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Design of MSR primary circuit with minimum pressure losses

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Abstract. This article describes a design of a MSR primary circuit with minimum pressure losses. It includes a brief description of this type of a reactor and its integral layout, properties, purpose, etc. The objective of this paper is to define problems of pressure losses calculation and to design a proper device for a primary circuit of MSR reactor, including its basic dimensions. Thanks to this, it can become an initial project for a construction of a real piece of work. This is the main contribution of the carried out study. Of course, this article is not a detailed solution, but it points out facts and problems, which future designers may have to face. The further step of our work will be a reconstruction of the current experiment for a two-stage flowing.

1 IV Generation Molten Salt Reactor

The development policy for these reactors has been planned so that at least some of them are prepared to be used in 2020 to 2030, when a service life of currently used reactors will have expired. They are reactors able to provide us with sufficient energy safely and economically. Molten salts will be used as coolants; substances enabling an operation under much higher temperature and consequently efficiency as well.

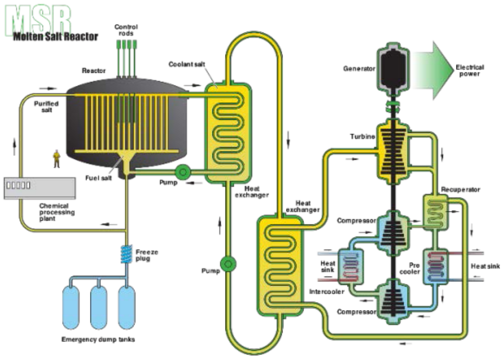

Fig. 1. MSR reactor

From a long-term point of view of nuclear power use, it is necessary to assure sufficient fuel for reactors. Therefore it is necessary to introduce fast reactors, which can use plutonium Pu as well as uranium 238U. They are capable to provide enough fuel for milleniums in a configuration of a fast breeder reactor [1,2].

2 MSR Primary circuit

Nuclear fuel is dissolved directly in a fluoride molten salt of a primary circuit and it flows around a graphite moderator along with dissolved fission products. This type of a reactor has several benefits. It allows for broader possibilities of processing nuclear fuel (Th^{-233} U cycle of denatured Th^{-233}), including the use of a fast breeder reactor regime for Th^{-233}U cycle. It provides a better "on-line" control of the whole reactor (fuel is liquid, homogeneous; so-called campaigns related to the fuel replacement in reactors with solid propellants are dropped) [5].

Table 1. Reference parameters of MSR system

Reactor parameters	**Reference value**
Assumed power	1000 MWe
Coolant inlet/outlet temperature	565/700 °C at pressure of approx. 0,5 MPa
Specific volume power	22 MWt/m^3
Net efficiency	44 to 50 %

On the other hand, this type of a reactor is very sensitive to corrosion and material compactibility (continuous operation, increased corrosion activity of molten salts with dissolved nuclear fuel and dissolved fission products to construction material). This reactor concept offers probably the largest complex benefit potentially out of all the IV generation reactor types (particularly in its fast breeder version), but also the biggest technological challenge, despite successful testing. These advanced reactors should include all so far known positive experience; they represent the needed safety standard, high operational reliability, long-term life cycle and economical competitivness with other sources. Fuel consisting of molten fluorides of uranium

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UF_4 or plutonium PuF_3 dissolved in a mix of molten fluorides LiF + BF_2 + NaF circulates in the MSR reactor. The fuel will be in a form of molten fluorides of uranium, sodium and zirconium, a moderator is solid graphite. The salts used have melting points at 425 to 510 °C. They are perfectly liquid at working temperatures of approx. 550 to 750 °C. The salts don't actively react with air nor water, which significantly reduces construction problems. Steam tension is very low and thus the system can be non-pressure operated. The salts have very good corrosion characteristics and some materials conforming these systems have already been tested, e.g. MoNiCr (Škoda JS) [6].

