Studies on Components for a Molten Salt Reactor

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ABSTRACT
The aim is contribute to a design of selected components of molten salt reactors with fuel in the molten fluoride salt matrix. Molten salt reactors (MSRs) permit the utilization of plutonium and minor actinides as new nuclear fuel from a traditional nuclear power station with production of electric energy. Results of preliminary feasibility studies of an intermediate heat exchanger, a small power molten salt pump and a modular conception of a steam generator for a demonstration unit of the MSR (30MW) are summarized.

KEY WORDS: heat exchanger, molten fluoride salt, centrifugal pump, heat carriers, steam generator.

INTRODUCTION

Three-circuits layout of the MSR in the molten fluoride salt matrix is assumed. A molten nuclear fuel flows in the primary circuit; a suitable heat carrier in the secondary circuit and the power tertiary circuit is based on the Rankin-Clausius cycle with water and steam. A simplified scheme of the power part of the Molten Salt Reactor (MSR- Demonstration Unit-30MW thermal) is shown in Fig.1.

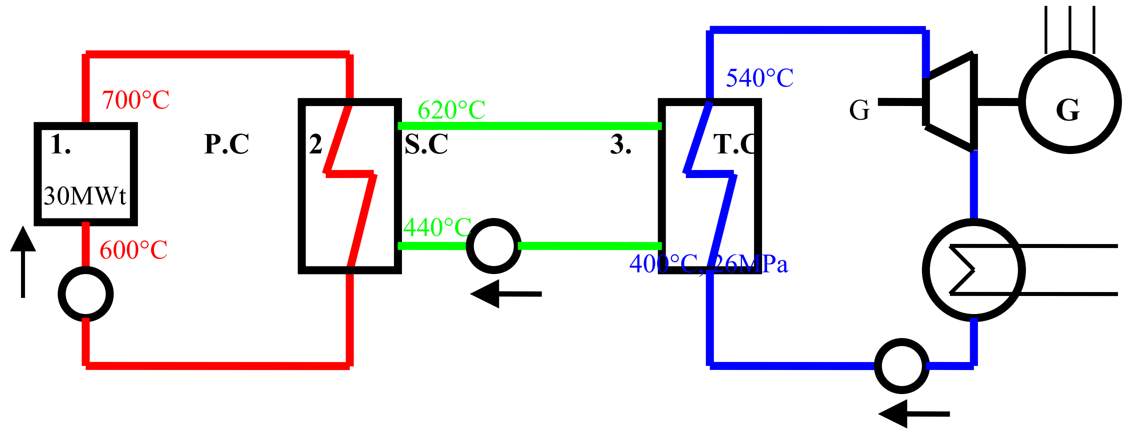


Fig..1 A Simplified Scheme of the Power Part of a Molten Salt Reactor (MSR- Demonstration Unit-30MW)
1.- Transmutation Reactor, 2.- Intermediate Heat Exchanger, 3.- Steam Generator, P.C – Primary Circuit, S.C- Secondary Circuit, T.C- Tertiary Circuit, G-Turbo-generator,

A needed power of the main circulating pump of suitable heat carriers in the secondary circuit can be expressed by the equation:

$$P\check{c} = \dot{m} \cdot \frac{\Delta p}{\rho} = \dot{m} \cdot \xi \cdot \frac{c^2}{2} \quad [W] \tag{1}$$

Simultaneously, continuity equation is valid in the form:

$$\dot{m} = \rho \cdot S \cdot c \, [kg/s] \tag{2}$$

The thermal power of a transmutation reactor can be expressed in the simplified form:

$$\dot{Q}t = \dot{m} \cdot Cp \cdot \Delta T \quad [W] \tag{3}$$

After the expression of mass flow rate from the equation (3) and average flow velocity from the equation (2) and their substitution into the equation (1) the needed power of the main circulating pump can be expressed by the equation:

$$P\check{c} = \frac{\xi}{2 \cdot S^2} \cdot \left(\frac{\dot{Q}t}{\Delta T} \right)^3 \cdot \rho \cdot (\rho \cdot Cp)^{-3} = F_{H\,SC} \cdot F_{PC} \cdot F_E \quad [W] \tag{4.}$$

Where:

- The factor of the secondary circuit configuration is defined as:

$$F_{H\,SC} = \frac{\xi}{2 \cdot S^2} \quad \left[m^{-4} \right] \tag{5.}$$

- The factor of the heat content (enthalpy) in the heat carrier is defined as:

$$F_{PC} = \left(\frac{\dot{Q}t}{\Delta T} \right)^3 \quad \left[\frac{W^3}{K^3} \right] \tag{6.}$$

