State Scientific Center of Russian Federation – Institute for Physics & Power Engineering named after A. I. Lejpunskij, Obninsk

РОСАТОМ

Experimental Study of Thermal hydraulics on the Model of Helical Coiled Steam Generator Heated by Liquid Lead with Longitudinal and Transverse Flow

Grabezhnaya V.A., Mikheyev A.S.,

«**Heavy liquid-metal coolants in nuclear technologies»,**
HLMC-2018, October 8 – 11, Obninsk, Russia

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1 Experimental models and facility loop

1.1 Research stand

1.2 The model of the steam generator with two three-tube sections (version 2000)

1.3 Fragment18-tube steam generator model

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3 About thermal hydraulic stability

CONCLUSION

INTRODUCTION

- The BREST-OD-300 RU steam generator project being developed is pioneering both in terms of the heat carrier used, which is lead, and in the construction embodiment (twisted heat transfer coil). In 2011–2013 in the State Research Center of the Russian Federation - IPPE, at the SPRUT stand, thermal-hydraulic tests of the BREST-OD-300 twisted-steam generator model (2000 version) were carried out with a longitudinal lead flow of heat-exchange tubes. The model developer is OKB “GIDROPRESS”.

- The test program of the steam generator model was aimed at studying the heat transfer and thermal-hydraulic stability of the steam generating tubes under the parameters of partial and start-up modes. In the entire range of variation of the operating parameters, no pulsation regimes with overturning of the circulation in the secondary circuit were detected.

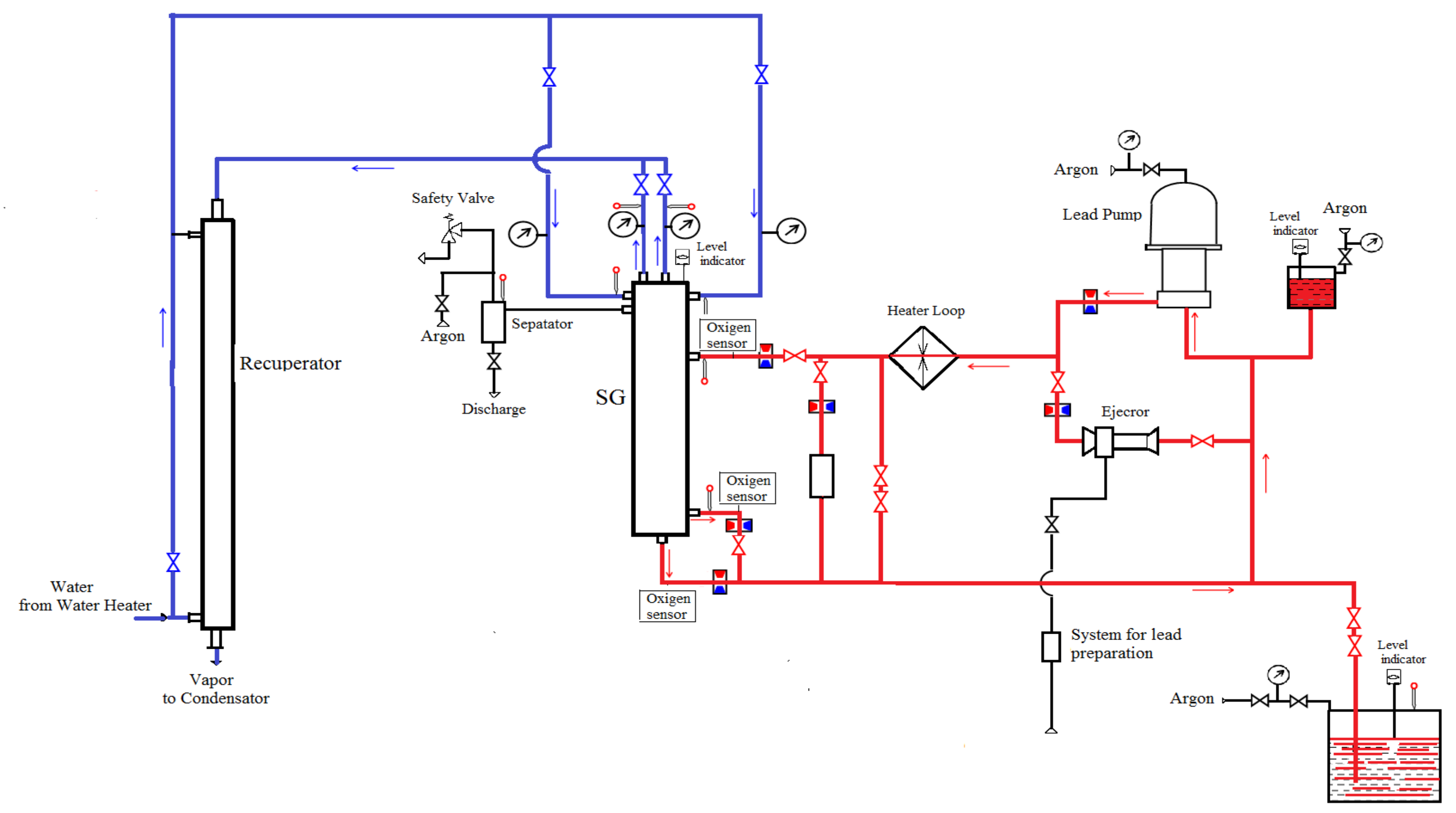
- Insufficient argumentation of transferring the results obtained in the experiments to a full-scale steam generator served as the basis for the need to conduct tests on a multi-tube model of a regular steam generator, the design of which was carried out at OJSC IC ZIOMAR.

- The partial-parameter tests carried out on the 18-pipe model of the steam generator showed that modes with pulsations of water flow, pressure in the collectors, and steam temperatures were not detected.

- The purpose of this work is to compare the results of tests relating to steam overheating and hydrodynamic stability obtained on both models of SGs, which differ in the method of flow around steam generating tubes.

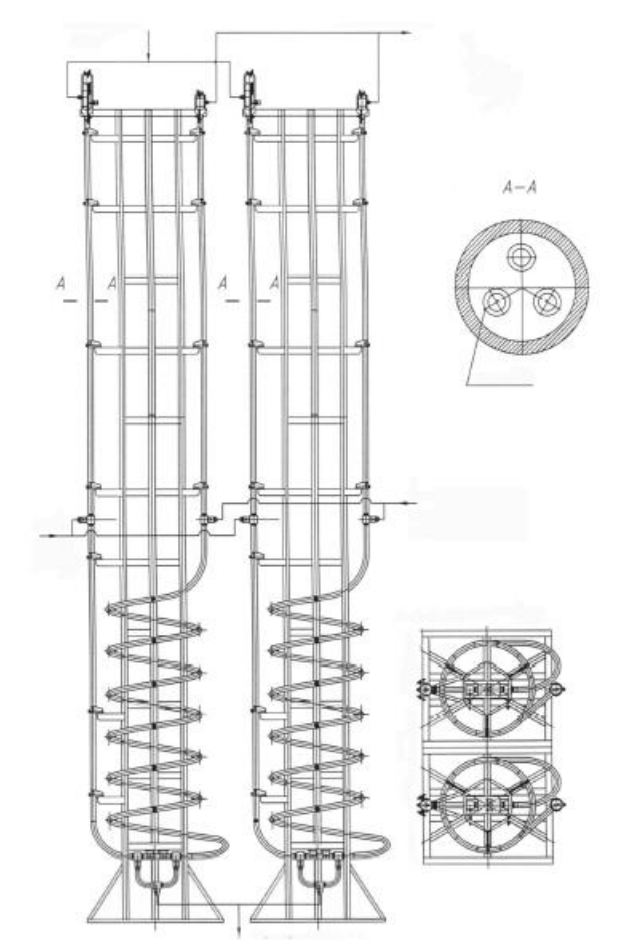
1.1 Research stand

Scheme of the SPRUT facility loop with SG model [1]



1.2 The model of the steam generator with two three-tube sections

General view of the model [1]



The steam generator model consists of two identical three-tube sections (modules). The coil average diameter of the heat-transfer tubes of the full-size steam generator of the BREST-OD-300 RF (1600 mm) is chosen as a diameter of the coil of the three-tube bundle.

Each module consists of a downcomer through which up to 5% of the total lead flow is pumped and a helical riser through which the main lead flow is pumped.

The outer diameter of the heat transfer tubes is 17mm, the wall thickness of the heat transfer tube is 3 mm. The tubes axial pitch is 25 mm. There are 15 ranging elements located at 750 mm from each other along the helical tube.

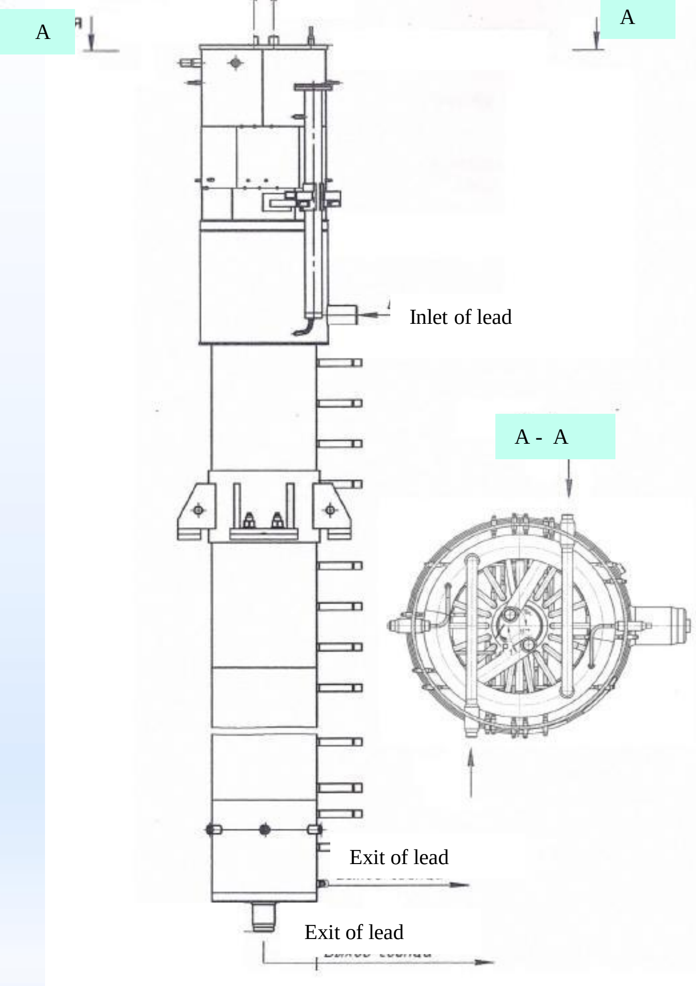
The modules are connected in parallel and can work both together and separately.

To measure the shell temperature the SG module is equipped with thermocouples arranged with a variable pitch.

At a distance of 19 m from the lead inlet downstream the flow 4 thermocouples are placed along the perimeter of the shell to detect possible upsets of lead temperature.

1.3 Fragment thermal-hydraulic model of the steam generator

General view of the 18-tube SG model [2]



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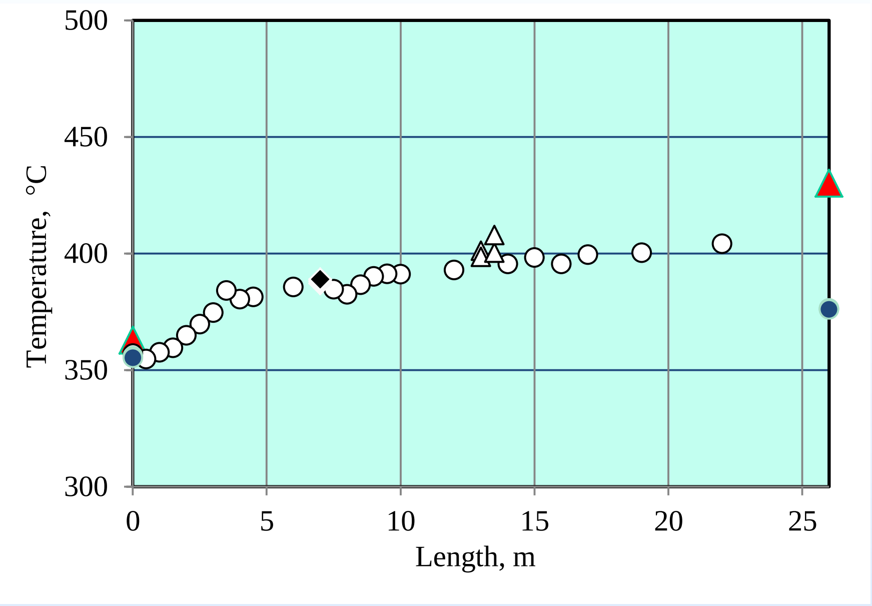
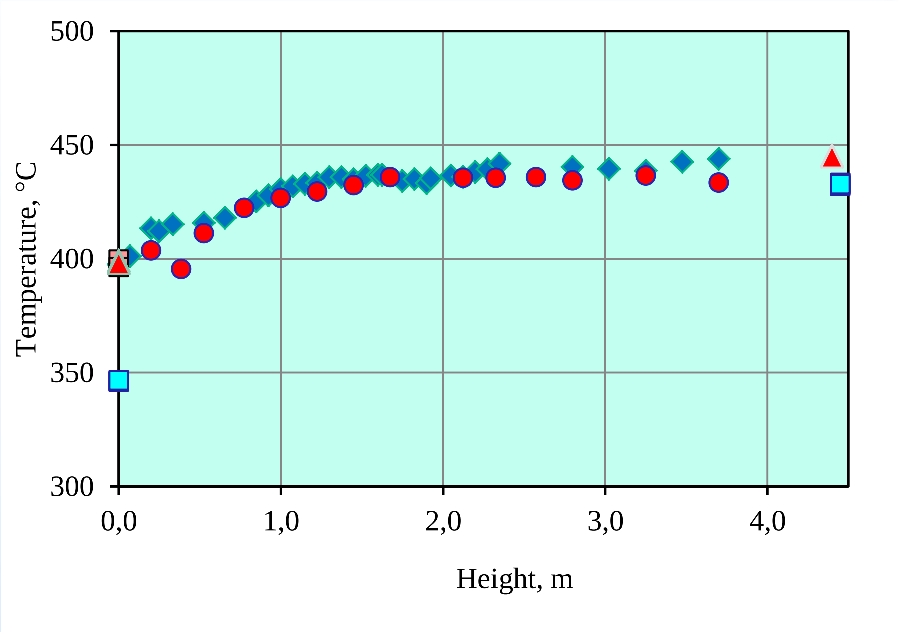
2 About heat transfer

Temperature distribution on the body models

Starting mode, water flow rate – 4% G_{nom}





Three tube section (longitudinal lead) [3]

$T_{Pb} – t_{vaper} = 55$ °C

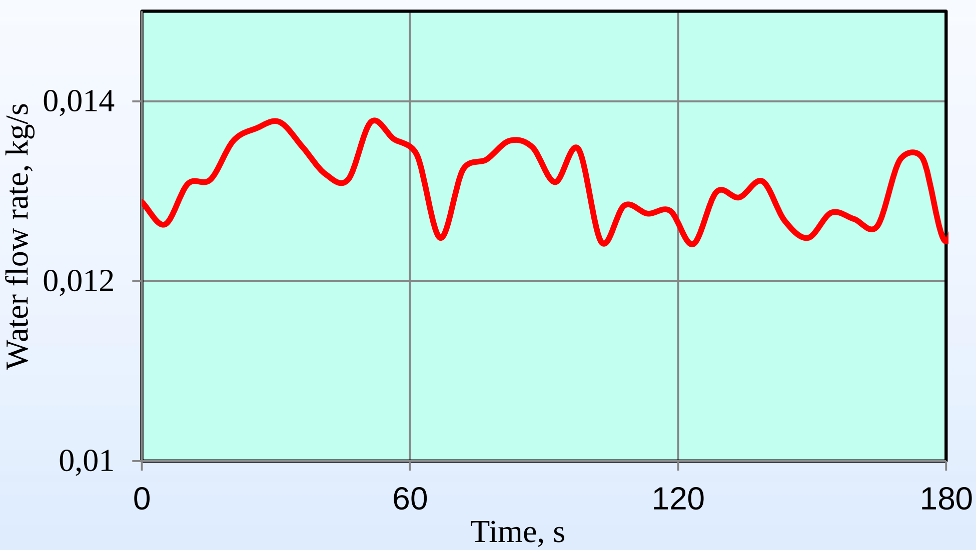
Fragment model (cross lead) [2]

$T_{Pb} – t_{vaper} = 13$ °C

In the case of longitudinal flow of lead this difference decrease with increasing G_w. At nominal parameters t_{vapor} at the output of the model is 507 °C, at T_{Pb} = 540 °C [3].

