Flow distribution in spherical header of a liquid metal-cooled fast breeder reactor

K Natesan, K Velusamy, P Selvaraj & P Chellapandi
Mechanics and Hydraulics Division, Indira Gandhi Centre for Atomic Research, Kalpakkam 603 102, India

Received 13 December 2001; accepted 2 October 2002

Liquid sodium from primary pump of a typical Liquid Metal-cooled Fast Breeder Reactor (LMFBR) reaches a spherical header through a vertical pipe and flows to the inlet plenum of the reactor through two discharge pipes, which connect the header to the plenum. The header is provided with a central cone and flow directing baffles for the purpose of having a smooth propagation of sodium flow and hence a reduced pressure drop. 3D hydraulic analyses of sodium flow in the header for various design configurations have been carried out to investigate the effectiveness of flow baffles and to assess the pressure drop in the header. It has been found that a configuration of 3D baffle combined with a central cone reduces the pressure drop in the header to the desirable level (1.7 mla).

Sodium flow in the primary circuit of an LMFBR is maintained by two centrifugal pumps, known as primary sodium pumps (PSP), operating in parallel. Each pump is designed to supply a nominal sodium flow rate of 4.13 m³/s against a head of 75 mla at 590 rpm. The pressurised sodium from each pump reaches a spherical header of 1.41 m diameter through a 0.9 m diameter vertical pipe. Sodium from the header is then supplied to the inlet plenum through two 0.6 m diameter pipes. Schematic of the header-pipe assembly is shown in Fig. 1. It is well known that whenever there is a sudden change either in the flow area or in the direction of the flow, large recirculations are induced in the ducts. These recirculations are the potential sources of large pressure drop in the system. Large pressure drop leads to high operating cost, which is unwarranted. Hence, one of the objectives of the hydraulic design of the components is to contour the duct, carrying the fluid, to avoid sudden changes in the flow area and direction. Achieving this objective is becoming increasingly simpler due to the advancement in the computational fluid dynamics and development of computer technology. With this in view, the primary sodium header is provided with a central cone of 0.69 m diameter base and 1.102 m height as well as flow directing baffles. However, the effectiveness of these devices needs to be investigated in detail.

In order to assess the effect of central cone and flow baffles in the PSP header, the following four configurations of the header have been considered and the flow/pressure distribution in each configuration assessed: (i) Simple header (Fig. 2); (ii) Header with the central cone alone (Fig. 3); (iii) Header with the central cone and a simple axisymmetric baffle (Fig. 4); and, (iv) Header with the central cone and a non axisymmetric 3D baffle (Fig. 5).

In the present investigations, comparison of flow distributions in the various design configurations of the header (Figs 2-5) has been made and effectiveness of various devices has been assessed from the point of view of pressure drop in the header.

---


---
NATESAN et al.: FLOW DISTRIBUTION IN SPHERICAL HEADER OF A FAST BREEDER REACTOR

Section A-A

Section B-B

Fig. 2—Simple header

Fig. 3—Header with a central cone

Section A-A

Section B-B

Fig. 4—Header with a central cone and an axisymmetric baffle

Fig. 5—Header with a central cone and a non-axisymmetric 3D baffle
Modelling Details

Governing equations

Sodium flow process in the header is governed by 3-D conservation equations of mass and momentum. For a steady incompressible flow in Cartesian coordinates \((x, y, z)\) with velocity components \((u, v, w)\), pressure \((p)\) and density \((\rho)\), the equations are:

\[
\frac{\partial (\rho u)}{\partial x} + \frac{\partial (\rho v)}{\partial y} + \frac{\partial (\rho w)}{\partial z} = 0
\]

\[
\frac{\partial (\rho u u)}{\partial x} + \frac{\partial (\rho vv)}{\partial y} + \frac{\partial (\rho w w)}{\partial z} = \frac{\partial p}{\partial x} + \frac{\partial (\tau_{xx})}{\partial y} + \frac{\partial (\tau_{xy})}{\partial z} + S_u
\]

\[
\frac{\partial (\rho w w)}{\partial x} + \frac{\partial (\rho v w)}{\partial y} + \frac{\partial (\rho u w)}{\partial z} = \frac{\partial p}{\partial y} + \frac{\partial (\tau_{yy})}{\partial x} + \frac{\partial (\tau_{yx})}{\partial z} + S_v
\]

where, \(\tau\) represents the viscous and turbulent stresses. The turbulent stresses are evaluated from the eddy viscosity based \(k-\varepsilon\) turbulence model. The governing equations for the turbulent kinetic energy \((k)\) and its dissipation rate \((\varepsilon)\) are:

\[
\frac{\partial (\rho u k)}{\partial x} + \frac{\partial (\rho v k)}{\partial y} + \frac{\partial (\rho w k)}{\partial z} = \frac{\partial p}{\partial x} + \frac{\partial (\tau_{xx})}{\partial y} + \frac{\partial (\tau_{xy})}{\partial z} + S_k
\]

