. Similarity Criteria

Sodium is selected as the coolant in PFBR because of its efficient heat removal capability, higher boiling point and very low vapor pressure along with various other desired characteristics. It is always better to validate the performance of these devices in sodium flow conditions however experiments using sodium is expensive and need extra precautions leading to enhanced cost. Moreover operating and maintaining a sodium loop is also very difficult. Therefore it is necessary to choose a model fluid which is cheap, easily available and easy to handle. The important hydraulic properties (density and kinematic viscosity) of water are very close to that of sodium [2] and hence water was selected as simulant fluid. Pressure drop across the orifice assembly and labyrinths depends upon its geometry, surface roughness and the Reynolds number (Re, ratio of inertia and viscous force). The studies were carried out using full scale model of same prototype material. The surface roughness is maintained as in prototype by choosing the appropriate machining procedure. For maintaining dynamic similarity the non dimensional number to be simulated is Reynolds number [3].

As per the Re similitude,

$$\frac{V_m}{\upsilon_m} = \frac{V_p}{\upsilon_p} \text{ Since, scale factor is 1: 1}$$

where,
V = velocity of flow (m/s),
υ = Kinematic viscosity (m^2/s)
Subscripts 'm' and 'p' denote model and prototype respectively.

Therefore, the model flow rate can be estimated as follows:

$$Q_m = V_m \times A_m = V_p \times \left(\frac{\upsilon_m}{\upsilon_p}\right) \times A_p = Q_p \times \left(\frac{\upsilon_m}{\upsilon_p}\right)$$

where,
Q = volumetric flow rate (m^3/h).
ρ = density of fluid (kg/m^3).
A = Flow area (m^2)

Euler similitude is used for transposition of the results to reactor condition.

As per Euler similitude the pressure drop at prototype can be estimated by following equation

$$\Delta P_p = \Delta P_m \times \left(\frac{\rho_p}{\rho_m}\right) \times \left(\frac{\upsilon_p}{\upsilon_m}\right)^2$$

For Cavitation studies Incipient Cavitation Index (CI) are compared with the Operating Cavitation index for the given orifice assembly.

Where CI is defined as given in following. P_u is upstream pressure before the test assembly, P_v is the vapor pressure of the fluid and ΔP is the net pressure drop across the test assembly:

$$CI = \frac{P_u - P_v}{\Delta P}$$

V. Experimental Methodology

The subassemblies, orifice assemblies and labyrinths were all tested using water as simulant. The test assemblies under tests were installed in the suitable water test rig. Tests were conducted at 343K for the pressure drop testing and below 325 K for the cavitation studies.

Pumps of different capacities were used to provide the flow through the test section for testing various subassemblies and devices for pressure drop and cavitation performance. Pressure drop device installed in the foot with the tapping details is shown in Fig. 5. In order to measure the pressure drop across the subassembly, orifice, or labyrinth seal assembly, differential pressure transmitters have been utilized. Static pressure measurement was carried out with the help of pressure transmitters of appropriate ranges. The flow rate is measured using the orifice flow meter with accuracy ± 1%. Low flow rates were measured using volume collection method having accuracy of ± 1%. Temperature measurement was carried out by RTD with accuracy ± 0.5%. For evaluating the cavitation performance, suitable accelerometers with accuracy ± 2% were employed.

VI. Experimental Results

The experimental results obtained from the water tests carried out on various subassemblies, devices and labyrinths are discussed below.

A. Core Subassemblies

The subassembly pressure drop was measured using water as simulant and the results were transposed to the reactor condition using Euler's criteria as mentioned under the similarity criteria paragraph. The prototype flow rate for central SA is highest at 36 kg/s and reduces gradually radially outward for outer subassemblies. The major portion of the pressure drop in the subassembly is offered by the fuel pin bundle located in the axial center of the subassembly. Rest losses are shared by SA entry, bundle entry and exit, SA exit etc. It is found from the experiments that a maximum rated fuel subassembly offers pressure drop of 57.5 mNa at nominal flow condition. This pressure drop is much less than the pump head of 75 mNa. The cavitation tests were also carried out on the subassembly and it is seen that the subassembly is free from cavitation [4]. A typical pressure drop curve for fuel subassembly obtained after the experiments is shown in Fig. 6. The other subassemblies viz. blanket, reflector and shielding subassemblies were also tested for pressure drop. These pressure drops across the subassemblies at their rated flow rate were utilized for determination of pressure drop needed for devices required to be placed in the foot of the individual subassembly.