3 About thermal hydraulic stability

Model of the steam generator with longitudinal flow of lead



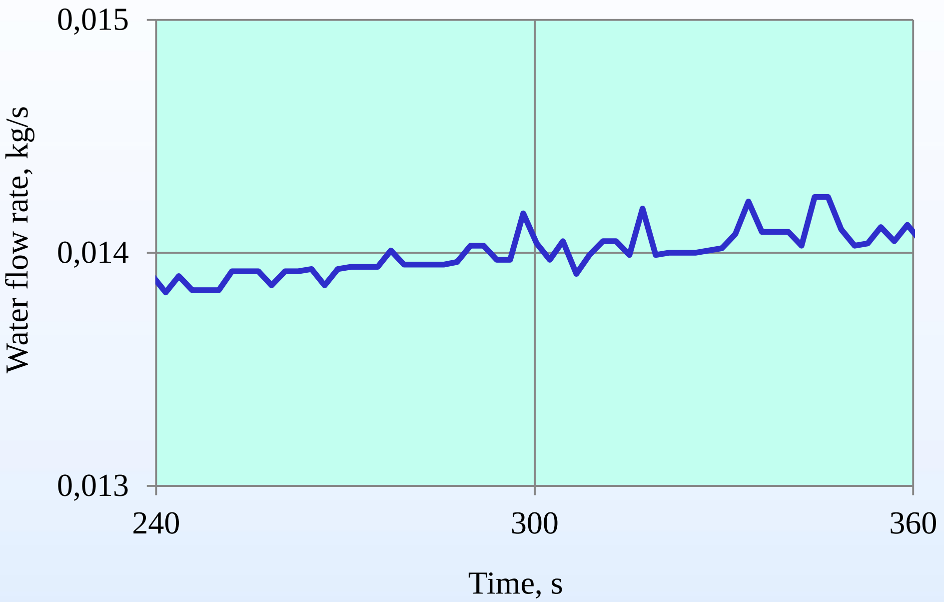
Time recording of water flow rate [4]

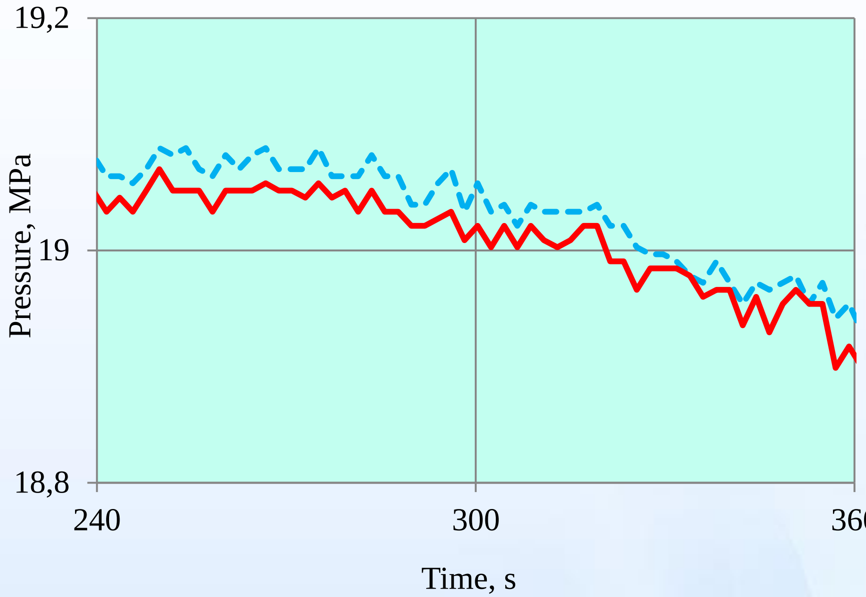
- The results of tests of a single section under partial and transient modes showed that there are no modes with overturning of circulation in water circuit in the entire range of the regime parameters change.

- Observed fluctuations in the water flow rate at the entrance to the steam generator section are due to the operating conditions of the module and the test facility as a whole.

3 About thermal hydraulic stability

Combined operation of two three-tube modules



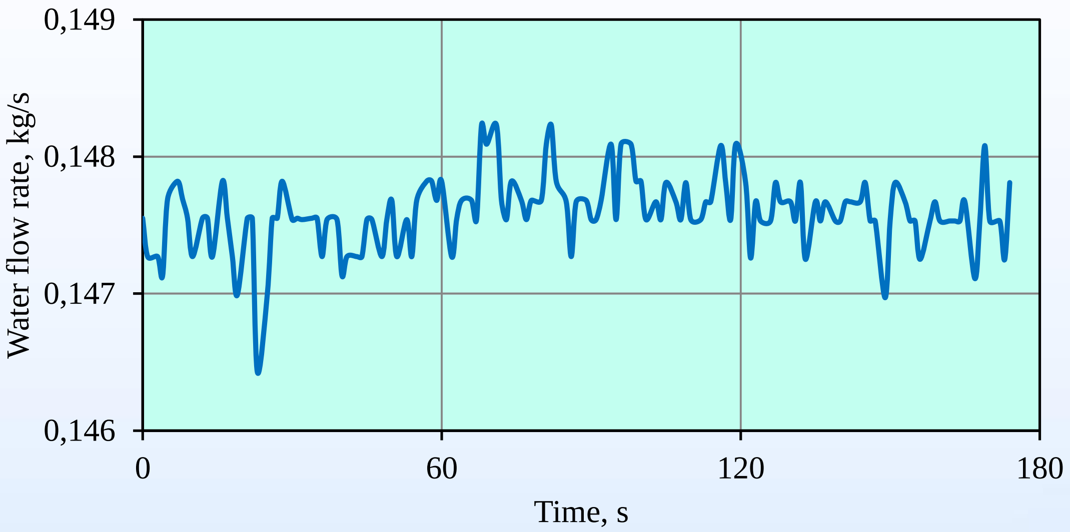


Time recording of water flow rate and pressure at the inlet / outlet of the section [5]

Tests of the two-section model carried out in the range of the flow rate of feed water from 4% to 125% of the nominal value showed complete absence of hydrodynamic instability in heat transfer tubes. It should be emphasized that at the inlet of the steam generating channels there were no throttling devices that increased the hydrodynamic stability.

3 About thermal hydraulic stability

Fragment model. Combined operation of two collectors

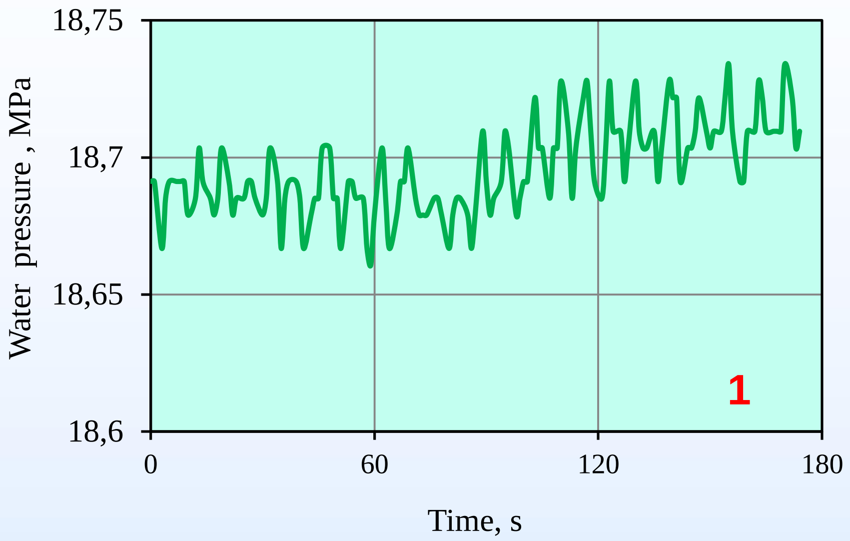


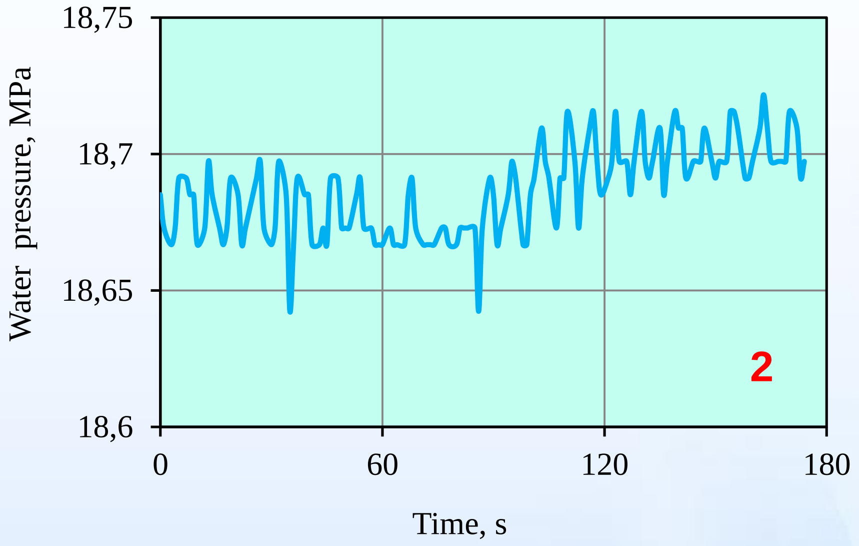
Time recording of water flow rate at the inlet of the model

Despite the fact that inlet water temperature in the collectors was different from the saturation temperature for a given pressure less than 5 °C, i.e. in the descending branch of the steam-generating tube boiling took place, oscillations of water flow rate at the inlet to the collector, which would indicate thermal-hydraulic instability, not to mention the overturning circulation, were not found. Oscillations of water flow rate were less than 1%.

3 About thermal hydraulic stability

Fragment model. Combined operation of two collectors





Time recording of water pressure at the inlet of the collectors

The water pressure oscillations at the input of the collectors correlated with each other and with the oscillations of water flow rate. The double amplitude of water pressure oscillations did not exceed 0.045 MPa.

CONCLUSION

- The analysis of tests of two models of steam generator, differing in the way of lead-coolant flowing around the steam-generating tubes, showed that with a transverse (oblique) flow past a heat exchange is more efficient than with a longitudinal one. This is especially noticeable in regimes with reduced feed water flow rates. Therefore, data on steam overheating, obtained on models with longitudinal flow of lead, are obviously conservative, which must be taken into account when verifying the calculation codes.
- There was no unstable operation of the steam generating tubes on any model of the steam generator in a wide range of regime parameters. The main stabilizing factor is the presence of secondary currents that form in helically coiled channels.
- Tests of both models of the steam generator showed that under the conditions of the nominal mode of operation of the PG RU BREST-OD-300 at the outlet, the temperature of the superheated steam corresponds to the calculated values.
- The obtained results should be used when verifying the calculation codes that determine the operating modes of the steam generator.

References

1 **Grabezhnaya V.A., Mikheyev A.S., Stein Yu.Yu.** Tests of the model of the steam generator BREST at the SPRUT facility // Scie. – Tech. Proc. "Results of scientific and technical activities of the Institute of Nuclear Reactors and Thermal Physics in 2011". – Obninsk: SSC RF-IPPE, 2012. P. 227-235. (in Russian)

2 **Grabezhnaya V.A., Mikheyev A.S.** Thermal-hydraulic tests of a multi-tube model of a steam generator in the regime of partial parameters // Problems of Atomic Science and Technology. Series: Nuclear-reactor constants. – 2017. – Vol. 3. – P. 177-186. (in Russian)

3 **Berezin A.N., Grabezhnaya V.A., Mikheyev A.S., Orlov Yu.I., Parfenov A.S., Sergeev V.V.** Calculation and experimental study of steam generator RU BRES-OD-300 // Proceedings of the Third International Scientific and Technical Conference "Innovative Nuclear Power Projects and Technologies (MNTK NIKIET-2014)", October 7 - 10, 2014. – M.: "NIKIET", 2014. – Vol. 1. – P. 224-236. (in Russian)

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5 **Grabezhnaya V.A., Mikheyev A.S., Kryukov A.E., Stein Yu.Yu.** Some research results on the model of helical coiled steam generator heated by liquid lead // Proc. the 4th Conf. "Heavy liquid-metal coolants in nuclear technologies (HLMC-2013)". September 23 - 27, 2013, Obninsk. – Obninsk: SSC RF-IPPE, 2014. – Vol. 1. – P. 139-152. (in Russian)

THANKS FOR YOUR ATTENTION

РОСАТОМ

ГОСУДАРСТВЕННАЯ КОРПОРАЦИЯ ПО АТОМНОЙ ЭНЕРГИИ «РОСАТОМ»

Hydrodynamic Properties of Flow Parts in Various Types of Nuclear Power Unit Header Systems

SSC RF - IPPE, Obninsk

Del'nov V.N.