2.1 Determination and composition of material properties of fluoride salts for a primary circuit

The melting temperature was required to be ≤ 500 °C for the selection of a salt mixture. Minimum operational temperature is considered $T_{min} = T_{tav} + 100$ °C and its determination was based on experience from projects of fast sodium reactors as well as a course of solubility of P_uF_3. In the MSBR (Molten Salt Breeder Reactor) project, working in a thorium cycle, the temperature of 66 °C was used for a difference of a minimum operational temperature and the melting temperature. It can influence favourably a heat exchanger design but a reduction of a minimum operational temperature will also decrease solubility of tri – fluorides. Maximum temperature of a long-term run is $T_{max} \leq 710$ °C and it was determined on the basis of Hastelloy N type material properties [8].

Table 2. Values usable for thermo-physical analysis

Characteristics and temperature	Equation considering M [g mol^{-1}]
Density ρ [g/cm^3]	Relative error ± 0,9 %
800 K = 527 °C	$\rho = 1{,}9801 + 0{,}00421$ M
1000 K = 727 °C	$\rho = 1{,}8106 + 0{,}00578$ M
Viscosity η [cP]	Relative error ± (4 až 6)%
880 K = 527 °C	$\eta = - 24{,}606 + 0{,}85068$ M
900 K = 627 °C	$\eta = - 9{,}041 + 0{,}37085$ M
1000 K = 727 °C	$\eta = - 4{,}949 + 0{,}22002$ M
Thermal capacity c_p [kJ kg^{-1}K^{-1}]	Relative error ± (10 až 20)%
800 – 1000 K (527 – 724 °C)	$c_p = 3{,}73 - 0{,}037$ M
Thermal conductivity λ [W m^{-1} K^{-1}]	Relative error ± 15% (total)
800 K = 527 °C	$\lambda = 1{,}58 - 0{,}01796$ M
900 K = 627 °C	$\lambda = 1{,}63 - 0{,}01796$ M

We will determine the basic properties of fluoride salts according to the previous table, where *M* is molar weight. The purity of salts is important for their use and a failure to keep it may lead to increased corrosion on construction materials. Purity of inert gas is required as well. When using helium, the content of impurities (O, N, C, CO_2, water vapour) should be lower than 0,01% mol, as apparent from experience of operating helium-cooled reactors [8].

2.1.1 Advantages and disadvantages of fluoride salts

A large number of salt mixtures of various concentrations of particular elements is possible to use to cool down the reactor core. Single component salts are not used due to their higher melting points compared to two and multi component salts. Advantages of molten salts, in comparison with most of used coolants, can be summarized generally in four points:

- high specific thermal capacity
- high boiling point
- low pressures of saturated vapours under high temperatures
- low melting point

The following points rank among the main disadvantages of fluoride salts:

- high demands on liquid salts purity
- need of a perfect moisture removal from liquid salts – when in a contact with H_2O, hydrofluoric acid (HF) is created, which has strong corrosive effects
- relatively high solidification temperature of liquid salts
- high demands on construction materials – temperature, corrosive activity of liquid salts
- need of an embedded secondary circuit for radiation safety [8]

2.2 Design of an integral layout of a MSR primary circuit

An integral layout design of a homogeneous MSR with a gas lift is necessary when preparing a project. We have to provisionally design a pressure vessel considering the size of a core. We will apply experience from the MSBR project to select the wall thickness t = 60 mm. We are limited in the height since a compressive chimney is recommended to be H < 10 m. The tank diameter is chosen Dn = 6 m, so that we can place 6 plate exchangers in the upper part and the reflector zone.

Let's not forget that the gas lift efficiency is influenced by the height, in which the exchanger and the active zone are located. The problem is a volume compensator. We will use the analogy with a gas lift model where we obtain a space for the released gas (He). We suggest channels, between which there is enough space for regulating rods and He supply into the gas lift, to lead primary salts to particular heat exchangers. Delivery of secondary salts into the pressure vessel requires sensors on a reactor pressure vessel. There is a freezing valve located in the bottom part of the pressure vessel design for draining primary salts. The preliminary design enables to solve another tasks, such as: :

- He management
- solution of passively cooled subcritical vessels with a freezing valve providing emergency shutdown.
- solution of a reactor regulation. Solution of solid fissile products filtration.
- computations of a pressure vessel wall shielding.

