Resting Bottom Fast Reactor

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1. Introduction

Sodium is chosen as cooling fluid of fast reactors, due to its high vaporization temperature under atmospheric pressure, high conductibility and compatibility with construction materials. Difficulties arise from reactions with air or water. Known suspended primary sodium vessels integrate exchangers to external sodium transmitting heat to external sodium/vapor or sodium/gas exchangers, along the chosen cycle, to limit these reactions.

Another fast reactor with resting bottom primary vessel is proposed. It may receive sodium external circuits in case of water cycles, or, without external circuits, direct exchangers between primary sodium and nitrogen in Brayton cycle. The risk of gas leaks in the core, perturbing the neutronic cycle, is limited by construction options.

1. Resting bottom vessel.

Some vessels rest through their periphery, with a double curvature bottom. A flat bottom vessel is proposed, resting in disributed way through concentric sleeves in thermal gradient and relatively low stress, on the cooled bottom of the safety vessel contained in a civil engineering structure included in soil. The sleeves are welded on bottom with if necessary local reduced thicknesses providing articulations.

When the primary vessel is placed, the sleeves enter in grooves prepared under its bottom. The peripheral sleeve, in continuity with the vertical vessel wall, is entirely welded. In operation, the temperature regularly increases to the top, and the low stressed wall needs no cooling by a sodium diverted circuit. Vessel dimensions may by large.

Below the vessel, intervals between sleeves contain a solid refractory and isolating material, not reducible by sodium, as used in corium recuperators in other reactors (alumina, magnesium oxide, zircon). This material, in shape of columns with low voids, allows dilatations of vessel bottom and sleeves. It could rest on a cooled lead bed able to stop corium by its density. Sodium leakage risk is suppressed.

On this support, the primary vessel bottom is made of two superposed plates, joined by three sleeves limiting successively the core diagrid, an intermediary diagrid for core covers and stocked fuel elements, and a cooled sodium collector fed by distributed exchangers around the core. The last sleeve is the vessel wall. Pillars may be added between plates. The collector feeds in periphery several pumps, and radial pipes inject under pressure sodium to the core diagrid and restricted sodium flows in the intermediary diagrid. The radial pipes cross the second sleeve without contact through openings leaving low leaks to the collector. This extended in height second sleeve protects the core from earthquakes. Each pump, fed of cooled sodium by the collector, injects it in the radial pipe through a known articulation system, while the pump with its shaft and motor is articulated under the upper slab roof, allowing relative horizontal displacements.

The collector vessel bottom may be inspected during reactor stops, with ultrasonic devices introduced in sodium by trap-doors. Inspection under the core and covers needs a free height under subassembly supports.

Bore by the civil engineering structure, the roof slab covers argon atmosphere on sodium surface. Its cooled lower plate in steel, fixed to the safety vessel top, is protected against deposits by thermic insulation with argon circulation. Under this plate, not fixed to the primary vessel wall, a lower diameter welded skirt enters in the sodium. Between the wall and the skirt, sodium level is lowered by a pressure of argon injected around the wall basis and issuing to the argon atmosphere by calibrated holes on skirt top. Then the primary vessel is closed without using metallic bellows.

2. Sodium/gas exchangers.

If nitrogen cooling is chosen, Brayton cycle is used without intermediary circuit. The turbine-compressor and external gas/gas exchangers are not modified.

On Superphénix, the four 750 MW steam generators at 183 bar, in which the secondary sodium heats water in single pass without superheat, gave no leak. Each generator used 33 km of 25/30.2 mm diameter tubes (44m/MW or 0.56 m^2/kW) in spirals alterning the wrap up direction around an axial pipe. The tubes were maintained by eight radial vertical combs ensuring the radial spacing. A 22.5 m high, 2.9 m diameter, 148 m^3 vessel contains 220 m per m^3 of tubes exchanging 5 MW per cubic meter. These results and construction experience incite for a sodium/gas exchanger to use spiral tubes.

Each exchanger casing is made from a cylinder, its base open on the peripheric collector, and from an enveloping skirt without contact, fixed below the slab roof. The hot sodium flow produced by the core ascends between cylinder and skirt. This allows the dilatations of components without stress. A rigid removable lid resting on the roof fixes the feeding and leaving pipes of exchange tubes and is covered by a shell containing argon maintained.at a lower pressure than the argon above sodium on the core. Nitrogen leaks in the exchanger ascend against the sodium flow and arrive in this shell. They may be exhausted to atmosphere while urgency measures are applied.

3. Preliminary exchanger design

A design is attempted for a 1500 MW reactor in which the 3750 MW thermic power is transmitted to six 625 MW exchangers. In each exchanger, the descending sodium at 1230 J/°kg and 886 kg/m^3 is cooled from 550° to 370° (460° mean temperature) at flow 625000/(1.230x180)= 2823 kg/s or 3.2 m^3/s.

No gas density alterations are taken into account, for simplified calculations. Nitrogen at 180 bar is heated from 350° to 530°, mean temperature 440°, ρ= 92 kg/m^3, specific heat c=1040 J/°kg, viscosity μ=1/30000, on a flow of 625000 / (1.04x180)= 3338.7 kg/s or 36.3 m^3/s.