09-11.10.2018

Multi-physics CFD modeling for design and safety analysis of lead bismuth eutectic cooled nuclear reactors

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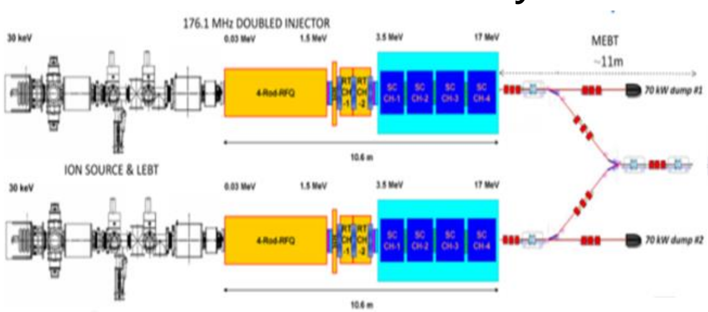
HLMC-18, October 08 -10, 2018, IPPE, Obninsk, Russian Federation

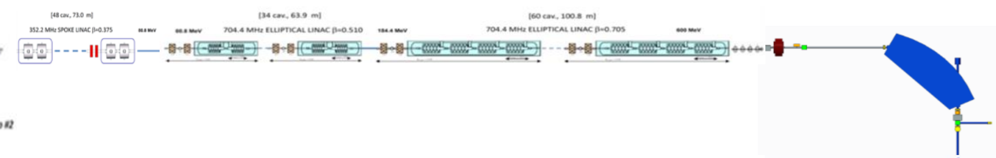
Introduction

MYRRHA Project

- MYRRHA – An Accelerator Driven System
  - Demonstrate the ADS concept at pre-industrial scale
    - Can operate in critical and sub-critical modes
  - Demonstrate transmutation
  - Fast neutron source → multipurpose and flexible irradiation facility

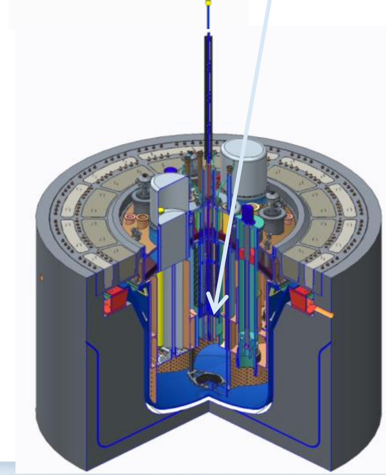
Target	
main reaction	spallation
output	$2{\cdot}10^{17}$ n/s
material	LBE (coolant)





Accelerator	
particles	protons
beam energy	600 MeV
beam current	2.4 to 4 mA

Reactor	
power	65 to 100 MW_{th}
k_{eff}	0,95
spectrum	fast
coolant	LBE



MYRRHA's phased implementation strategy

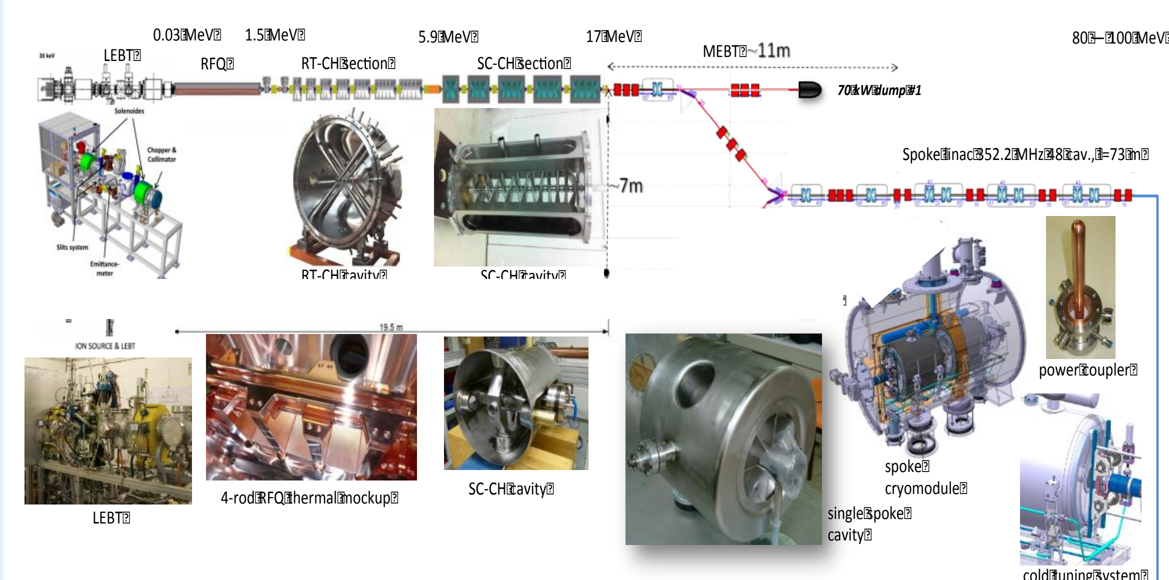
Benefits of phased approach:

- Reducing technical risk
- Spreading investment cost
- First R&D facility available in Mol end of 2026

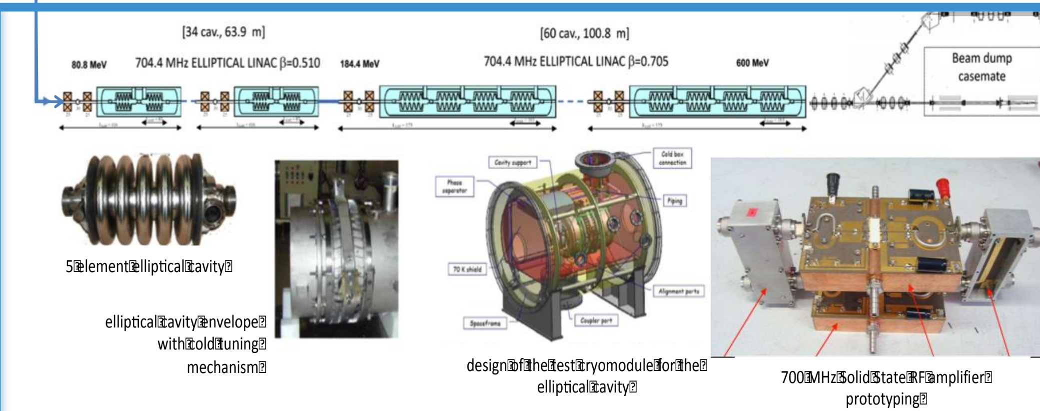
Financing of Phase 1 (including preparation to Phase 2 and 3)

is secured by the Belgian government

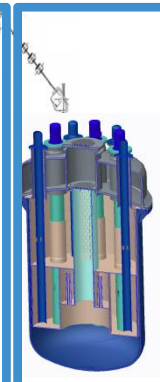
Phase 1 – 100 MeV



Phase 2 – 600 MeV



Phase 3 – Reactor



Source: SCK•CEN MYRRHA Project Team

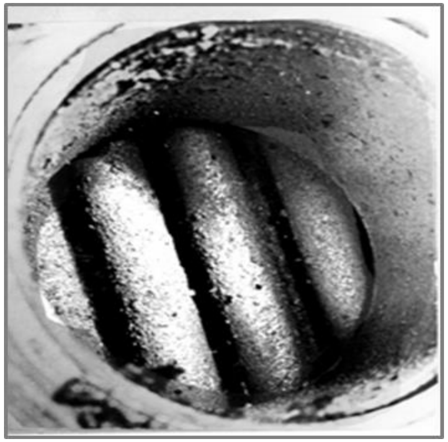
Lead-bismuth eutectic coolant

- **Lead-bismuth eutectic (LBE)** is the spallation target and primary coolant of MYRRHA:

- Why LBE?
  - Excellent neutron yield for spallation
  - Low neutron reaction cross sections
  - Low melting point
  - High boiling point
  - Excellent thermal properties

- Challenge: chemistry
  - **Corrosive to steel**
  - **Chemistry control**

Rig with corrosion samples extracted from CRAFT



Slag deposits on the heat exchanger

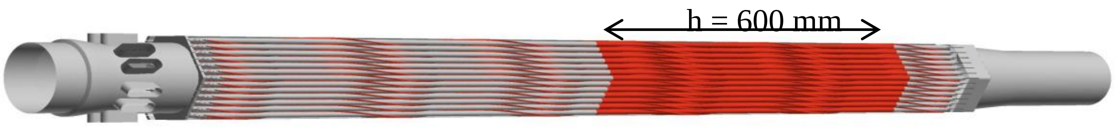
Outline

- Simulations for optimal designs
  - Fuel assembly
  - PbO mass exchangers
- Simulations in support to safety analysis
  - Corrosion product oxides mass transport in MYRRHA
  - Nucleation and growth of PbO particles
- Multi-physics simulation platforms
  - Online coupling of CFD with STH
  - Online coupling of CFD with GEM-solver

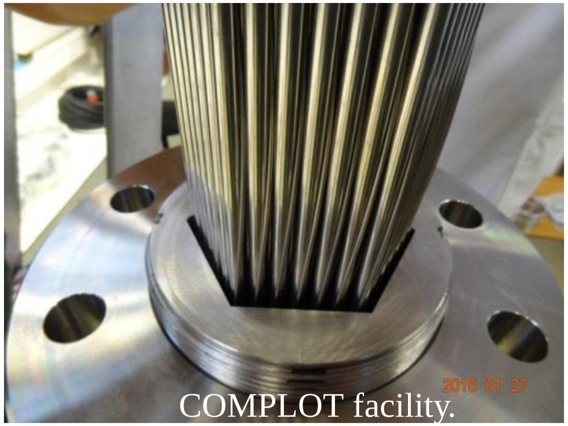
Simulations for optimal designs

Fuel assembly

- 127 pin wire-wrapped fuel bundle

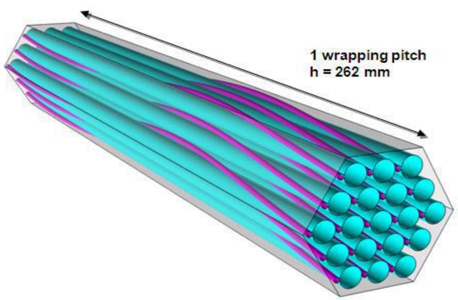


Full scale fuel bundle of MYRRHA reactor.

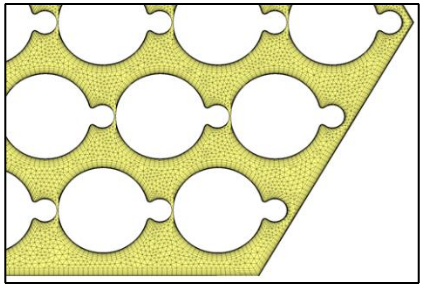


COMPLOT facility.

- **Required design information**
  - Maximum velocity and cladding temperature → Thermal-hydraulics
  - Local effects due to wire → Thermal-hydraulics
  - Local oxygen profiles for steel passivation → Hydro-chemistry

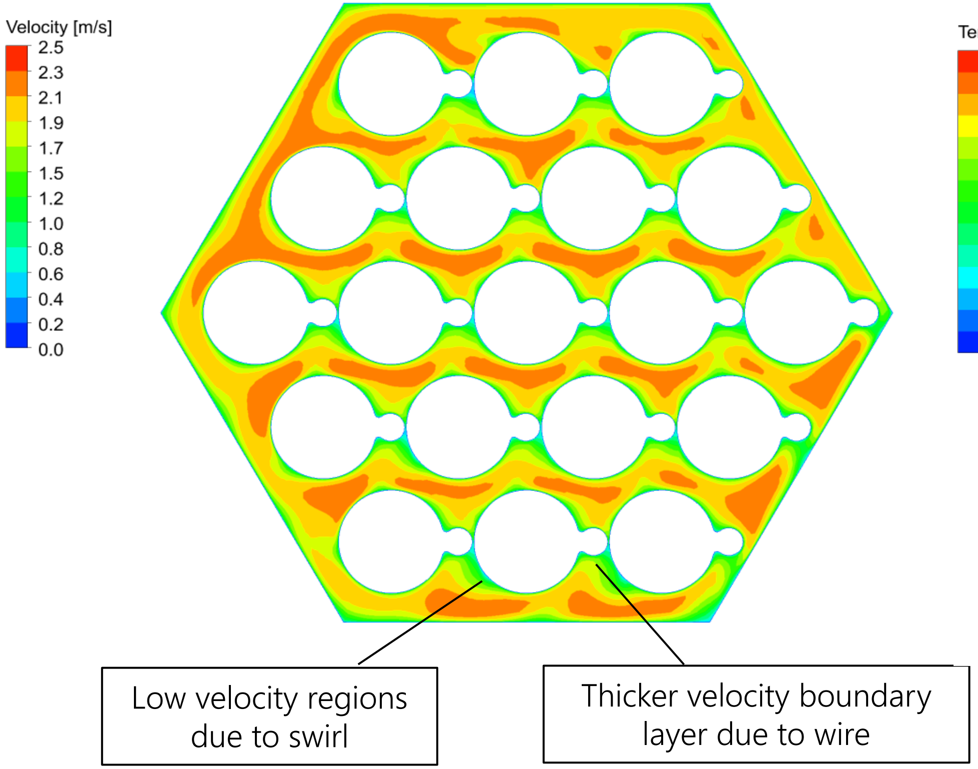


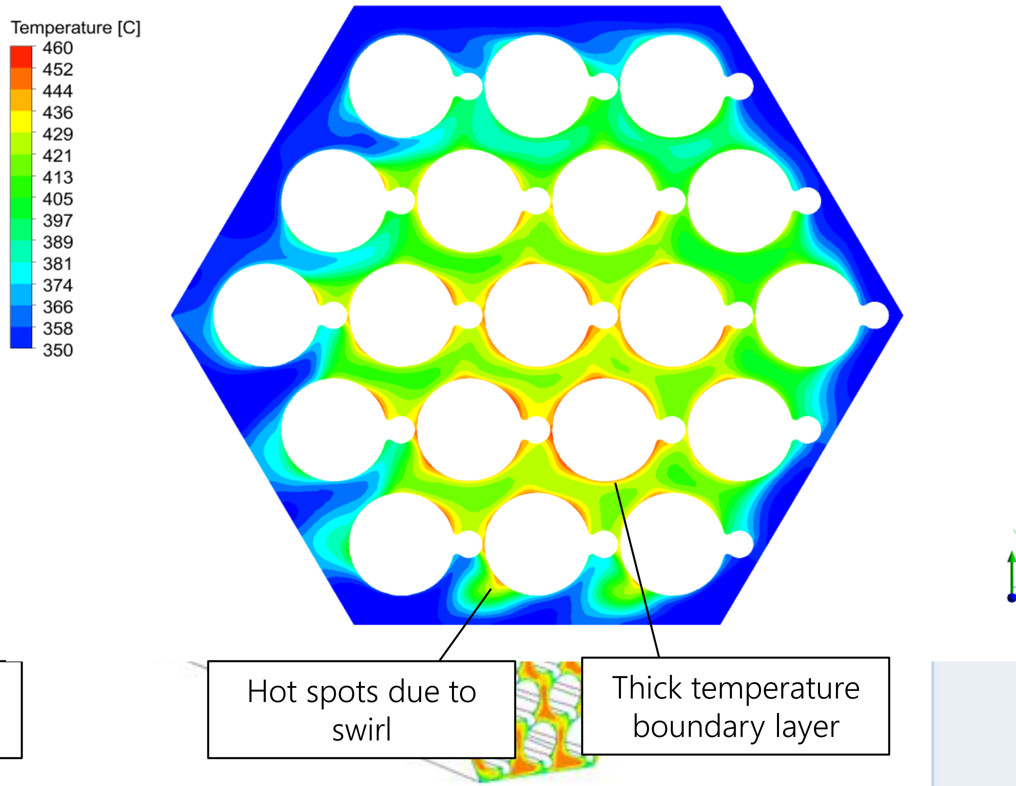
Computer simulations



Fuel assembly-thermal hydraulics

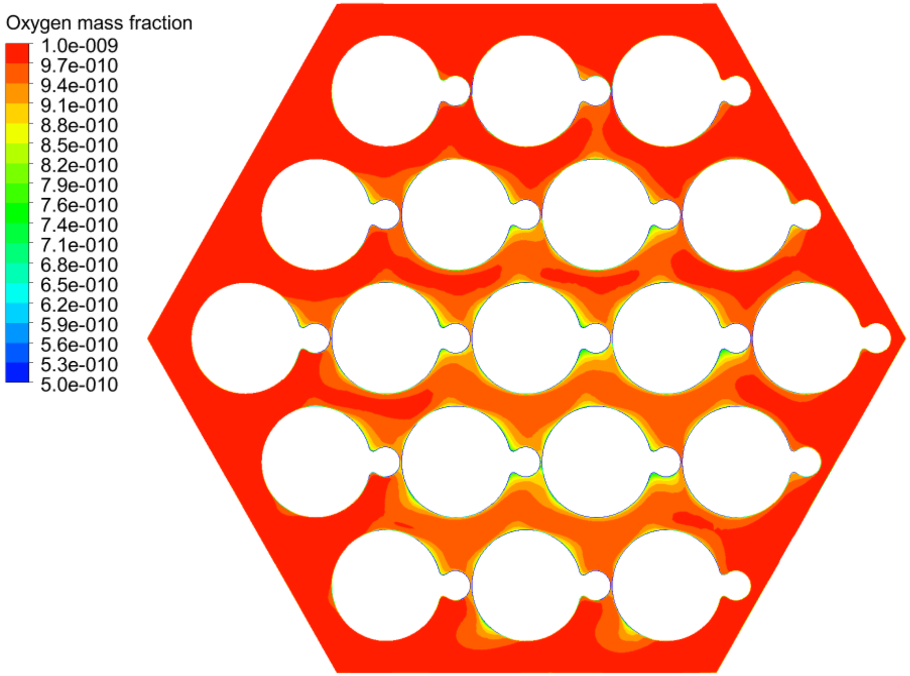
- Global swirl motion
- Local swirl due to wire