The gas lift efficiency goes up along with minimizing pressure dissipations, i.e. the pipeline design, 90 degrees arcs, bevelling, narrowing, extension, etc.

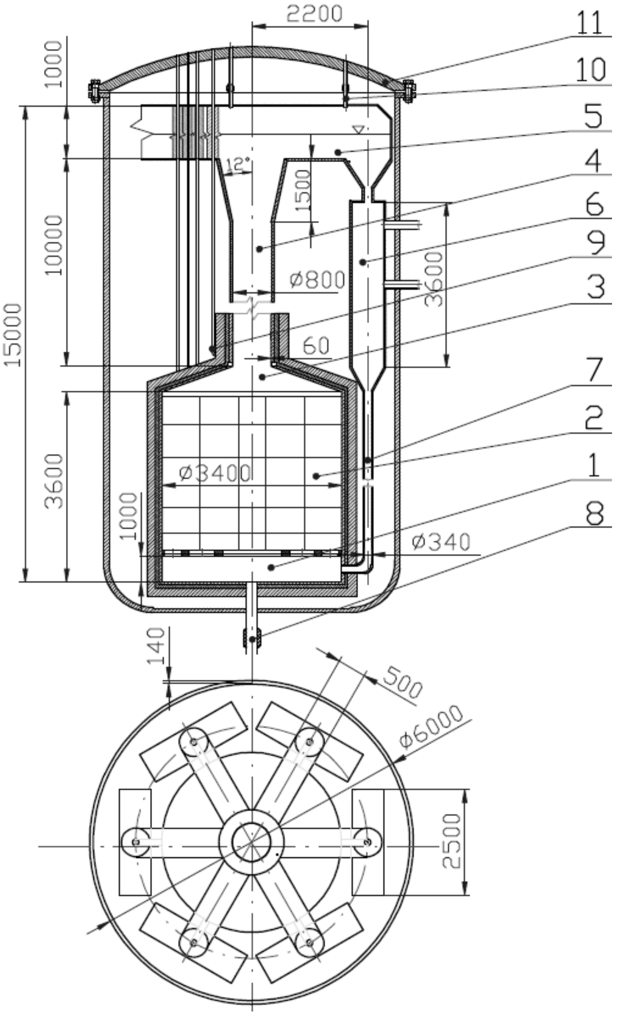

Fig. 2. Design of component layout of a MSR primary circuit with minimum pressure dissipations

We will place a ring in the bottom part of the chimney, into which we will deliver inert gas (helium) and inject it in the chimney through holes. As a result, density of fluoride salts reduces and a circulation improves. The gas will exhaust, being recycled and purified from gaseous fissile products. Consequently, it will be again used in the circuit.

Table 3. Description of a primary circuit components

Position	Description	Position	Description
1	Mixing chamber	7	Cold leg
2	Core	8	Outlet valve
3	Transition to chimney	9	Ring - helium inlet
4	Chimney	10	Helium outlet
5	Volume compensator	11	Top header
6	Counter-flow exchangers		

The use of a gas – lift in a primary MSR circuit offers a lot of benefits. The removal of a mechanical device, which needs a power source for its operation, significantly contributes to the increase of a reliability and safety of a nuclear power device.

All mechanical devices are outside the core, therefore it is possible to carry out repairs and adjustments while the reactor is running by switching to a back-up device. Furthermore, another advantage is a lower demand on energy and the fact that it is possible to be used even in reactors, which work with a medium of a temperature higher than 1000 °C, for which a pump doesn´t exist yet. Current industrial pumps can function up to 600 °C and new generations of pumps capable of working up to 700 °C are beginning to be introduced [4].