- The factor of thermodynamic properties of a heat carrier is defined as:

$$F_E = \rho \cdot (\rho \cdot Cp)^{-3} \quad \left[\frac{kg \cdot K^3 \cdot m^5}{J^3} \right] \tag{7.}$$

The needed power of the main circulation pump of a suitable heat carrier in the secondary circuit strongly depends on following factors:

- Thermodynamic properties of heat carriers. The pump power decreases by the second power of the density and the third power of specific heat capacity of a heat carrier.
- Temperature difference ΔT in the intermediate heat exchanger causes decrease the pump power by the third power.

Thermal heat power increases the pump power with the third power.

- Configuration of the secondary circuit (heat exchange surfaces of an intermediate heat exchanger and a steam generator).

A simplified comparison of heat carriers considered for the secondary circuit from the viewpoint of the needed power of the main circulating pump are shown in Tab.1, Tab.2 and Fig.2. The needed power of the main pump of a heat carrier is the lowest in the case of the molten fluoride salt 92% $NaBF_4$+8% NaF is used for the same hydraulic characteristics of the secondary circuit.

Tab.1 Some Characteristics of Selected Heat Carriers (average temperature - 530°C)

Heat Carrier	Tt	ρ	Cp	Reference
	°C	kg/m^3	J/kg.K	
92% $NaBF_4$+8% NaF	384	1870	1510	[10]
Na	98	829	1273	[9]
Na-K	-11	753	892	[9]
Pb	327	10476	147	[9]
Pb-Bi	123	10120	146	[9]
Sn	231	6790	255	[9]
Hg	-38	12480	138	[9]
He*	gas	3,27	5190	[11]
CO_2*	gas	37,04	1930	[11]

- at the pressure of 4 Mpa

Tab.2 Comparison of Different Heat Carriers from the Viewpoint of F_E and F_E/F_{ES} values.

Heat Carrier	F_E	F_E/F_{ES}
	kg.K^3.m^5	-
92% $NaBF_4$+8% NaF	8,31E-17 (F_{ES})	1,0
Na	7,05E-16	8,5
Na-K	2,48E-15	29,9
Pb	2,87E-15	34,5
Pb-Bi	3,14E-15	37,8
Sn	1,31E-15	15,7
Hg	2,44E-15	29,4
He*	6,7E-13	8064,1
CO_2*	1,01E-13	1220,9