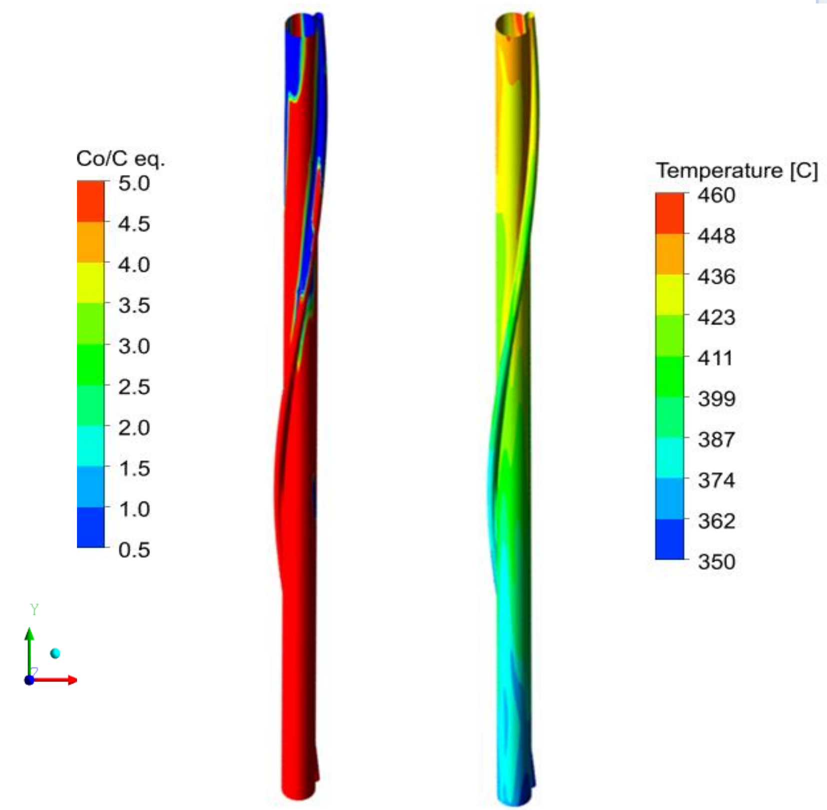


Fuel assembly-hydro chemistry

- Oxygen depletion around wire
- For $C_{oxygen} \approx 10^{-7}$ wt%. max. clad temperature below 400 °C



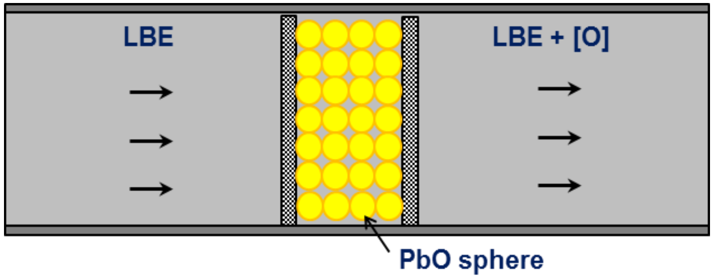
Outlet cross section. 1 μm thick oxide layer on the cladding. Inlet oxygen concentration 10^{-7} wt%.



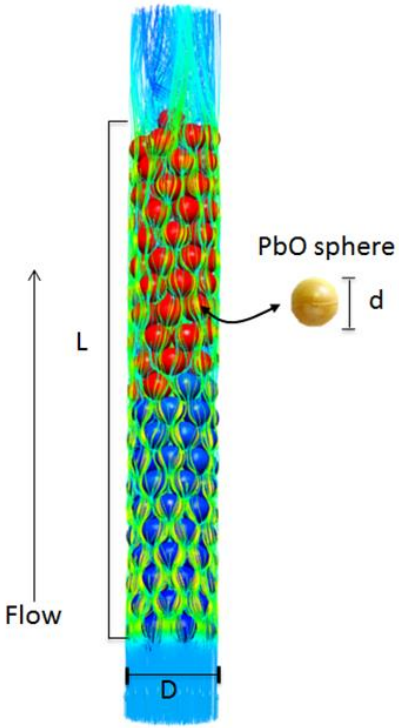
Normalized oxygen concentration (left) and temperature profile (right)

PbO mass exchangers

- **Required design information**
  - Local effects due to D_{tube}/D_p (R) → Thermal-hydraulics
  - PbO MX mass transfer coefficient → Hydro-chemistry
  - Poisoning effect → Chemistry



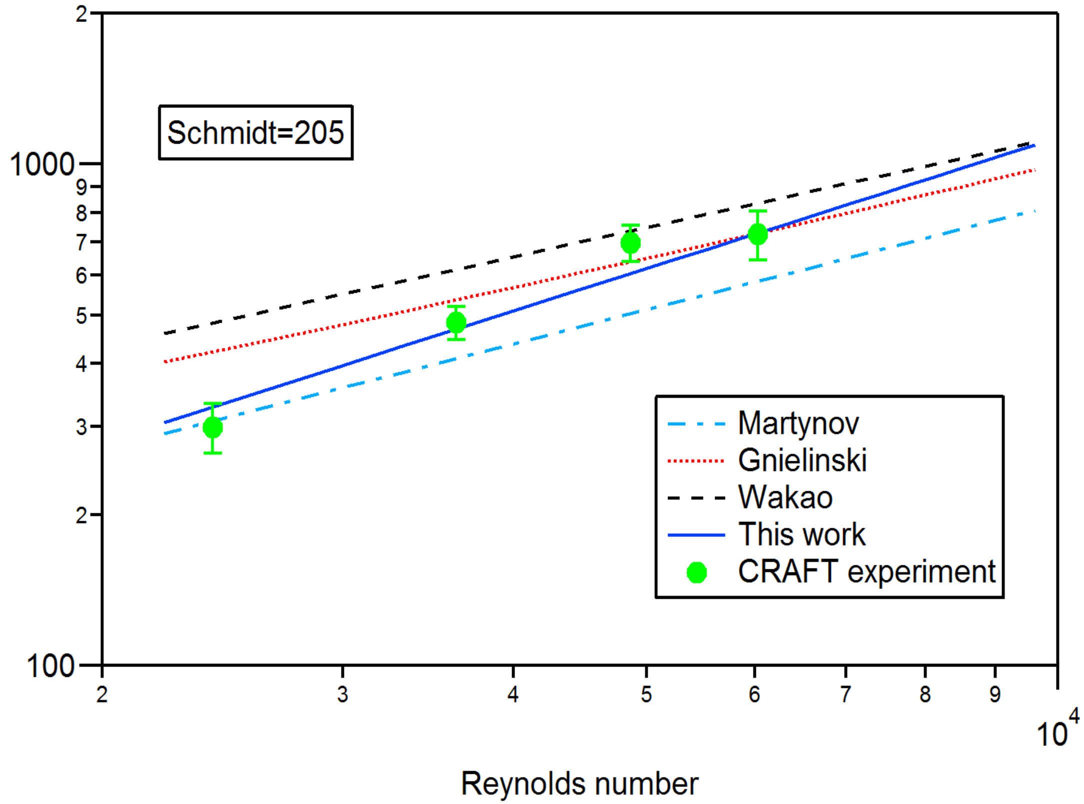
$$[PbO]_{surface} \rightarrow [Pb]_{LBE} + [O]_{LBE}$$

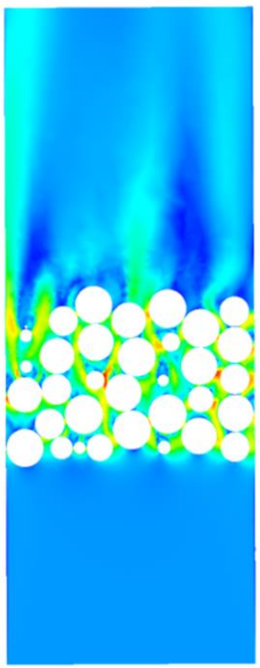


PbO mass exchangers-mass transfer coefficient

- Sherwood number correlation based on CFD
- Simulations validated against experiments

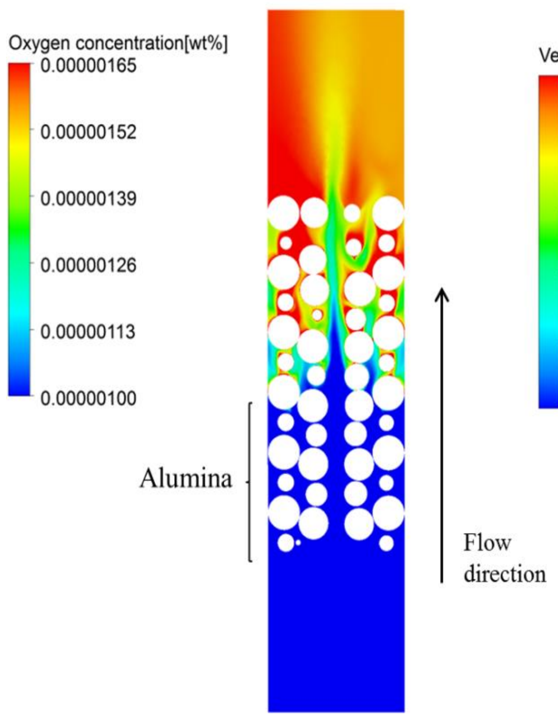
PbO sphere
: 12 mm diameter
: 92.4% of theoretical densi

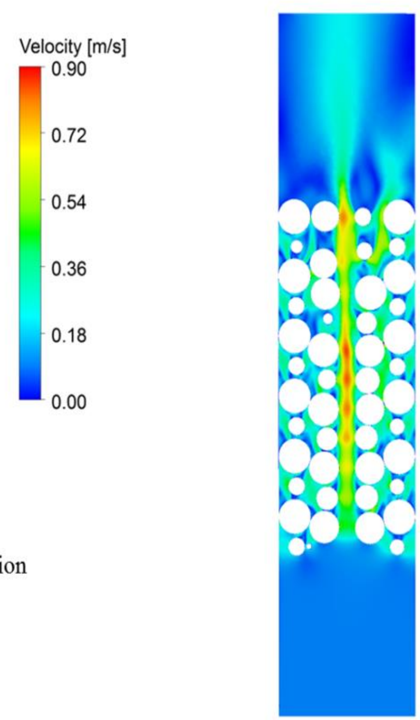


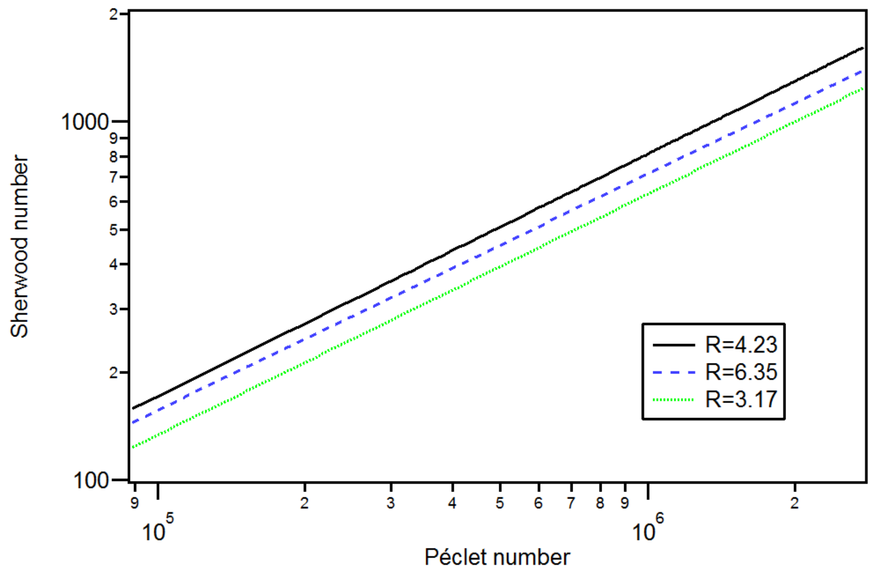


PbO mass exchangers-local effects

- The effect of channel to particle diameter ratio was assessed.
- A R higher than 6 provides a more uniform velocity distribution.



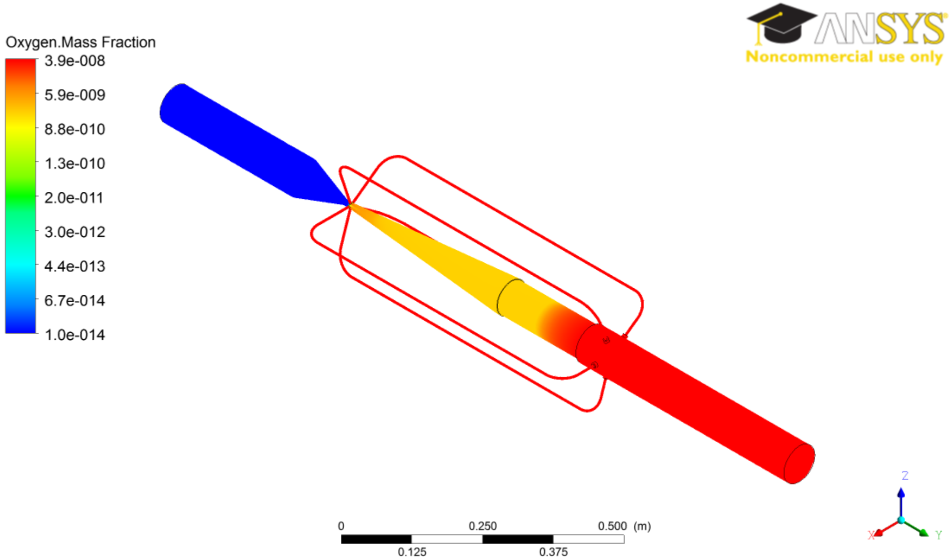


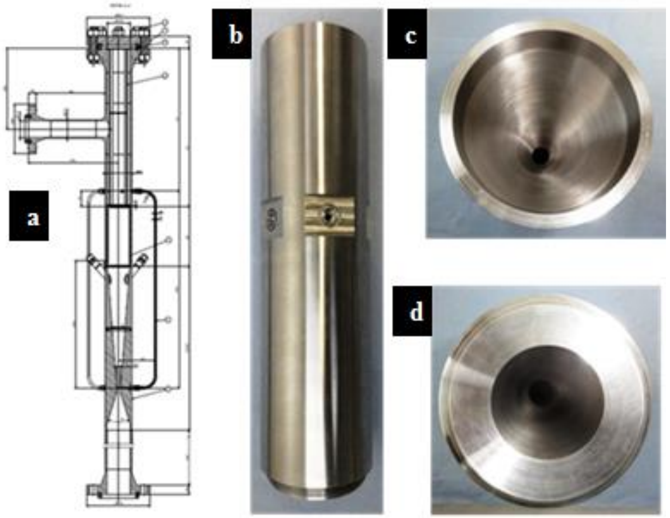


Sherwood number as function of Péclet number for PbO MX with different channel-to-particle ratios R.