3 Calculation of pressure losses of a MSR primary circuit

Thermal and hydraulic calculation of a nuclear power reactor along with physical, strength and technical-economic calculations of all components and the primary circuit itself serve to proceed the primary circuit project aiming at optimization and assuring nuclear safety.

Thermal and hydraulic calculation determine, along with a physical calculation, thermal power released by a nuclear reaction along the cross-section and height of the core. Further calculations determine the heat medium flow through the core, temperatures on the mixture surface and inside it, pressures in a circulation circuit and other parameters of the medium flowing through the primary circuit. Therefore it is necessary to know or estimate thermohydraulic characteristics of the primary circuit and its regime parameters, along with construction material, thermal and hydraulic characteristics of particular reactor components. [3]

The calculation of a designed primary circuit proceeds as follows:

3.1. Process of a calculation of hydraulic losses of a primary circuit

First, we will define basic dimensions of a primary circuit (*Fig. 2*). We will consider an integral setup in a reactor vessel of a homogeneous MSR reactor. The main construction material for a high-temperature reactor primary circuit is graphite and its composites.

Before proceeding, it is worth preparing a list of local losses and giving some thoughts to construction modifications leading to their minimizations. Dimensions, height data, temperature, subcriticality check outside the core, that all should be listed for individual parts of a primary circuit.

We have to specify the main parameters of the core based on requirements – e.g. we can determine the thermal power P_t from the requirement on electric power production with the help of efficiency η.

$$P_t = \frac{P_{el}}{\eta} \tag{1}$$

To determine the thermal power, we will choose the mean specific power q, it is for the gas - lift:

$$q = 25 \div 40 \left[\frac{MW_t}{m^3}\right] \tag{2}$$

Based on the above mentioned data we can define the core volume V, furthermore a suitable diameter D and height H. The diameter of a chimney d can be determined from a subcriticality condition ($k_{ef} \leq 0{,}95$).

We will proceed the calculation of the theoretical mass flow $W_{\infty\,T}$ from the free flow according to the primary circuit design:

$$W_{\infty\,T} = \frac{P_t}{\Delta T . c_p} \tag{3}$$

We know how to determine the mass flow rate from the above stated formula. We will choose a methodology to calculate the gas – lift. The most suitable model for nuclear reactors is a disperse bubble flow model, as it provides maximum intensification of natural flow and ensures an impact-free operation.
We can determine velocities in individual parts by the following relation:

$$v_p = \frac{W_{\infty\,T}}{\rho_p . A_p} \tag{4}$$

Friction losses must be considered in each part in order to calculate the total losses

$$\Delta p_{p\,fr} = \lambda . \rho_p . \frac{L_p . v_p^2}{D_p\ .2} \tag{5}$$

and local losses

$$\Delta p_{p\,l} = \xi_p . \rho_p . \frac{v_p^2}{2} \tag{6}$$

The total friction losses in a p part will be:

$$\chi_{tf} = \Delta p_{p\,fr} + \sum_{n=1}^{N} \Delta p_{p\,l} \tag{7}$$

After we have determined the total pressure losses, we are able to determine the real stabilized mass flow $W_{\infty\,R}$ for a natural flow in a primary circuit by using the gas - lift [3,4,7].

$$W_{\infty\,R} = \left[\frac{2.\rho^2.g.\beta.P_t}{\chi_{tf} \cdot c_p} . \left(z_e - z_{pc}\right)\right]^{\frac{1}{3}} \tag{8}$$

where : $W_{\infty\,R}$	real mass flow rate in a balanced state
ρ	mean density of a coolant in a circuit
g	gravity acceleration
β	thermal expansion coefficient
z_e , z_{pc}	mean heights of locations of a heat exchanger and core in a primary circuit
c_p	thermal capacity of the coolant
χ_{tf}	total hydraulic losses in a primary circuit