\[
\frac{\partial (\rho w w)}{\partial x} + \frac{\partial (\rho v w)}{\partial y} + \frac{\partial (\rho u w)}{\partial z} = \frac{\partial p}{\partial y} + \frac{\partial (\tau_{yy})}{\partial x} + \frac{\partial (\tau_{yx})}{\partial z} + S_v
\]

where \(\Gamma\) and \(S\) are respectively diffusion coefficient and source terms. Since the geometry of the header does not fit in to the regular Cartesian or cylindrical co-ordinate system, a boundary fitted co-ordinate system \((\xi, \eta, \zeta)\) is used, where, \(\xi = \xi(x, y, z), \eta = \eta(x, y, z)\) and \(\zeta = \zeta(x, y, z).\) All these governing equations can be represented by a single general equation of the following form, in the \((\xi, \eta, \zeta)\) co-ordinates as:

\[
\frac{\partial}{\partial \xi} (\rho U \phi) + \frac{\partial}{\partial \eta} (\rho V \phi) + \frac{\partial}{\partial \zeta} (\rho W \phi) = \frac{\partial}{\partial \xi} \left( \Gamma^0 \frac{\partial \phi}{\partial \xi} \right) + \frac{\partial}{\partial \eta} \left( \Gamma^0 \frac{\partial \phi}{\partial \eta} \right) + \frac{\partial}{\partial \zeta} \left( \Gamma^0 \frac{\partial \phi}{\partial \zeta} \right) + S^0 \phi
\]

In the above general equation \(\Gamma^0\) is the diffusion coefficient and \(S^0(\xi, \eta, \zeta)\) is the source term for the scalar variable \(\phi\) and \(J\) is the Jacobian of transformation with:

\[
J = x_\xi y_\eta z_\zeta + x_\zeta y_\xi z_\eta + x_\eta y_\zeta z_\xi
\]

\[
q_{11} = (y_\eta z_\zeta - y_\zeta z_\eta)^2 + (x_\zeta z_\eta - x_\eta z_\zeta)^2
\]

\[
q_{22} = (y_\zeta z_\eta - y_\eta z_\zeta)^2 + (x_\zeta z_\eta - x_\eta z_\zeta)^2
\]

\[
q_{33} = (y_\xi z_\eta - y_\eta z_\xi)^2 + (x_\xi z_\eta - x_\eta z_\xi)^2
\]

\[
q_{12} = q_{12} = (y_\zeta z_\eta - y_\eta z_\zeta)(y_\theta z_\xi - y_\xi z_\theta)
\]

\[
q_{13} = q_{13} = (y_\zeta z_\eta - y_\eta z_\zeta)(y_\theta z_\xi - y_\xi z_\theta)
\]

\[
q_{23} = q_{23} = (y_\zeta z_\eta - y_\eta z_\zeta)(y_\theta z_\xi - y_\xi z_\theta)
\]
The above set of equations are solved by the finite volume method using the PHOENICS* code.

Computational details

The spherical header with a single circular inlet and two symmetric outlet pipes (included angle as 136°) and flow deflecting cone and baffles has 180° symmetry. Hence, 180° symmetry sector of the header with one discharge pipe and one half inlet pipe is taken for analysis. The general purpose CFD code PHOENICS has been used for the analysis. A grid pattern comprising 15x36x65 grids in the radial axial and circumferential coordinate directions has been used in the analysis. In the various configurations studied (Figs 2-5), sodium in the regions below the cone and baffles are considered to be stagnant and hence they do not form a part of the calculation domain.

Validation

Although PHOENICS is a commercial software, its usage needs to be validated. For this purpose, the standard test problem of turbulent flow in a backward facing step (Fig. 6) at a Reynolds number of 38000 and expansion ratio of 1.67 is solved using PHOENICS. The numerical results are compared against the experimental results of Eaton and Johnston and the numerical results of Abe et al. The PHOENICS prediction of x-velocity distribution at a horizontal distance of 8H from the step location is shown in Fig. 7. Also shown in the same figure are the measured data of Eaton and Johnston. It can be seen that the predicted distribution matches satisfactorily with the measurements. Similar comparison was seen in the velocity distribution at other locations also. Likewise, the reattachment point computed by PHOENICS is 7.5 H and it compares well with the prediction of Abe et al., viz. 7.9 H.

Fig. 7—Comparison of flow distribution in the backward facing step at x/H=8 and ER=1.67

Fig. 8—Flow distribution without any devices in the circumferential planes at 0=0° and 0=180°
Results and Discussion

After the validation exercise, flow and pressure distributions in the spherical header of the LMFBR were analysed for various geometrical configurations as already explained. Flow distribution of sodium in two r-z planes viz. \( \theta = 0^\circ \) and \( \theta = 180^\circ \) of the simple header (without any flow directing devices) is shown in Fig. 8. Flow distribution in the peripheral radial plane adjacent to the inner surface of the spherical header is shown in Fig. 9. It is evident from these figures that there are strong recirculations of sodium within the header. The flow recirculation can be seen at the inlet to the discharge pipes also. It may be noted that discharge pipe is located at \( \theta = 68^\circ \). The maximum velocity at the discharge pipe location is 12.3 m/s. From the computed pressure distributions, the pressure drop in the header has been estimated to be 5.7 m of sodium column. This value of pressure drop being high, flow-directing devices are necessary for the smooth propagation of sodium flow within the header.