*at the pressure of 4 MPa

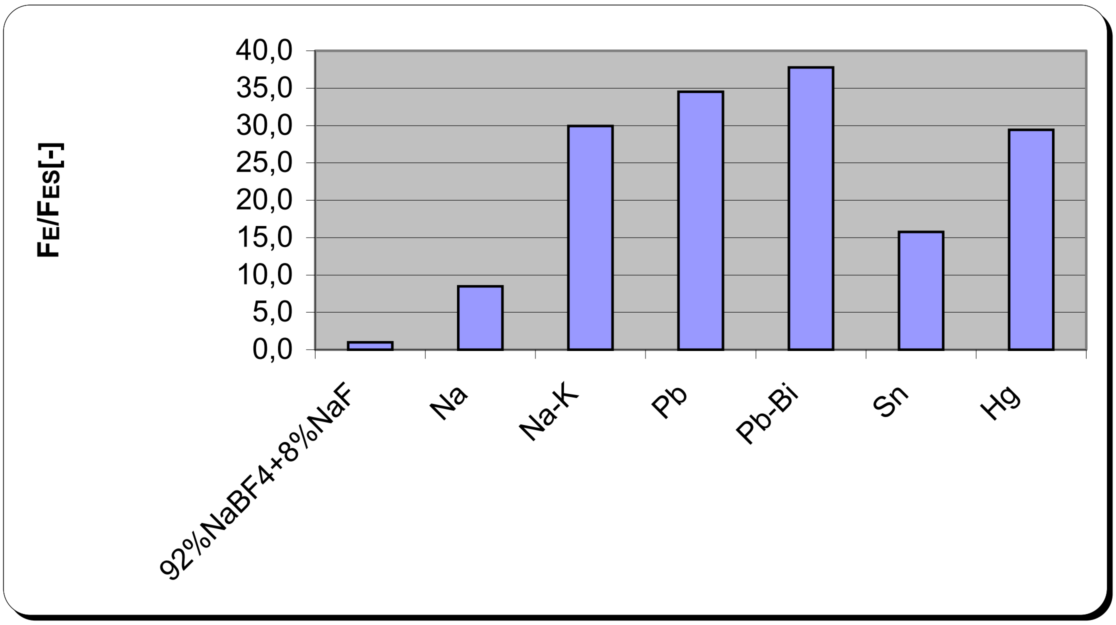


Fig.2 F_E/ F_{ES} Ratio for Different Heat Carriers (F_{ES} – factor for the salt 92% $NaBF_4$+8% NaF)

PRELIMINARY DESIGN FEATURES OF THE INTERMEDIATE HEAT EXCHANGER

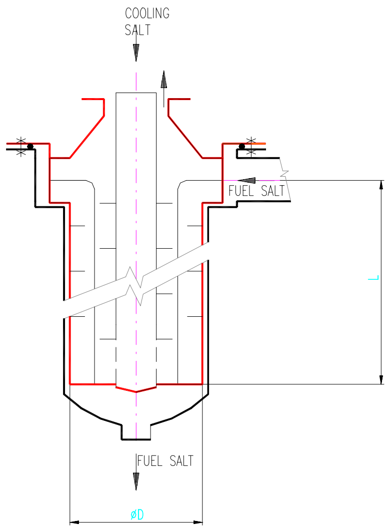
The feasibility study of the intermediate heat exchanger for the demonstration unit (30 MW thermal) started from a concept in [8]. The intermediate heat exchanger is designed as a vertically oriented heat exchanger, where molten fluoride fuel salt flows in tubes and the secondary heat carrier at the shell side .A simplified scheme of the intermediate heat exchanger is shown in Fig. 3. Design parameters and results of calculations are summarized in the Tab.2, Tab.3.

Tab.2 Design Parameters of the Intermediate Heat Exchanger 30MW (thermal)

Parameter	Value	Note
Thermal Power	30 MW	
Fuel Salt is based on LiF+BeF_2		UF_4 as fuel
Fuel Salt Temperature -Inlet	700°C	
Fuel Salt Temperature -Outlet	600°C	
Design Pressure in the Primary Circuit	0,35MPa	
Secondary Salt: 92% $NaBF_4$+8% NaF		
Salt Temperature- Inlet	440°C	
Salt Temperature -Outlet	620°C	
Design Pressure in the Secondary Circuit	0,55MPa	

Tab.3 Results of the Feasibility Study of the Intermediate Heat Exchanger for the Demonstration Unit 30MW

	Unit	Different Variants of the Intermediate Heat Exchanger (Fig.3)		
Diameter of Shell Tube (ØD)	mm	500	450	400
Average length of Tubes (L)	m	5,2	5,8	6,7
Mass Flow Rate of the Fuel Salt	kg/s	224	224	224
Mass Flow Rate of the Secondary Salt	kg/s	110,4	110,4	110,4
Average Velocity of the Fuel Salt in the Tubes	m/s	1,24	1,63	2,28
Average Velocity of the Secondary Salt at the Shell Side	m/s	0,66	0,81	1,0
Overall Heat Transfer Coefficient	$W/m^2.K$	1455	1715	2055
Number of Tubes- Ø10x1	-	1102	836	598
Heat Transfer Surface	m^2	178,6	151,6	126,5
Volume of the Fuel Salt	m^3	0,29	0,24	0,20



Obr.3 A Simplified Scheme of the Intermediate Heat Exchanger (30MW)

DESIGN AND TESTING OF A MOLTEN SALT PUMP

The feasibility study of a centrifugal pump for the future demonstration unit (30MW) was done at the small power pump at the experimental facility operating with a molten fluoride salt. The centrifugal pump has been developed for high temperatures and a molten fluoride salt environment in Energovýzkum Brno in cooperation with Brno University of Technology [1]. The pump is designed to the temperature of 550 °C and pressure of 0,5 MPa. The pump consists of a pressure bulk vessel, bearing and clutch boxes and an electrical motor, which is situated in the upper part of the pump. The pump was tested at a water loop preliminary, Fig.4, Fig.5. Afterwards the pump was implemented in the experimental fluoride loop and tested at the temperature of 400°C.

Obr.4. The Pump before Implementation into the Molten Fluoride Salt Loop

An overall characteristic of the pump and loop obtained at the water loop is shown in Fig. 5.