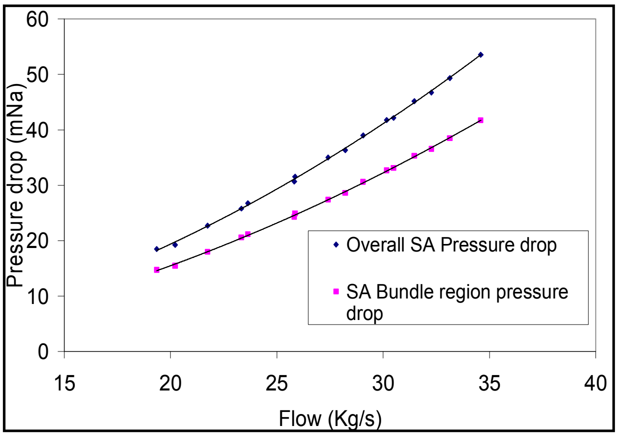


Fig. 6 Pressure drop across fuel subassembly

The individual pressure drop for devices in each zone was calculated by taking pressure drop across the maximum rated central fuel subassembly. Hence there is no device needed in the zone 1 subassembly. As we can see from Fig. 7 the pressure drop required in the devices go on increasing as we move towards the outer zone subassemblies. These devices were developed accordingly and discussed in the subsequent paragraphs.

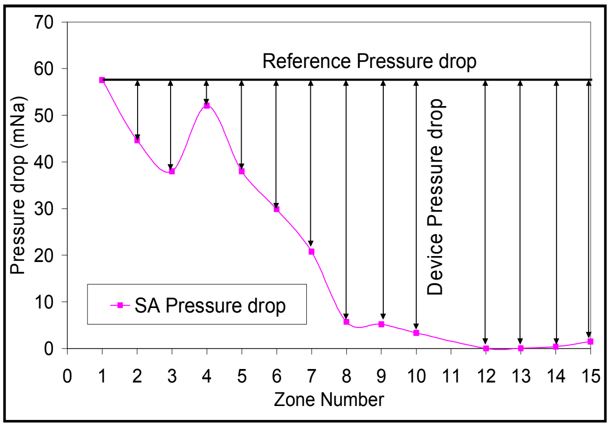


Fig. 7 Pressure drop across different zone subassemblies

B. Flow Zoning Devices

From experiments conducted earlier it is observed that conventional machined plates are not suitable from cavitation consideration for fuel zones where significant pressure drop is to be achieved over a wide range of flow rate for various fuel flow zones. Hence honeycomb geometry orifices were developed and tested for these zones and found suitable from both pressure drop and cavitation considerations. A typical honey comb orifice is shown in Fig. 8. These orifices were found to be better for cavitation performance in comparison to conventional orifices [5].

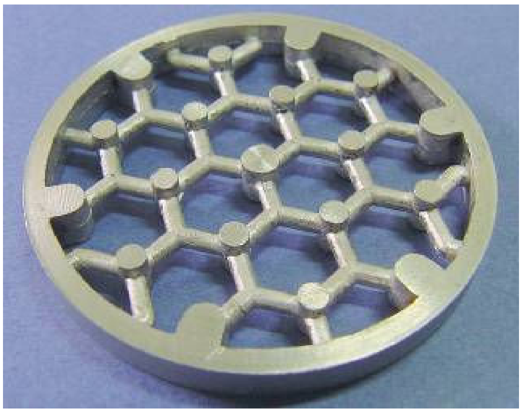


Fig. 8 Honey comb structured orifices

The pressure drop required and achieved for the fuel flow zones are given in Fig. 9 [5].