Each exchanger casing, of diameter 7 m and sodium height 10 m, volume 385 m3, contains an axial pipe for nitrogen descent, of diameter 1.2 m and section 1.13 m^2, giving a speed V=32 m/s with dynamic pressure p= 47100 Pa,. A straight length of 12 m gives a pressure drop of about 7000 Pa. This pipe with isolating argon sheet, thin tube protection and widening for nitrogen repartition on lower part takes a 2.5 m mean diameter and a volume of 50 m3. With 10 m3 for collectors and 20 m3 for pipe maintaining structures this leaves to exchanger tubes a volume 385-80=305 m3.

For exchange of 625 MW, 6250 tubes of length 20 m are chosen in diameter 20/24 mm, receiving 5 kW/m or 79.6 kW/m². The nitrogen flow per tube is 36.3/6250=0.0058 m3/s and V=0.0058/0.000314=18.47 m/s. For ρ=92, viscosity μ=1/30000, the Reynolds Re=ρVD/μ=1019544 is obtained, and Nüsselt Nu=0.0205 $Re^{0.8}$=1313. With conduction λ=0.053 W/°m, the heat flux is h=Nu $\lambda\,\delta t/2R$=1313x0.053x δt/0.02=3480 δt. For 79.6 kW/m², δt=22.9°. The tube volume is 6250 x 20 x 0.000452=56.5 m3.

The dynamic pressure p=$\rho V^2/2$=15710 Pa gives on 20 m a pressure drop 0.015 x 15710 x20/0.02= 235650 Pa or 2.356 bar . The theoretical pump power per tube is 0.0058x 235650=1.367 kW and 8544 kW for 6250 tubes, in practice 10000 kW.

The exchanger uses 125000 m of tubes with steel section of 0.66 cm² and mass 0.53 kg/m, say a mass 66.25 tons and a volume 125000x0.0004524= 56.5 m3. The section for sodium is (305-56.5)/10=24.85 m² giving for 3.2 m3/s the speed 0.129 m/s .

For repartition and reception of nitrogen in many tubes of limited diameter, tubulary plates of usual collectors are difficult to place in limited casings. Collectors may be chosen of honeycomb type, where the tubes are pressed together, each one joined to others along three longitudinal welds, of a length giving the shear force corresponding to the applied pressure on the whole plug obtained. For 6250 tubes of diameter 24mm, total section 2.827 m²; the plug of 3.1 m² needs a diameter of 2 m, contained in a widening to 2.4 m of the feeding pipe.

4. Gas bubbles

It is to be avoided that a gas leak would be carried by sodium to the core, inducing cooling lack and nuclear accident. Water at 20° and sodium at 450° have comparable masses and viscosities. Small gas bubbles take a spherical shape due to liquid superficial tension. The drag of a sphere $c\,\rho\,\pi\,R^2\,V^2/2$ could equilibrate a floating $4/3\,\rho\,\pi\,R^3\,g$ giving $c\,V^2= 20\,Rg/3$ without effect of density ρ of liquid. Prandtl (1952) indicates for gas bubbles in water c near 0.4 for an extended scale of Reynolds numbers, in spite of changes from laminar to turbulent. This gives a diameter 2 mm for a 0.13 m/s speed. Along other data found in Wikipedia the speed for 1 to 10 mm diameter could be 0.2 m/s, more for larger diameters or bubble swarms. It seems that sodium would carry bubbles of diameter less than 1 cm without core perturbation. Admissibility of gas leaks should be confirmed.

5. Safety aspects.

- The resting vessel with integrated exchangers, inscribed in soil, allows that no sodium could react with air.

- A general temperature increase gives elevation of core elements and descent of suspended safety rods, with a useful supplement to the negative temperature coefficient.
- No accident is found, even by earthquake, able to pierce the refractory material with sodium leak into soil. The inscribed vessel in soil receives less seismic motions than a suspended vessel.
- Suppression of hot sodium external circuits, vulnerable to aggressions, and of exchangers in pressurized vessels, favors safety.
- The large volume of cooled sodium favors natural convection and safety.
- This vessel without double curvature, wall cooling circuits, peripheric suspension and complex core support,is easy to build. It presents less risk of defects than the suspended vessel needin, aga periodically inspected welds. During extended stops, it could be examined by ultrasounds.
- The direct azote Brayton cycle heating by primary sodium in tube exchangers is to be accepted if no gas leak arriving in the core is able to perturb the neutronic reaction or the cooling. The large section exchangers allow a low speed for sodium, in which a larger bubble ascends at larger speed.
- A lower temperature at reactor basis would lower the obtained energy but also flows and pressure drops, making easier natural convection and better safety.

6. Conclusion

The resting bottom sodium vessel may receive several applications. For a fast reactor, the direct gas circuit without intermediary sodium may increase the thermal efficiency and, conveniently studied, presents no risk of gas arrival perturbing the core. A construction economy seems to appear and, at end of use, the under soil vessel needs no dismantling and could contain radioactive remains, again with economy. This fast reactor should be studied.