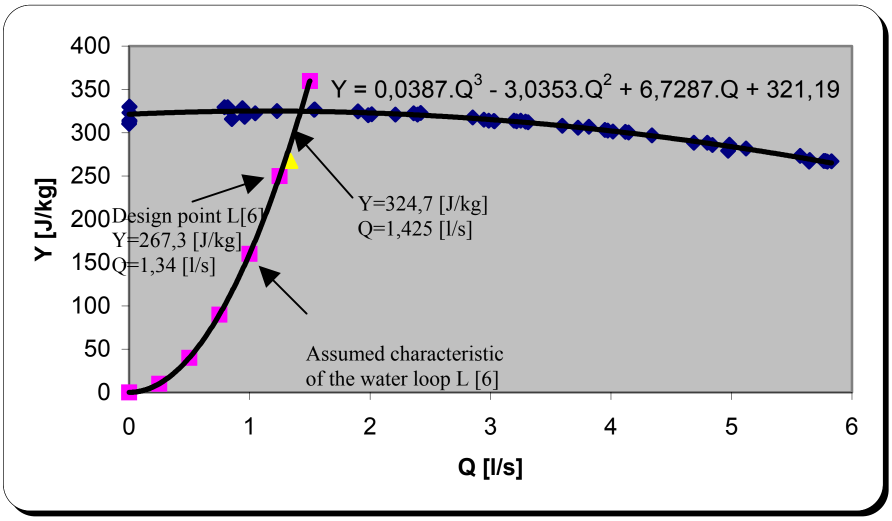


Fig.5 Overall Characteristic of the Pump (Specific Energy Y versus Volume Flow Rate Q, Y=f (Q)) at nominal revolutions (1440 1/min).

Acid potassium fluoride (KHF_2) was chosen for the experimental loop as heat carrier because of:

- Relatively low melting temperature (240°C) in comparison to the 92% $NaBF_4$+ 8% NaF (384°C)
- Availability on the Czech market.
- Relatively low costs for the KHF_2 (30 US $/kg) in comparison to for example SnF_2 (more then 300 US $/kg) [4]
- Relatively simple preparation of the salt for the loop (It is not necessary to mix an eutectic mixture)
- Some practical experience [3].

PRELIMINARY DESIGN FEATURES OF STEAM GENERATOR FOR MSR

A modular steam generator (SG) for a demo unit of 30 MW thermal has been studied with supercritical parameters of H_2O heated by the molten fluoride salt. The parameters of the modular steam generator are shown in Tab.4. The concept of the steam generator is based on experiences obtained during development, manufacture, delivery and operation of the steam generators for A1 nuclear power station (coolant -CO_2) and Russian fast breeder reactor BOR 60, [12]. Results of the feasibility study are summarized in Tab.5.

Tab.4 Design Parameters of the Steam Generator 30MW

Parameters	Dimension Value
Thermal Heat Power	30 MW
Secondary Salt: 92% $NaBF_4$+8% NaF	
Salt Temperature –inlet	440°C
Salt Temperature –outlet	620°C
Design Pressure in the Secondary Circuit	0,55MPa
Temperature of the H_2O- inlet	400°C
Temperature of the H_2O- outlet	540°C
Design Pressure of the H_2O at the inlet	26 MPa

Tab.5 Some results of the SG 30 MW Feasibility Study

	Unit	
Number of Branches	-	6
Thermal Power of One Branch	MW	5
Mass Flow Rate of the Salt	kg/s	18,4
Mass Flow Rate of the H_2O	kg/s	6,81
Average Velocity of the Salt	m/s	0,93
Average Velocity of the H_2O	m/s	28,9
Overall Heat Transfer Coefficient	$W/m^2.K$	2245
Number of Tubes	-	31
Heat Transfer Surface	m^2	38,6
Average Length of Tubes	m	12
Pressure Drop at the H2O Side	MPa	1,98