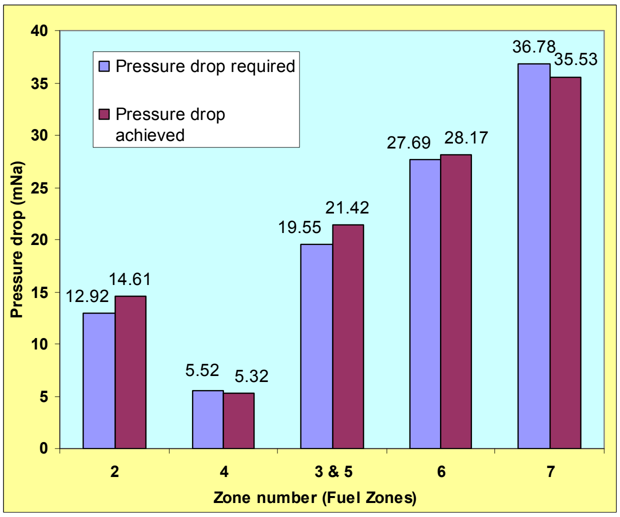


Fig. 9 Pressure drop results for fuel zones

Even from cavitation consideration multi-hole orifices performance is quite better compared to single hole orifice design. Experimental results published in literature also indicate that in the developed cavitation regime, a multi-hole orifice is much more preferable than a single- hole orifice with same total cross-sectional opening [6]. Hence looking at the low flow rates devices for the blanket subassemblies were developed using muti hole orifices in series.

This approach distributes the pressure drop in series such that the lowest possible pressure (near vena-contracta) in system remains always above the vapor pressure and achieves the cavitation free performance. The pressure drop in different zones were achieved by varying the hole diameter in the plate where as the no. of plates were kept constant at four. The SS sleeves were used between the two consecutive orifice plates.

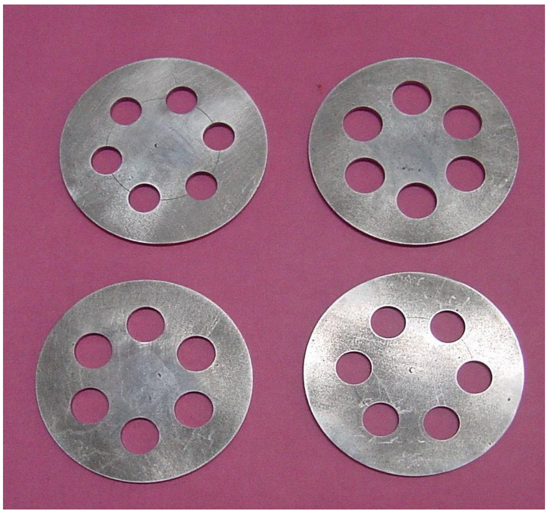


Fig. 10 Orifice plates for blanket zone (Typical)

The photo of a typical four orifice plates utilized for blanket zone is shown in Fig. 10 and the assembly of the orifice plates is shown in Fig. 11.

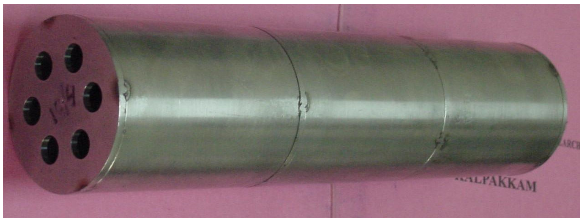


Fig. 11 Orifice assembly for blanket zone (Typical)

The experimental results for all the three blanket zone orifices are given below in Fig. 12.

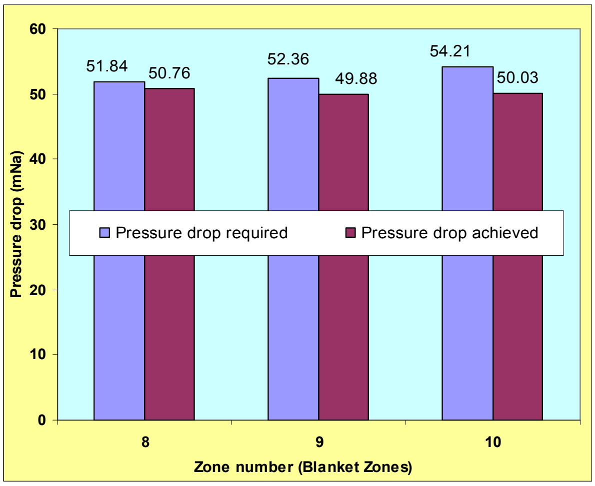


Fig. 12 Pressure drop results for blanket zone orifices

All the orifice assemblies were subjected to the tests to verify its cavitation performance and it is found that all the assemblies were free from cavitation. A result of a typical (blanket- zone 9) cavitation experiment is given in Fig. 13. From the figure it can be seen that the operating cavitation index is before the incipient cavitation point and hence it gives cavitation free performance at rated flow condition.