To start with, a central vertical cone is fixed to the bottom of the header as shown in Fig. 3. The computed flow distribution in the r-z planes at \( \theta = 0^\circ \) and \( \theta = 180^\circ \) and the peripheral radial planes of the header are shown in Figs 10 and 11, respectively. It can be seen that in this case also, there are strong recirculations in the sodium flow. Recirculation can also be seen at the inlet to the discharge pipe. The maximum velocity at the inlet to the discharge pipe is 11.9 m/s. The pressure drop in the header has been estimated to be 5.28 m of sodium. Thus, there is no significant improvement in the sodium flow and pressure drop within the header due to the introduction of a central cone alone. Hence, it was decided to introduce an axisymmetric baffle along with the central cone as shown in Fig. 4. The radius of curvature of the baffle considered is 1.35 m. The

---

[Figures 9, 10 are shown here with flow distribution diagrams.]

---

18 m/s

---

19 m/s
The flow distribution in the $r$-$z$ planes at $\theta=0^\circ$ and $\theta=180^\circ$ and peripheral radial plane ($\theta$-$z$ plane) of the header, having a central cone and an axisymmetric baffle, are shown in Figs 12 and 13, respectively. It is seen from the figures that the strength of recirculation has reduced in this case compared to that in the earlier cases. The maximum velocity at the inlet of the discharge pipe is $10.8$ m/s. The pressure drop in the
header is 3 m of sodium, which is significantly less than that seen in the earlier cases.

Since the baffle is seen to influence the flow and pressure drop favourably, in the next case, the baffle configuration has been altered. In this case, the baffle is made non-axisymmetric as depicted in Fig. 5. The profile of the baffle changes both radially as well as circumferentially. At $\theta=0^\circ$ and $\theta=180^\circ$, the baffles on either side of symmetry plane form two wedges. The elevation of these wedges with reference to the central cone is similar. At the angular location of the discharge pipes ($\theta=68^\circ$), the profile changes to that of the axisymmetric baffle discussed in the previous paragraph. The flow distributions for this case are shown in Figs 14 and 15, respectively. It is evident that with modifications in the baffle geometry, the recirculations within the header have nearly vanished and sodium is drawn smoothly towards the outlet pipes. The maximum velocity at the inlet to the discharge pipe is 9.4 m/s. The pressure drop in the header in this case is 1.74 m of sodium. This shows the necessity/usefulness of the 3D non-axisymmetric baffle in the header for having a smooth velocity field and hence low pressure drop.

In the investigations discussed so far, the radial domain of the computational model was taken to end at the periphery of the header. No part of the discharge pipe is considered in the model with a view to reduce the computational time. In order to assess the impact this simplification, the case of 3D baffle with central cone is re-analysed by considering a 200 mm length of the discharge pipe. The predicted flow distribution in the peripheral radial plane within the header for this case is shown in Fig. 16. Comparing this with the flow distribution obtained for the corresponding case without the outlet pipe (Fig. 15), it can be seen that exclusion of outlet pipe in the model does not affect the flow distribution in the header. The maximum value of velocity at the inlet to the discharge pipe is same in both the cases (9.4 m/s). The pressure distributions in the header are also similar in both the cases. Similarly, the pressure drop in both the cases were found to be the same. Thus, it can be concluded that modeling of discharge pipe is not essential in the numerical prediction of flow distribution and pressure drop in the header.

It may also be mentioned that the hydraulic analyses of the header have also been carried out for various other geometrical configurations, which are marginally different from that of the 3D baffle. The configurations studied are: (i) Raising the elevation of the wedges (at $\theta=0^\circ$ and $\theta=180^\circ$) from the nominal position by 150 mm, (ii) raising the elevation of the baffle-cone junction at the location of outlet by 100 mm and (iii) raising the elevations of the wedges as well as that of baffle-cone junction by 150 mm. It is found that the pressure drop in all these configurations is in the range of 1.8 m to 1.9 m, which is higher than that in the reference geometry. Thus,
the reference geometry of the baffle (Fig. 5) offers the minimum pressure drop in the header.

Conclusions

3D hydraulic analysis of the primary sodium header has been carried out for the various design configurations such as: a simple header, header with a central cone alone, header with central cone and an axisymmetric curved baffle and header with central cone and a non-axisymmetric 3D baffle. It has been found that the pressure drop in the header for the above mentioned configurations is: 5.7 m, 5.28 m, 3 m and 1.74 m of sodium, respectively. The configuration of the header with central cone and 3D baffle gives a smoother flow profile in the header with minimum recirculations and pressure drop.

References