PbO mass exchangers-poisoning

- Minimize PbO surface reaction with dissolved impurities
- More information
  - *A. Marino, 'Numerical modeling of oxygen mass transfer in the MYRRHA system', ISBN: 978-9-4619730-5-4.*
  - *A. Marino et al, Nucl. Eng. Des., 265 (2013) 567-581.*
  - *J. Lim et al, J. Nucl. Sci. Technol., 54 (2017), 131-137.*





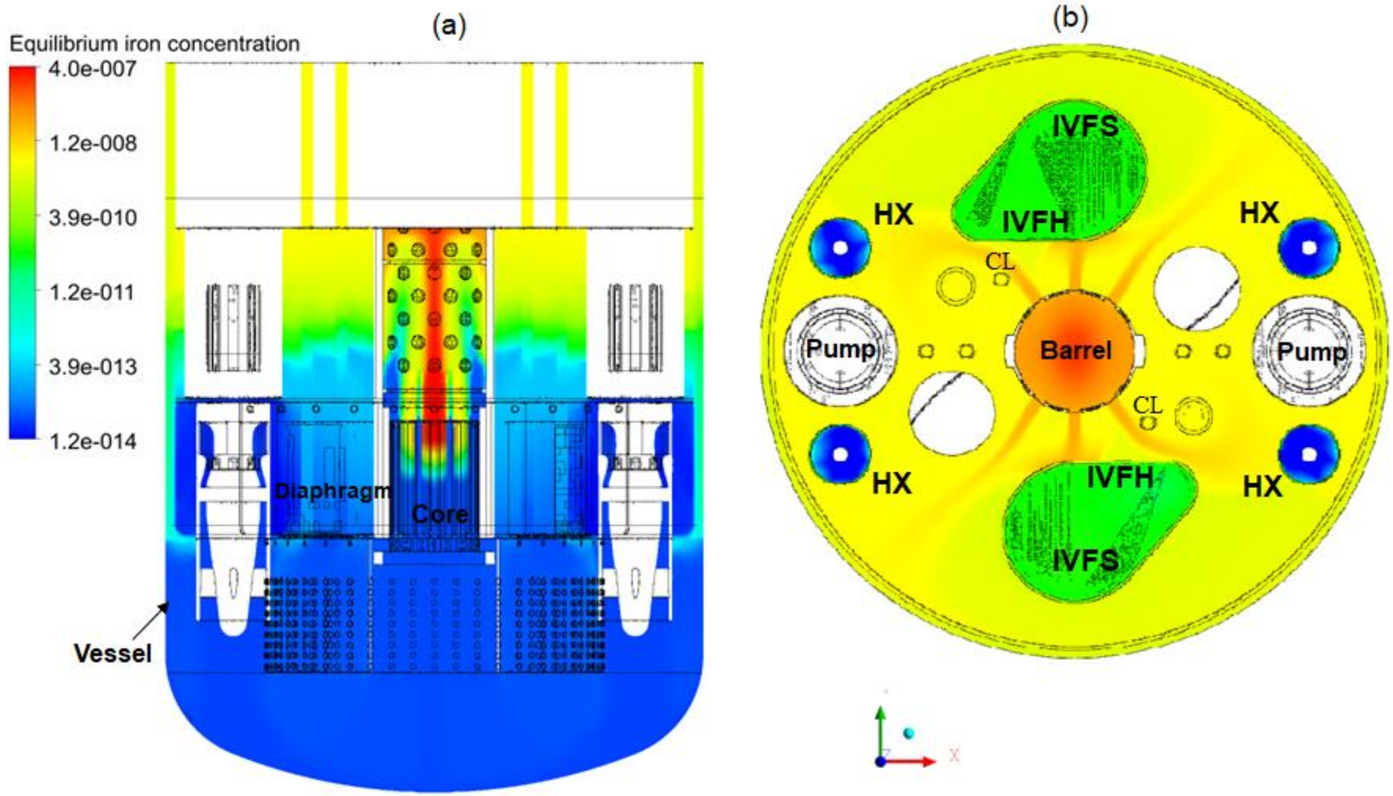
Oxygen concentration distribution in the PbO venturi type MX. Flow rate 1 kg/s, Temperature 400 °C.

Simulations in support to safety analysis

Corrosion product oxides mass transport in MYRRHA

- Safety question: where oxides are formed?
  - Single-phase chemical equilibrium model based on “solubility product”

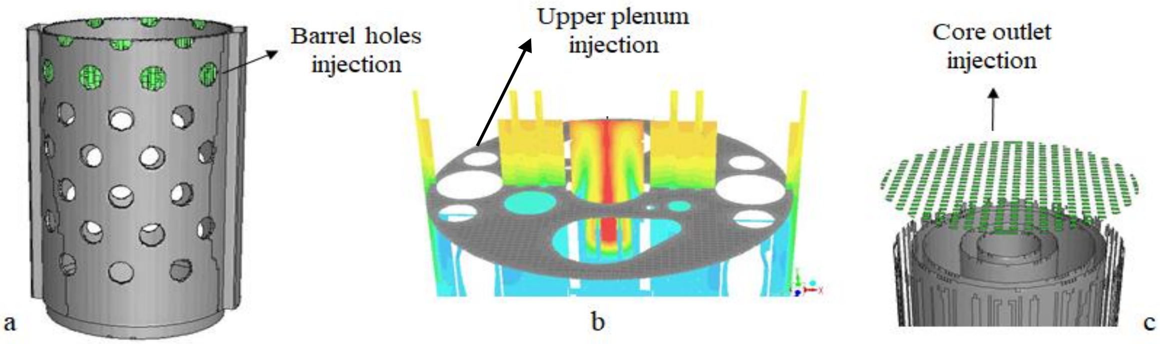
  → Fe-oxides formation is more probable in the upper plenum



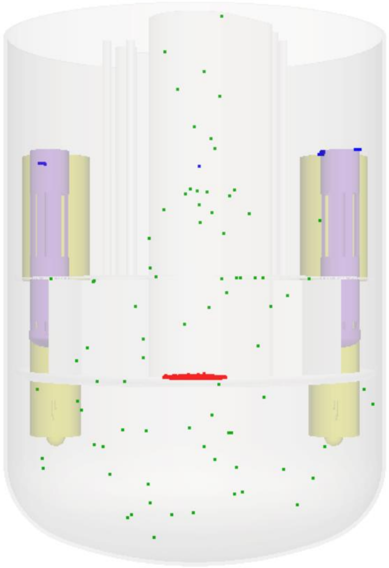
Corrosion product oxides mass transport in MYRRHA

- Safety question: where oxides accumulate?

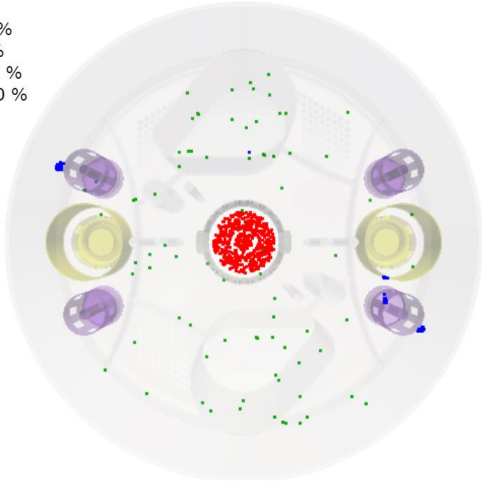
Injection areas

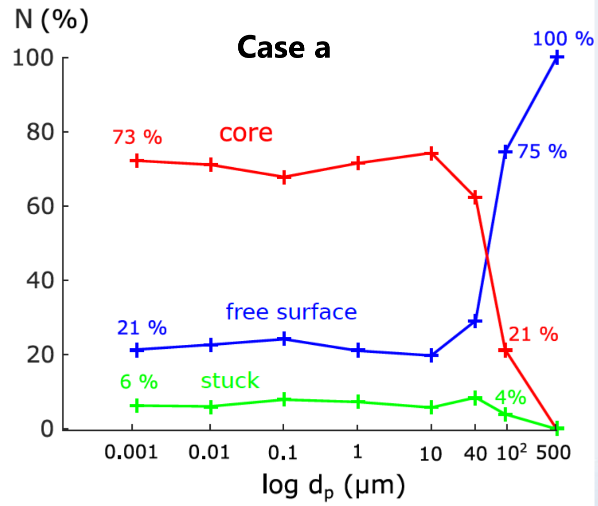


Simulation results case a



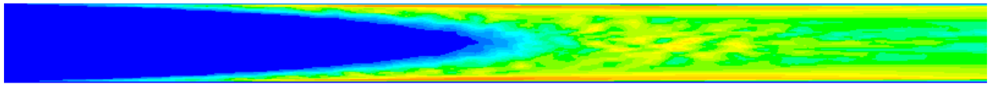
Core: 62 %
Free surface: 29 %
Stuck:
- LP: 46 %
- UP: 5 %
- DIA: 19 %
- else: 30 %





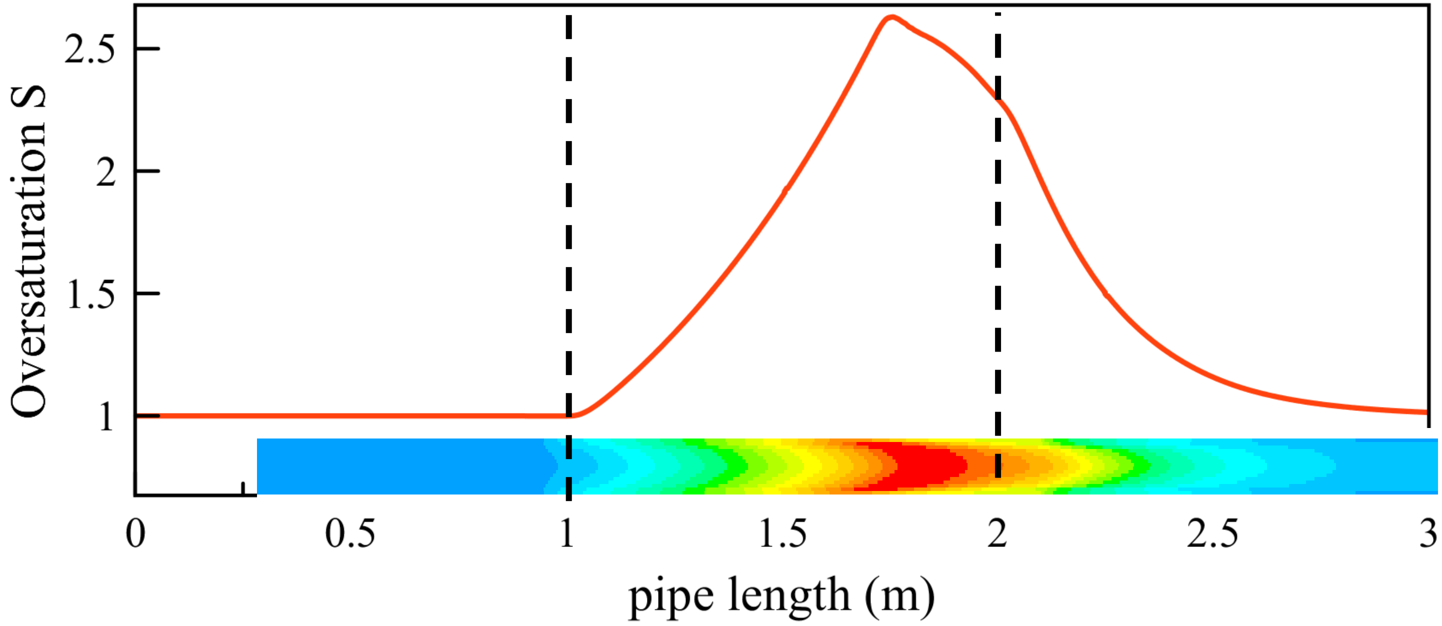
Nucleation and growth of PbO particles

- Rate of PbO formation (arbitrary units)



- Oversaturation: $S = \frac{C_O}{C_{O,s}}$

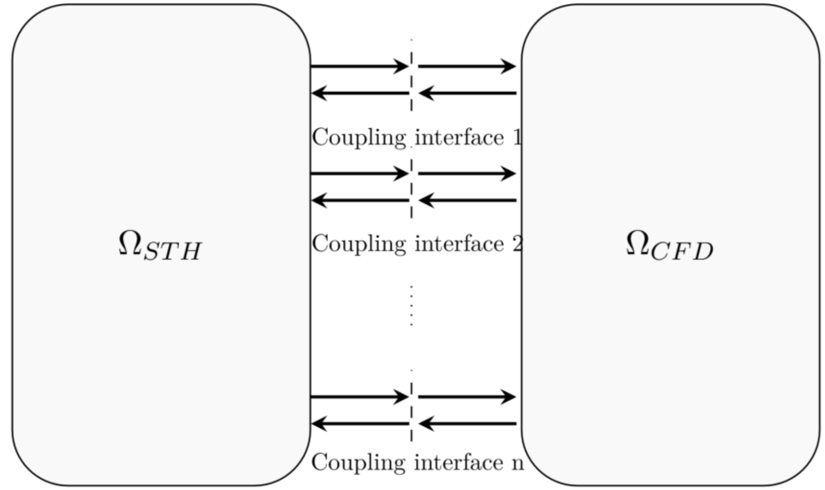
$$C_{o,meta(LBE)}(wt.\%) = 2.07 - \frac{4004}{T(K)}$$