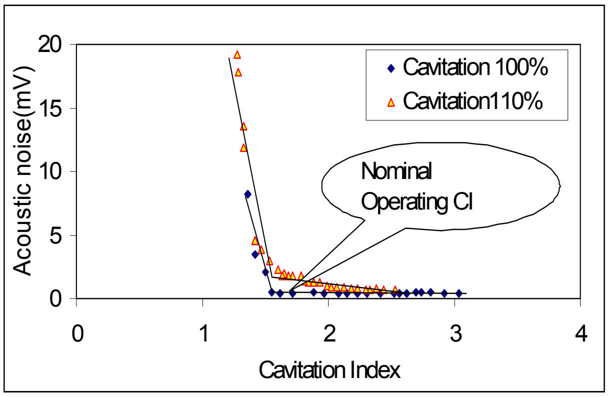


Fig. 13 Blanket Subassembly results

Table I gives the cavitation results for all blanket zone orifice assemblies and we can observe that operating cavitation index for each zone is higher that incipient cavitation index ensuring cavitation free performance.

TABLE I
CAVITATION RESULTS FOR BLANKET ZONE DEVICES

Zone No	Inception CI (Nominal flow)	Operating CI (Nominal flow)
8	1.60	1.645
9	1.56	1.674
10	1.46	1.668

Flow zoning devices for reflector and shielding zone consist of combination of orifice and labyrinths to achieve higher pressure drop at low flow rate. Fig. 14 shows the device developed for reflector and shielding zones.

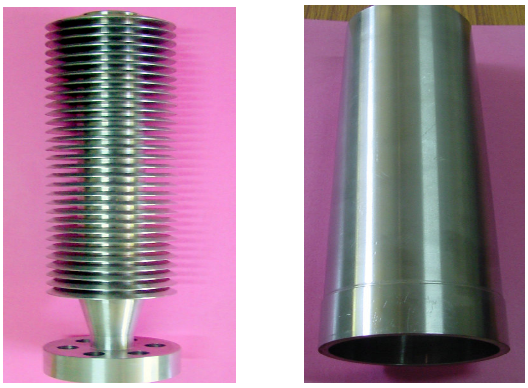


Fig. 14 Orifice cum labyrinth type devices

C. Labyrinth Type Sealing Devices

The length of the GP sleeve imposes restriction on the length of the labyrinth profile. The maximum length allowed for top and bottom labyrinths are 225mm and 80mm respectively. There is also restriction in the minimum annular radial gap between labyrinth and the GP sleeve to facilitate easy removal of SA's during fuel handling operations. More annular radial gap is preferable for easy withdrawal of SA's, but this will lead to more leakage flow. Thus the development of such pressure drop devices requires the optimization of the profile within the above mentioned restrictions. Different top and bottom labyrinth geometries were tested to optimize the design. Studies were carried out using the helical square profile and varying the other geometrical parameters. Based on the various parametric studies final labyrinth profile is optimized for pressure drop performance and cavitation tests were conducted to find its suitability in PFBR [7]. Typical geometry of the top labyrinths tested in water is shown in Fig. 15.

Fig. 15 Top labyrinths for model testing

VII. Conclusion

Hydraulic testing of the components of reactor core plays an important role in its design and validation. Some of the important components of reactor core viz. subassemblies, pressure drop devices and sealing devices have been hydraulically tested using water as simulant to understand its pressure drop and cavitation characteristics. Tests carried out on the subassemblies were useful in finding the pressure drop requirements for flow zoning devices as well as it is a useful input to qualify the pump discharge head requirements. These flow zoning devices were developed successfully based on series of water tests carried out on different types of orifices geometries. Honeycomb type orifices were selected for fuel zone where as machined multi-hole orifice plates in series are selected for blanket zones. Combination of orifices and labyrinth is developed to offer the required pressure drop for reflector and shielding assemblies. All assemblies are tested for cavitation and found that the operating Cavitation index for the device in the reactor is higher than the incipient cavitation index for nominal flow and thus ensuring a cavitation free performance. Labyrinth type sealing devices were also developed for PFBR subassemblies using experimental approach. After optimizing these parameters a final geometry was developed and recommended for PFBR.

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