The relation (8) shows the dependence of the zone P, flow-carried, on the cube of the mass flow rate $W_{\infty\,R}$. When using the "gas-lift", the following applies for the chimney with a cross-section

$$A_{ch} = \frac{\pi}{4} . D_{ch}^2\ [m^2] \tag{9}$$

according to the law of conservation of mass

$$W_{\infty}^{gas-lift} = \left(W_{\infty\,R} + W_g\right) \left[\frac{kg}{s}\right] \tag{10}$$

For the use of $W_{\infty}^{gas-\ lift}$, it is generally necessary to use c_p and ρ for a double-phase mixture, as well as to determine new losses at the same time, as $W_{\infty}^{gas-lift}$ enlarges the flow velocity in the whole primary circuit. The volume of gas supplied by m holes into the chimney of the gas – lift $W_g \left[\frac{kg}{s}\right]$ can be determined by the following expressions:

This relation was derived for W_g

$$W_g = C_d\ .\ \frac{\pi}{4} . d^2 .\ m\ .\ p_1 . \sqrt{\frac{1}{r\ .T_g} - \left(\frac{2\ .\ \kappa}{\kappa - 1}\right)} .$$
$$. \sqrt{\left(\frac{p_2}{p_1}\right)^{\frac{2}{\kappa}} - \left(\frac{p_2}{p_1}\right)^{\frac{\kappa-1}{\kappa}}} \tag{11}$$

Where: m	is a number of holes of a diameter d
p_1	gas pressure in front of the throttle hole
p_2	gas pressure behind the throttle hole

According to the anglo-saxon literature, the dissipation coefficient is determined by the relation:

$$C_d = \mu . \sqrt{\left[1 - \frac{D^2}{d^2}\right]^{-1}} \tag{12}$$

Where: μ outlet coefficient

D channel diameter

The following relation applies for the critical coefficient

$$K_{cr} = \left(\frac{p_2}{p_1}\right)_{crit} = \left(\frac{2}{\kappa + 1}\right)^{\frac{\kappa}{\kappa-1}} \qquad (13)$$

3.3. Evaluation and conclusion

The meaning of the calculation is to optimize basic circuit dimensions and summarize concrete local and friction losses, see Fig. 2, and particular local and friction losses are summarized, whereas they were calculated onto the whole primary circuit of the reactor, see the results stated in Tab. 3. Dissipation coefficients ξ_p , λ for each part of the primary circuit were calculated as well. Let's point out that losses are summed up when counting presure losses in a series primary circuit, however, they are considered only once in case of a parallel system. It means that when having six loops, pressure loss from six or more loops will be the same since it is a parallel system.

The following table summarizes pressure losses in particular components. As apparent, the biggest local pressure loss occurs at the inlet to a mixing chamber, this loss could be reduced by a gradual expansion of an inlet neck; it is a detailed issue which requires more attention and a more detailed and precise solution in the future.

Table 3. Concrete pressure losses in particular places

Component	Name of the component	Pressure loss
1.	Core	3,3 Pa
2.	Inlet into chimney (cone restriction)	27,7 Pa
3.	Chimney	14550,7 Pa
4.	Outlet from chimney (cone expansion)	721,6 Pa
5.	Channel	360,7 Pa
6.	Inlet into heat exchanger (cone restriction)	512,2 Pa
7.	Heat exchanger	22800 Pa
8.	Outlet from heat exchanger (cone expansion)	256,5 Pa
9.	Cold leg	24943,3 Pa
10.	Cold leg arc	10477,1 Pa
11.	Inlet into mixing chamber	62451,7
12.	Mixing chamber screen	55000 Pa
13.	Total pressure losses of primary circuit	0,196 MPa

This calculation aimed at more concrete examples of local and friction dissipations as well as relations defining them and proving which parameters or dimensions influence the given dissipations the most. As my hydraulic calculation must correspond with physical and thermal calculations I certainly acknowledge individual minimal changes in parameters and dimensions. The main objective was to design a circuit for the further project, which will provide a more detailed solution of this matter.

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