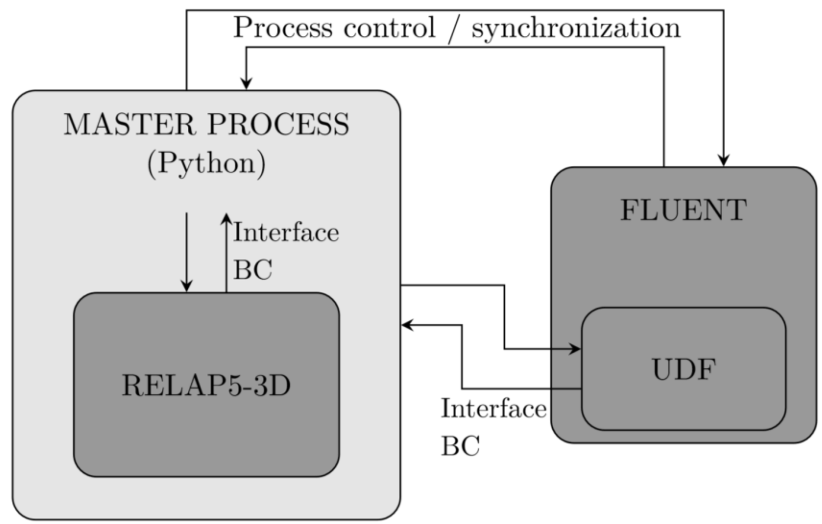


Multi-physics simulation platforms

Online coupling of CFD with STH-approach

- Coupled codes
  - STH code: **RELAP5-3D**
  - CFD code: **FLUENT**
- Domain decomposition method
- Two-way exchange of BC at each time step
  - Hydraulic interfaces
  - Thermal interfaces
- Implicit numerical algorithm

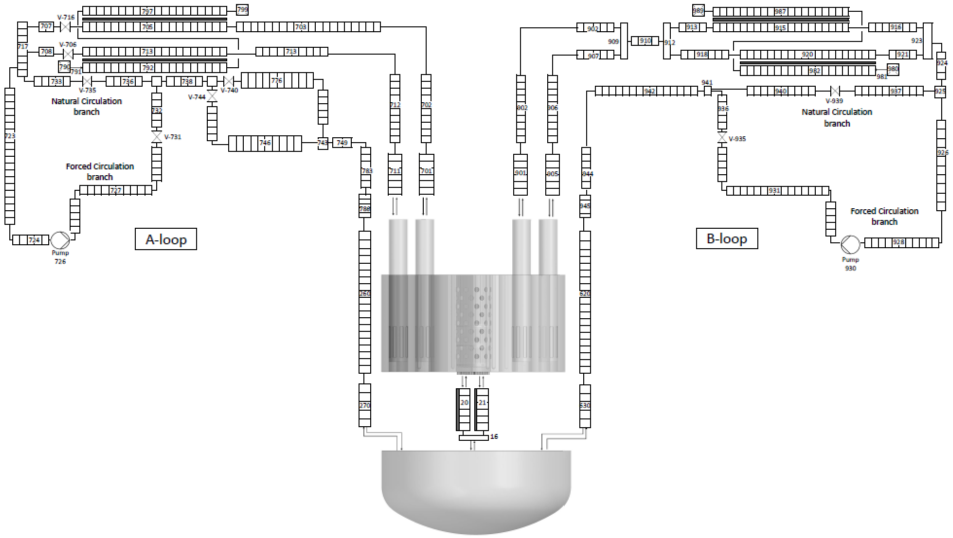


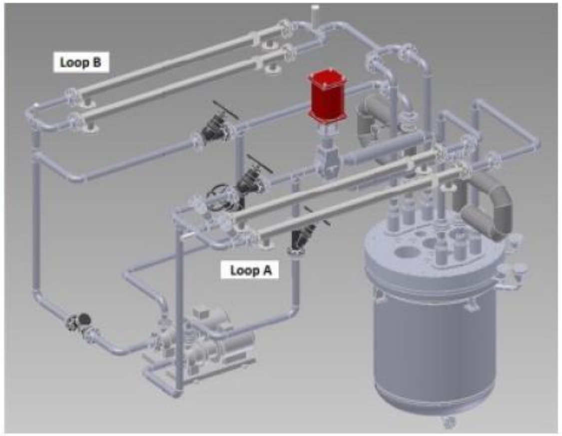


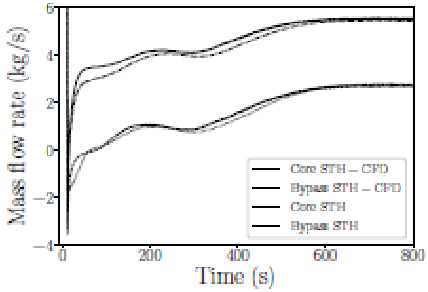
Source: *A. Toti et al., Nucl. Eng. Des., 331 (2018) 83-96.*

Online coupling CFD with STH-results

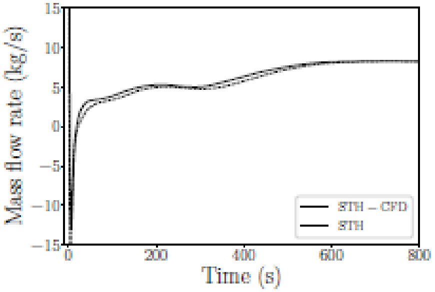
- E-SCAPE – pre test LOF coupled simulation



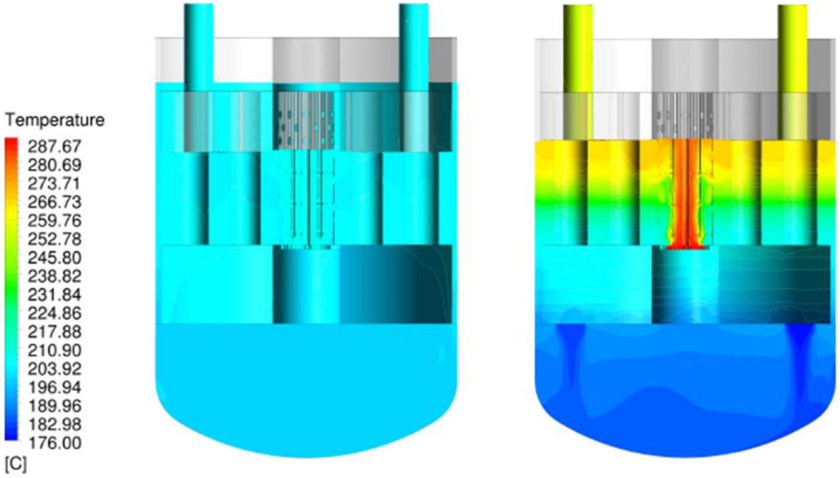




(a) Core active and bypass regions



(b) Total hx channels



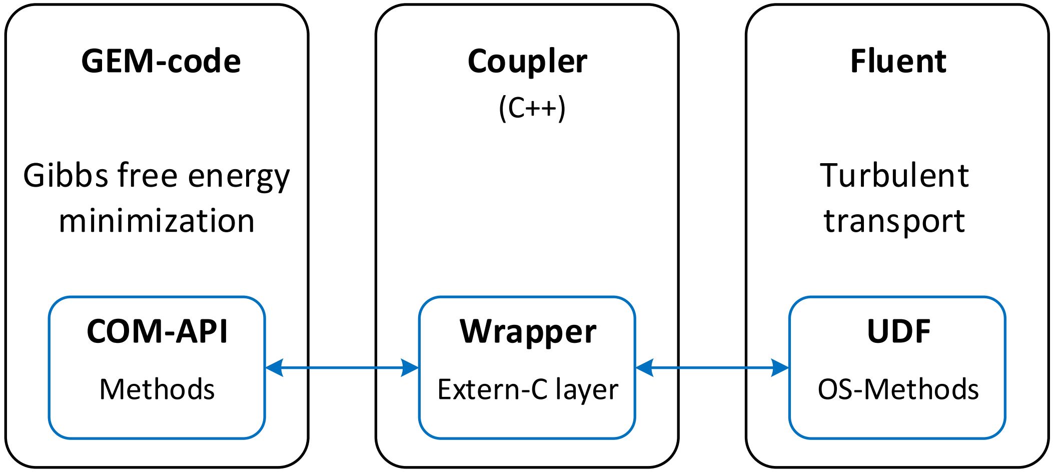
t = 0.0 s

t = 800.0 s

Source: A. Toti et al., Nucl. Eng. Des., 331 (2018) 83-96.

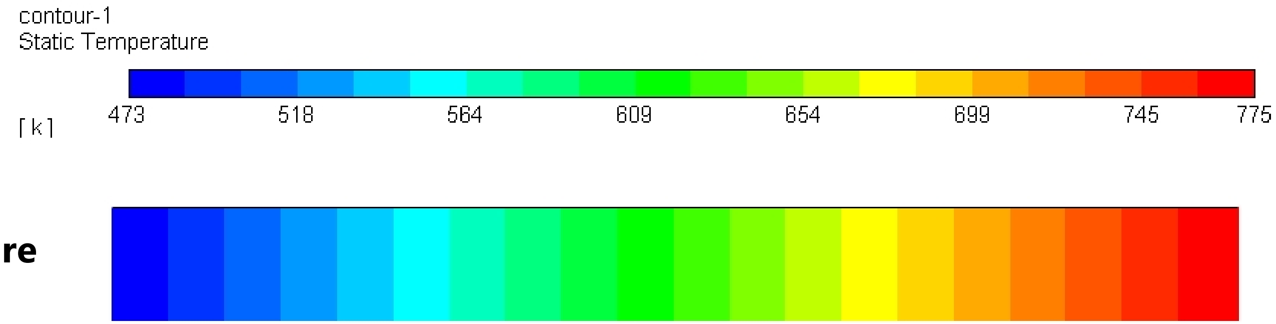
Online coupling of CFD with GEM-solver

- Coupled codes
  - CFD code: **FLUENT**
  - GEM-solver: **high-fidelity**
- Operator-splitting method
- Sequential non-iterative (steady state) or Iterative (transient) numerical scheme



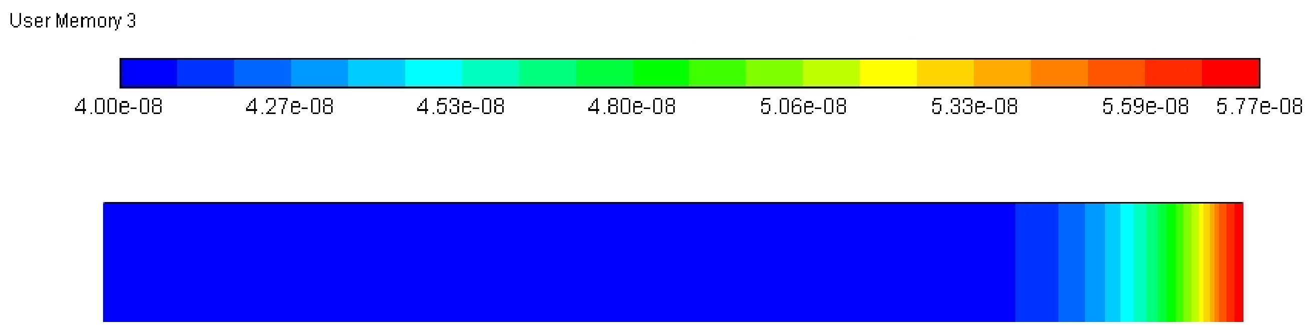
Application exercises-2D pipe flow

Temperature



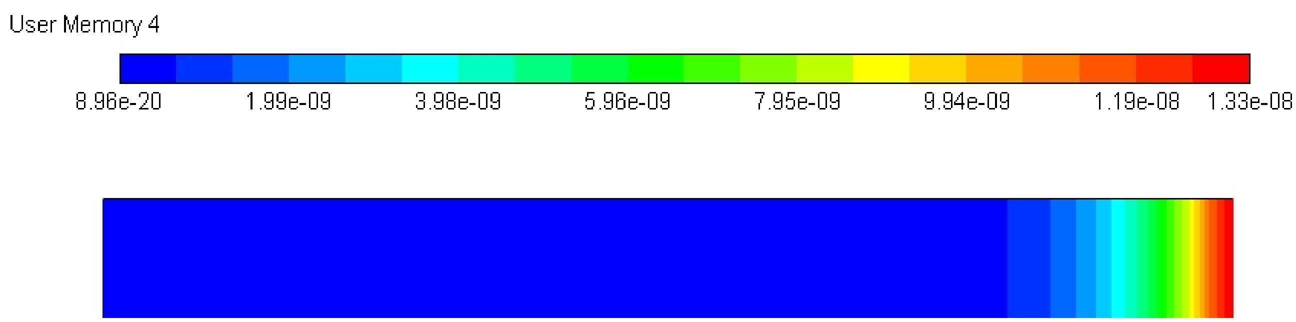
Oxygen

[mole fraction]

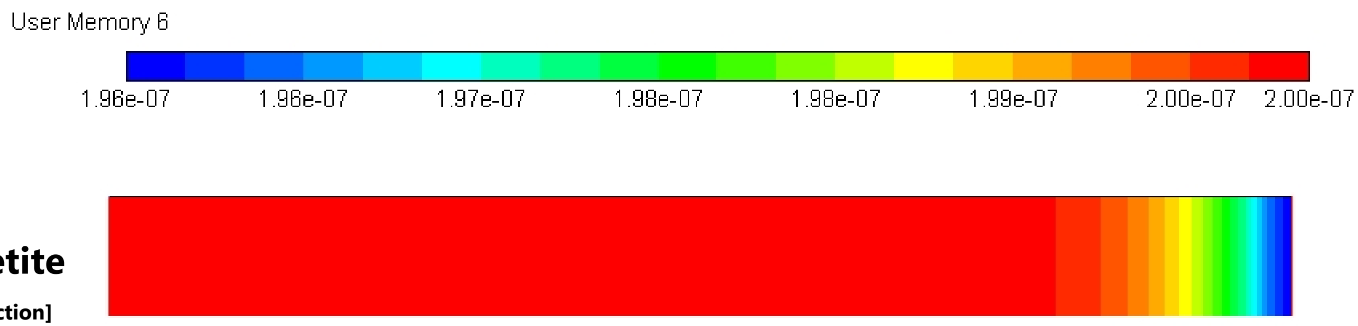


Iron

[mole fraction]

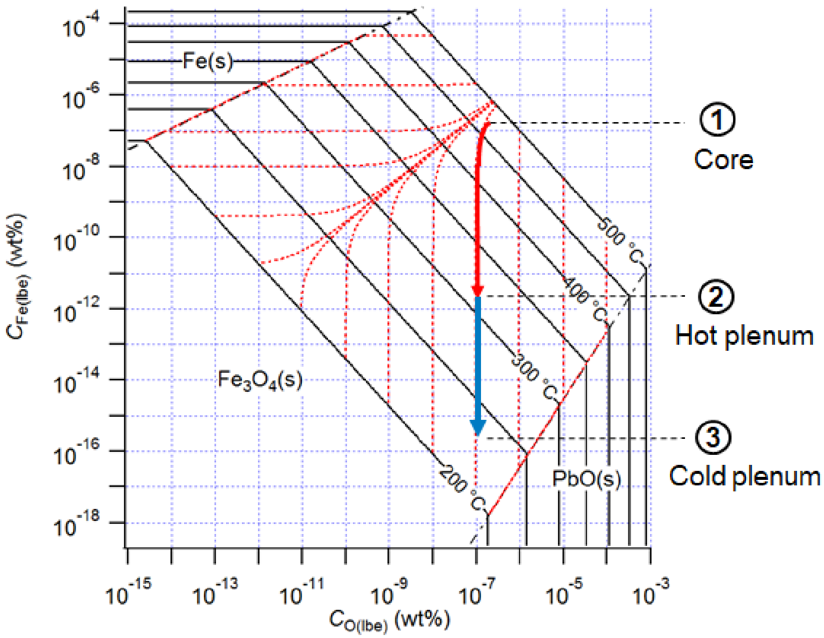


Application exercises-2D pipe flow



Magnetite

[mole fraction]



Executive Summary

Numerical simulations play an important role in MYRRHA development

- **Specific contribution to designs discussed today :**
  - PbO MX→ Sherwood correlation, geometry effects, poisoning of PbO
  - Fuel Assembly→ Maximum clad temperature as a function of bulk oxygen concentration
  - Additional contributions include reactor thermal-hydraulics, oxygen control and filtering system etc.
- **Specific contributions to safety analysis discussed today :**
  - Transport of corrosion product oxides → Assessment of core blockage risk
  - Nucleation-growth PbO particles → Assessment of blockages during accidents
  - Contribution to filtering system design as well
- **Multi-physics simulation platforms enhance modeling capability towards MYRRHA development**

Спасибо!