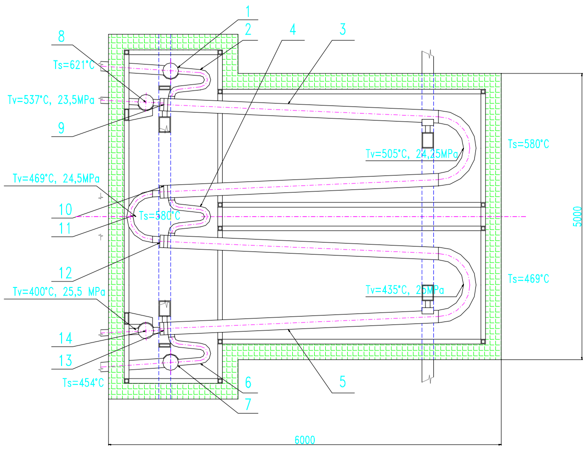


Fig. 6 Front View on the Modular Steam Generator

1) Salt Inlet Collector, 2) Salt Inlet Pipeline, 3) Shell Tubes of the SG, 4) Salt Auxiliary Pipeline, 5) Lower Section of the SG Modules 6) Salt Outlet Pipeline, 7) Salt Outlet Collector, 8) Outlet Collector of H_2O, 9) Outlet of the SG Module (identical with 10,12,13) 11) Auxiliary Pipeline of H_2O, 14) Outlet Collector of H_2O.

The Steam Generator (30MW) consists of six branches, parallel connected to steam, water and salt collectors. Each module is "V" shaped (Fig.6). Auxiliary pipelines connect both modules. The salt flows in the input pipeline and is divided into six modules of the SG. The salt is designed to flow at the shell side and heat the H_2O through 31 duplex- tubes Ø17x1,5 mm and Ø14x2 mm (Fig.7, Fig.8). Tubes are connected to the tube plates, which are designed as double tube plates on the side of high-pressure water because of safety.

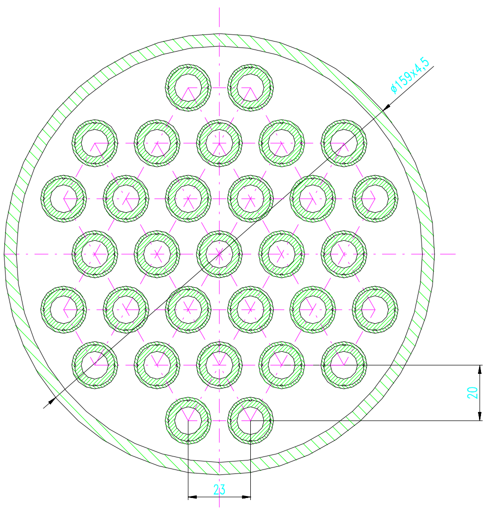


Fig.7 Arrangement of Tubes in the SG Shell Tube.

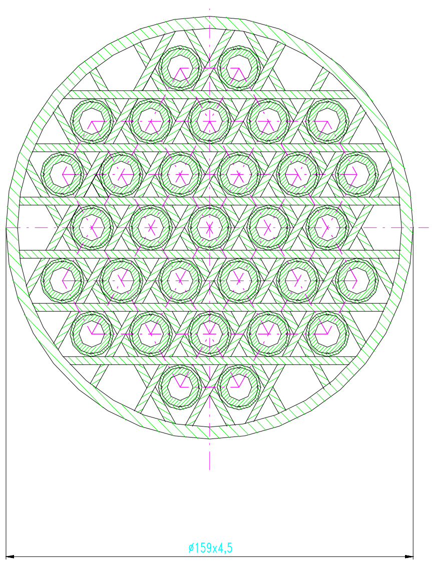


Fig.8 Arrangement of the Tube Bundle Fixing Grids in the SG Module

CONCLUSION

Studies on components for Molten Salt Reactor have been performed with data and tools not verified by experiments sufficiently. Therefore more detailed analysis of components supported by many experiments must be done in future.

NOMENCLATURE

c	Average Velocity of a Heat Carrier in the Secondary Circuit, m/s,
Cp	Specific Heat Capacity, J/kg.K,
$\dot{m}$	Mass Flow Rate, kg/s,
Pč	Needed Power of the Main Circulating Pump, W,
Qt	Thermal Power, W,
S	Cross Section, m2,
Tt	Melting Temperature, °C,
Δp	Pressure Difference between Inlet and Outlet of the Pump, Pa,
ΔT	Temperature Difference of a Heat Carrier in the Secondary Circuit, °C,
ξ	Pressure Drop Coefficient of the Secondary Circuit Pipeline, -,
ρ	Density, kg/m^3,
F_{H-SC}	Factor of the Secondary Circuit Configuration, m^{-4},
F_{PC}	Factor of Heat Content in the Heat Carrier, W^3/K^3
F_E	Factor of Thermodynamic Properties of a Heat Carrier

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