...?

SCK•CEN
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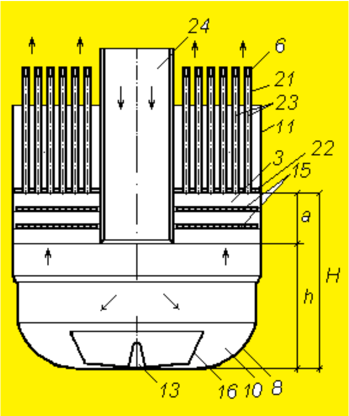
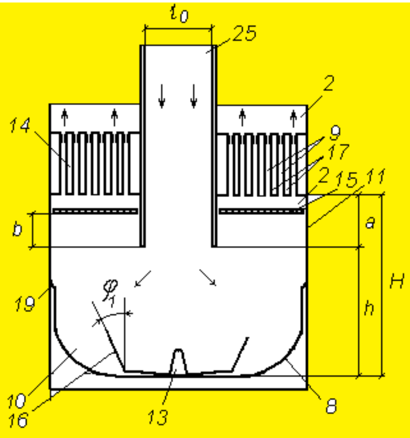
The purpose of this work

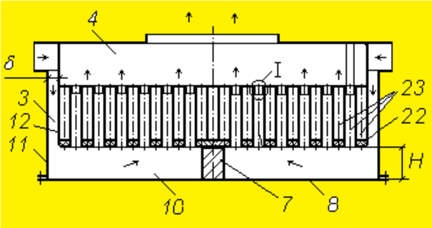
POCATOM

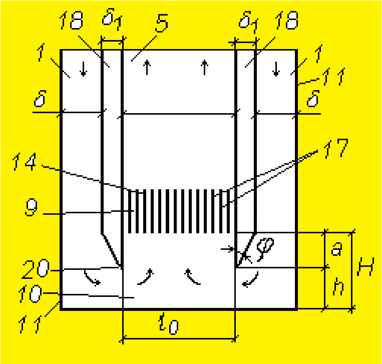
The purpose of this work is to identify the previously unknown peculiarities of the flow part hydrodynamics in axially symmetric DHS with various arrangement of coolant inlet and outlet.

Schematic diagrams of typical variants of DHS









Common variants of DHS design:

a) and b) – cylindrical and flat-type DHS with central coolant inlet and lateral outlet; c) and d) – cylindrical and flat-type DHS with lateral coolant inlet and central outlet.

1 - side inlet channel; 2 - side channel; 3 - side annular channel; 4 – outlet chamber; 5 - outlet channel; 6 - the diaphragm; 7 - spacing insert; 8 - bottom; 9 - plate system channel; 10 - header; 11 - vessel; 12 - shell; 13 - fairing; 14 - grid plates; 15 - grid; 16 - distributor; 17 - plate system; 18 - outlet channel wall; 19 - step; 20 - end part of the outlet channel wall; 21 - tube; 22 - tube plate; 23 - tube bundle; 24 - central pipe; 25 - central channel.

Factors affecting the hydrodynamics of flow parts of various types of DHS

The hydrodynamics of the flow parts of various types of DHS are influenced by hydrodynamic and structural characteristics.

1. ***Hydrodynamic characteristics:***

   - mass flow rate and average coolant velocity in the holes of the output element;

   - coefficients of hydraulic resistance of DHS flow part elements;

   - coolant density;

   - coolant flow regime.

Design characteristics of flow parts of the DHS with central coolant inlet and lateral outlet

ROCATOM

2.1. Design characteristics of the flow part of the DHS of a cylindrical type with a central inlet and lateral coolant outlet: the radii of the lower and upper parts of the housing; inner and outer radii of the central pipe, the height of the header and the height of its entrance, the distance from the bottom to the step in the housing, the radius of the upper part of the housing, the radii of the lower and upper bases of the distributor made in the form of a truncated cone, the position of the distribution grids relative to the end of the central pipe and relative to each other (in the presence of two or more grids) (Fig. a).

2.2. Design characteristics of the flow part of the DHS of a flat type with a central inlet and lateral coolant outlet: the width of the lower and upper part of the housing (if there is a step in the housing); the outer and inner width of the central channel, the height of the header and the height of its entrance, the distance from the bottom to the step in the housing (Fig. b).

Design characteristics of flow parts of the DHS with lateral coolant inlet and central outlet

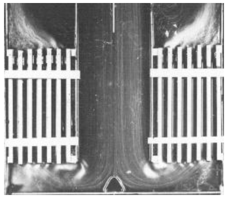
POCATOM

2.3. Design characteristics of DHS of cylindrical type with lateral flow supply and its central drainage without a spacer insert: maximum radius of the perforated part of the grid, height of the header and height of entrance to it, number of holes in the grid and their radius, maximum radius of the perforated part of the grid, internal and external radii of the cylindrical shell and the inner radius of the housing.

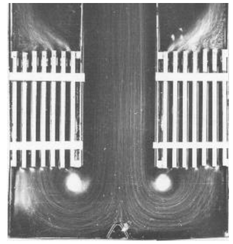
For a similar DHS in the presence of a spacer cylindrical insert in the header, besides the factors listed above, additional factors play a significant role: the minimum radius of the perforated part of the grid, the radius of the cylindrical insert. (Fig. c).

2.4. Design characteristics of the flow part of the DHS of a flat type with lateral inlet and a central coolant outlet without a spacing insert: the maximum radius of the perforated part of the grid, the height of the header and the height of its entrance, the number of holes in the grid and their radius, the maximum radius of the perforated part of the grid, the inner and outer radii cylindrical shell and the inner radius of the housing (Fig. d).

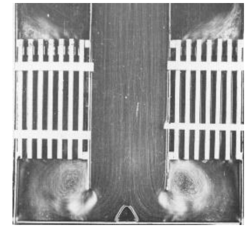
The results of flow pattern study in the flow part of the DHS of a flat type with central coolant inlet and lateral outlet at Re = =3,26·10^{4}- -4,62·10^{4}



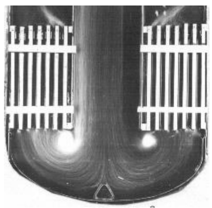
$\tilde{H}$ =0,41;
$\tilde{h}$ =0,41;
$\tilde{a}$ =0



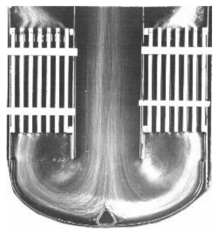
$\tilde{H}$ =0,97;
$\tilde{h}$ =0,97;
$\tilde{a}$ =0



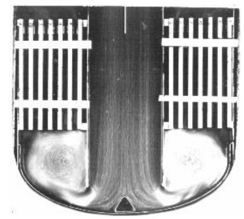
$\tilde{H}$ =0,76;
$\tilde{h}$ =0,41;
$\tilde{a}$ =0,38



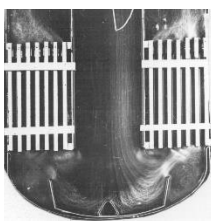
$\tilde{H}$ =0,97;
$\tilde{h}$ =0,97;
$\tilde{a}$ =0



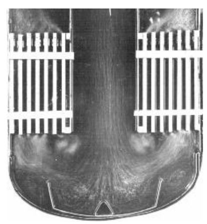
$\tilde{H}$ =1,35;
$\tilde{h}$ =0,97;
$\tilde{a}$ =0,38



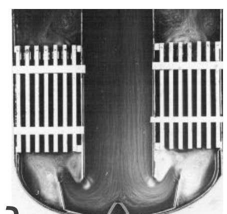
$\tilde{H}$=1,16;
$\tilde{h}$ =0,41;
$\tilde{a}$=0,75



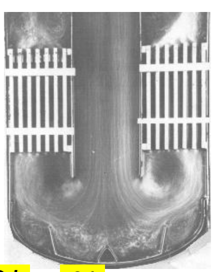
$\tilde{H}$ =0,97;
$\tilde{h}$ =0,97;
$\tilde{a}$ =0;
φ_p =10-14 град.



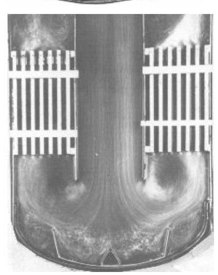
$\tilde{H}$=1,29;
$\tilde{h}$ =1,29;
$\tilde{a}$ =0,38;
φ_p=10-14 град.



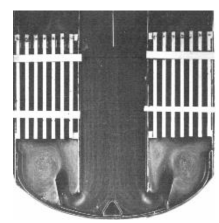
$\tilde{H}$ =0,97;
$\tilde{h}$=0,60;
$\tilde{a}$=0,41;
φ_p=10-14 град.



$\tilde{H}$=1,35;
$\tilde{h}$=0,97;
$\tilde{a}$=0,38;
φ_p=10-14 град.



$\tilde{H}$=1,67;
$\tilde{h}$=1,29;
$\tilde{a}$=0,38;
φ_p=10-14 град.



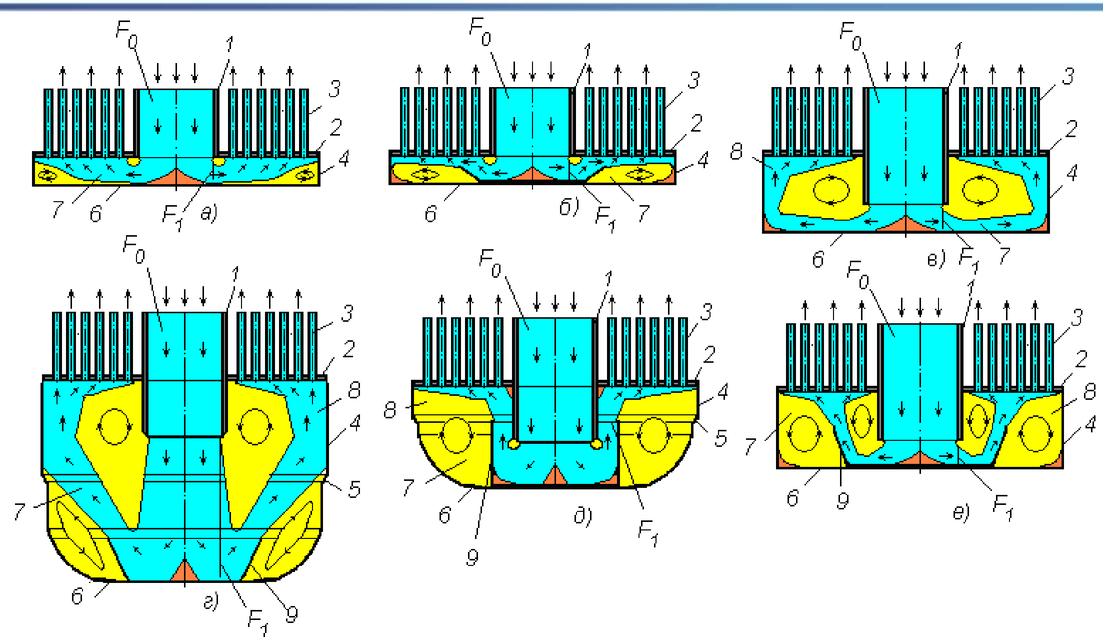
$\tilde{H}$=1,16;
$\tilde{h}$=0,41;
$\tilde{a}$=0,75;
φ_p =10-14 гр.

$\tilde{H}$ и $\tilde{h}$ - the height of the header and the height of its outlet;

$\tilde{a}$ - central channel stand-out; φ_p - distribution angle.

Typical designs and flow patterns in the flow parts of the axisymmetric cylindrical type DHS with central coolant inlet and lateral outlet

РОСАТОМ



a and b - DHS with a relatively small height of header entrance, in the absence and presence of the central tube stand-out of the tube plate, respectively; b - DHS with a relatively small height of the header entrance, in the presence of a distributor and the absence of a central tube stand-out of the tube plate; g - DHS with a relatively large height of the header entrance, in the presence of a distributor and a central tube stand-out of the tube plate; d and e - DHS with a distributor and a central tube protruding from a tube plate, with a pressed inlet part of the header and a relatively small height of its entrance, respectively;

1 - central tube; 2 - tube plate; 3 - beam tube; 4 - housing; 5 - step; 6 - bottom; 7 - header; 8 - side annular channel, 9 - distributor

Features of the flow in the inlet part of cylindrical - type DHS with central coolant inlet and lateral outlet

РОСАТОМ

After the coolant leaves the central tube, a circular submerged jet is formed in the inlet part of the header.

When $a \geq 0$ and $F_O/F_1<1$, with a relatively small or big height of the header entrance h, the round submerged jet rotates in the direction of the DHC periphery, above the bottom or above the stagnant zone above it, respectively.

When $F_O/F_1<1$, the area f_1 is approximately equal to the maximum cross-sectional area of the circular submerged jet at the inlet section of the flow part of the header;

When $F_O/F_1 \geq 1$, the area f_1 is approximately equal (0.7 - 0.8) F_1

where f_1 is the cross-sectional area of the jet.

Features of the flow in the main part of cylindrical-type DHS with central coolant inlet and lateral outlet

ROCATOM

In the DHS with $a \geq 0$ and $F_O/F_1 < 1$, two options are possible for the transformation of a circular submerged jet as a result of its rotation:

1). with a relatively large h, the jet above the stagnation zone either immediately takes the form of an annular semi-submerged jet on the wall of the housing, or is subsequently converted into a cylindrical submerged jet and an annular semi-submerged jet on the wall of the housing;

2). at a relatively small height h, the indicated jet either immediately takes the form of a semi-submerged jet or is subsequently converted into a cylindrical or conical semi-submerged jets and then takes the form of a semi-submerged jet.

In DHS with $a \geq 0$, $F_O/F_1 < 1$ and relatively large h, installation of the distributor with a height $h1$, relatively small compared to h, on the bottom (in the stagnant zone), has practically no effect on the flow pattern of the coolant.

Features of the flow in the main part of the DHS of a cylindrical type with central coolant inlet and lateral outlet

POCATOM

In the main part of the header, with a stand-out value of $a \geq 0$ and various F_O/F_1 ratios, the flow has the form of an annular semi-submerged jet along the housing wall and the inner surface of the side wall of the distributor, parallel to the longitudinal axis of symmetry; the form of the conical submerged jet after its leaving the distributor; the annular submerged jet after leaving the step in the point of junction of the butt end of the elliptical shaped bottom and the housing; cylindrical and conical semi-submerged jets, along the bottom of flat and elliptical shapes, respectively .

In the inlet part of the annular channel with a> 0 in the direction of the tube plate, the following phenomena take place:

- flow of the annular submerged jet;

- movement of the coolant with simultaneous touching the inner and outer side surfaces of the housing and the central tube, respectively;

- flow of the annular semi-submerged jet along the inner or outer side surfaces of the housing or the central tube, respectively.

Features of the flow in the main part of the DHS of a cylindrical type with central coolant inlet and lateral outlet

РОСАТОМ

As a result of the inverse spatial rotation, an axisymmetric round submerged jet in the lower and upper parts of the distributor is converted, respectively, into a conical semi-submerged jet and submerged jet. The first of them is located on the inner surface of the side wall of the distributor, and the second - in its upper part.

When a conical submerged jet interacts with the upper part of the distributor, the direction of its movement relative to the side wall of the distributor deviates towards the periphery.

When a >0, in the inlet part of the annular channel, the following types of flow are observed: the flow of the annular submerged jet, the flow movement with touching the inner and outer side surfaces of the housing and the central tube, the flow of the annular semi-submerged jet along the inner or outer side surfaces of the housing or the central tube.

In the DHS, the flow is characterized by the presence of stagnant and (or) vortex zones, as well as the redistribution of the velocity profile in the jets.

Features of the flow in the outlet part of the DHS of a cylindrical type with central coolant inlet and lateral outlet

РОСАТОМ

The places where the coolant enters the tube plate:

- Ingress of annular submerged and semi-submerged jets into the entire area of the tube plate, its peripheral and (or) middle part.

Specific features of coolant outflow from the header:

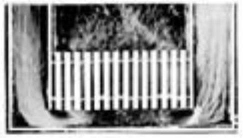
- coolant outfow through the peripheral part of the tube plate, with movement of the annular semi-submerged jet along its middle and (or) central part, with distribution of coolant flow rates along the way;

- coolant outfow through the central part of the tube plate, with movement of annular semi-submerged jet along its middle and (or) peripheral part, with distribution of coolant flow rates through a way;

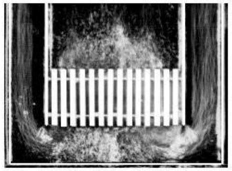
- coolant outfow through the middle part of the tube plate is accompanied with movement of flat semi-submerged jets, with variation of coolant flow rate on the way along its peripheral and central parts.

- coolant outflow simultaneously through the whole tube plate, without distribution of coolant flow rates along the way;
- depending on the ratio of the dimensions of the header and the structural elements used in it, the jet falls on the tube plate at different angles.

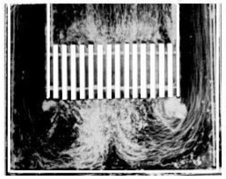
The results of the study of hydrodynamics of DHS flow part of with lateral coolant inlet and central outlet



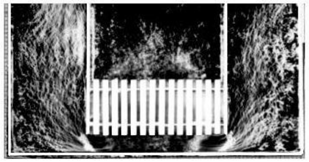
$\tilde{H}$=0.5; $\tilde{\delta}_1$ =0.011; $\tilde{a}$ =0; φ=90 degr. $\tilde{s}$=4.0



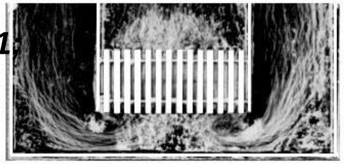
$\tilde{H}$=1.0; $\tilde{\delta}_1$ =0.011; $\tilde{a}$=0; φ =90 degr.; $\tilde{s}$=2.0



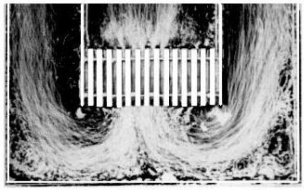
$\tilde{H}$=2.0; $\tilde{\delta}_1$=0.011; $\tilde{a}$=0; φ=90 degr.; $\tilde{s}$=2.0;



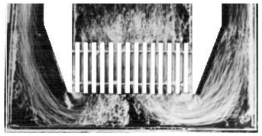
$\tilde{H}$=0.25; $\tilde{\delta}_1$ =0.011; $\tilde{a}$=0; φ=90 degr. $\tilde{s}$=4.0



$\tilde{H}$=0.5; $\tilde{\delta}_1$ =0.011; $\tilde{a}$ =0; φ =90 degr.; $\tilde{s}$=2.0



$\tilde{H}$=1.0; $\tilde{\delta}_1$ =0; $\tilde{a}$=0; φ=90 degr.; $\tilde{s}$=1.0



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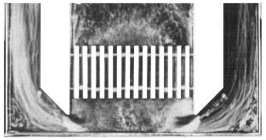
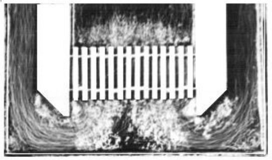
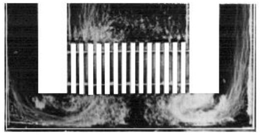


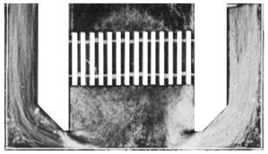
$\tilde{H}$=1.0; $\tilde{\delta}$ =0.022; $\tilde{a}$=0; φ=60 degr.; $\tilde{s}$=4.0; $\tilde{h}$=0.5



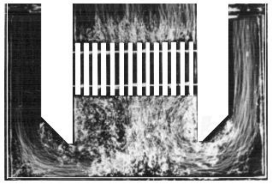
$\tilde{H}$=1.5; $\tilde{\delta}_1$=0.022; $\tilde{a}$=0.14; φ=60 degr.; $\tilde{s}$=2.0; $\tilde{h}$=1.0;



$\tilde{H}$=1.0; $\tilde{\delta}$=0.022; $\tilde{a}$ =0; φ=90 degr.; $\tilde{s}$=2.0; $\tilde{h}$=1.0



$\tilde{H}$=1.78; $\tilde{\delta}_1$ =0,022; $\tilde{a}$=0.36; φ =60 degr.; $\tilde{s}$=4.0; $\tilde{h}$=0.5



$\tilde{H}$ =2.28; $\tilde{\delta}_1$ =0.022; $\tilde{a}$ =0.36; φ=60 degr.; $\tilde{s}$=2.0; $\tilde{h}$ =1.0

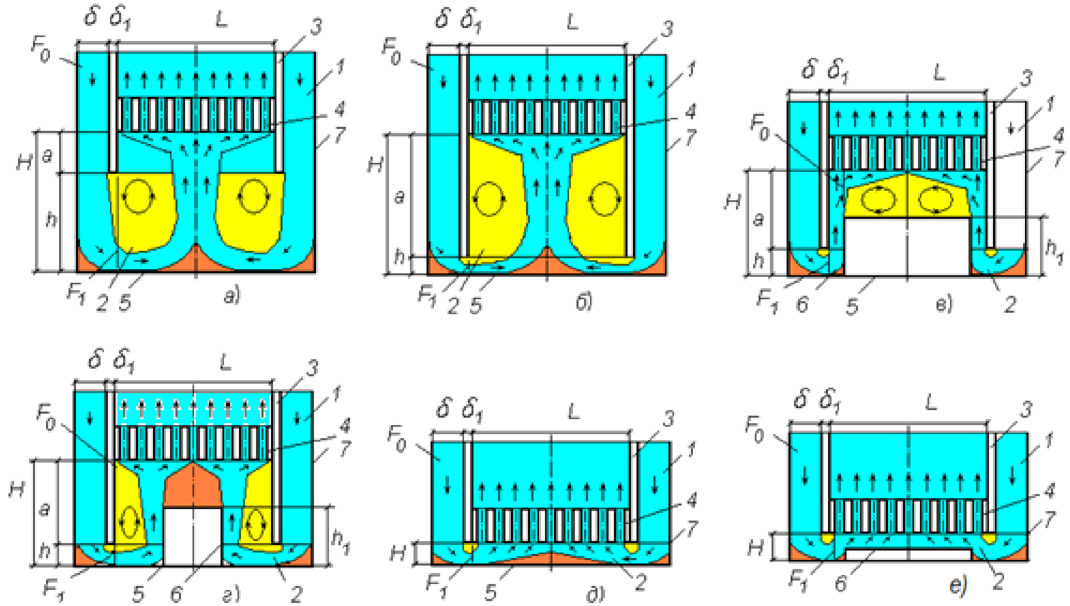
$\tilde{H}$ u $\tilde{h}$ - the relative height of the header and its inlet;

φ - cut angle of the end part of the side wall; $\tilde{\delta}_1$ - side wall thickness;

$\tilde{a}$ - relative displacement of the grid from the end part of the side wall;

$\tilde{s}$ - relative size of the grid flow area.

Typical designs and flow patterns in the flow parts of the axisymmetric cylindrical type DHS with lateral coolant inlet and central outlet



a, b - DHS with a relatively large and small height of the entrance to the header and an offset grid in the central shell; c, d - DHS with a relatively small height of the entrance to the header with an offset grid in the central shell in the presence and absence of an insert on the bottom, respectively; d - DHS with a relatively small height of the entrance to the header, without displacement of the grid in the central shell in the presence of an insert on the bottom; 1 - annular channel; 2 - header; 3 - central shell; 4 - grid; 5 - bottom; 6 - insert; 7 - housing

Features of the flow at the cylindrical DHS inlet with lateral coolant inlet and central outlet

When $a \geq 0$ and $F_O/F_1<1$ with a relatively small and large height of the entrance to the header h, the submerged jet rotates in the direction of the DHS periphery, respectively, above the bottom or above the stagnant zone above it.

When $F_O/F_1<1$, the area f_1 is approximately equal to the maximum cross-sectional area of the circular submerged jet at the inlet section of the header flow part;

For $F_O/F_1 \geq 1$, the area f_1 is approximately equal to (0.7 - 0.8) F1, where f_1 is the cross-sectional area of the jet.

Features of the flow in the cylindrical DHS main part with lateral coolant inlet and central outlet

РОСАТОМ

The flow of coolant in the main part of the header is determined by the position of the grid a in the central shell.

When a = 0 and $F_0/F_1 \geq 1$, the semi-submerged cylindrical jet is converted into a stream moving to the header center in the slotted channel between the bottom and the grid with flow distribution along the path through the holes in the middle and (or) central part of the grid.

When a ≥0 and $F_0/F_1 < 1$, the cylindrical semi-submerged jet is converted into a circular submerged jet as a result of rotation in the main part of the header.

When a> 0 in the inlet part of the central shell, there is a possibility of circular submerged jet flow, coolant movement with touching the sidewall inner surface of the central shell and the cylindrical insert outer surface, and coolant flow with touching the outer surface of the cylindrical insert.

The presence of stagnant and (or) eddy zones and the redistribution of coolant velocity profile in various types of jets are characteristic of the flow in the DHS flow part.

Features of the flow at the cylindrical DHS outlet with lateral coolant inlet and central outlet

Coolant and grid meeting point:

- flat jet, annular submerged and semi-submerged jets hit the entire area of the grid, its periphery and (or) middle part;

Features of coolant exit from the header:

- Exit of coolant through a grid periphery as the flat semi-submerged jet is moving along middle and (or) central part of the grid with flow distribution on the way;

- Exit of coolant through a grid central part as the flat semi-submerged jet is moving along middle and (or) central part of the grid with flow distribution on the way;

- Exit of coolant through the middle part of the grid as the flat semi-submerged jets are moving with the flow variation on the way along its periphery and central parts.

- Exit of coolant simultaneously through the entire tube plate without flow distribution on the way.

Characteristic areas of DHS flow part and the similarity property of hydrodynamics in them.

POCATOM

Characteristic areas of the DHS flow part

In DHS of various types with different conditions for the coolant inlet and outlet, the common characteristic sections of the flow part are the inlet, main and outlet parts of the header.

The property of hydrodynamics similarity in the DHS flow part.

As a result of the comparative analysis, a previously unknown similarity property of flow part hydrodynamics of cylindrical and flat-type axially symmetric DHS with coolant reversing at various points of coolant inlet and outlet was established.

The specified property is based on:

- the presence of jet-eddy coolant flow in the flow parts of above-mentioned DHS, submerged and semi-submerged jets;

- the generality of coolant flow properties;

- the identity of the mechanisms of conversion between jet types;

- the impact of certain hydrodynamic characteristics of the jet feeding the outlet element and local hydraulic resistance coefficient ratio of the outlet element and header on the mass flow rate distribution at the header outlet.

This property is specified by (beginning)***:***

- expansion of the cross-section area of submerged and semi-submerged jets and, consequently, decrease of average coolant velocity in them due to coolant slowdown;

- submerged and semi-submerged jets flow with a single-end expansion angle equal to 12°;

- conversion of submerged jets into semi-submerged ones and vice versa;

- change of maximum velocity location in the jet cross-section on turns and further along the path of the coolant;

- coincidence of locations of maximum coolant velocity in the jet feeding the outlet element and flow rate of the coolant at its outlet;

- direct proportion between the average velocity of the jet feeding the outlet element and maximum flow rate of the coolant at its outlet;

The similarity property of hydrodynamics of DHS flow parts

This property is specified by (ending) :

- inverse proportion between the maximum mass flow rate of coolant at the header outlet and the ratio between the coefficients of local hydraulic resistance of the outlet element and header;

- throttling the flow and, accordingly, increasing the coolant flow rate in the inlet part of the header with the ratio of the areas of the clear opening of the inlet channel and the annular (slotted) gap at the header inlet greater or equal to unity;

- entrance of one part of the coolant into the holes (channels) of the outlet element located at the meeting point of the jet, and spreading of the other part of the coolant along the rest of the outlet element with flow variation along the way with the jet hitting the outlet element

The differences in the designs and hydrodynamics of DHS flow parts

Differences in DHS flow part design.

In the DHS of the cylindrical and flat types, the tube plate and the plate system are used as an outlet element, respectively, and at the exit from the outlet element the coolant mass flow rate and velocity are determined.

Differences in DHS flow part hydrodynamics.

Cylindrical DHSs feature axisymmetric round, cylindrical, conical and annular jets, and flat DHSs are characterized by the jets with a rectangular (square) cross-sections.

In the DHS of a cylindrical type, along the path of the flow, one type of jets is converted to another type, and in flat DHS, the common jet is divided into separate parts or separate parts of the jet merge into a common jet.

DHS with different places of coolant inlet and outlet differ in the sequence of conversion of some types of jets into others.

These differences do not call into question the fact that a previously unknown property of hydrodynamics similarity of diverse DHS with reversing of coolant in different locations of coolant inlet and outlet has been established.

The pattern of coolant distribution at the DHS outlet

(beginning)

ROSATOM

Experimental and analytical methods were used to identify a previously unknown pattern of coolant distribution at the outlet of cylindrical and flat axially symmetric DHS with flow reversing in the header.

This pattern in induced by the following factors:

- coolant distribution at the axially symmetric DHS outlet is of universal identical nature;

- each of the mentioned distributions has at least two areas;

- only single area features the maximum coolant mass flow rate and the average coolant mass flow rate value that is higher than the average coolant mass flow rate in the other areas;

- the coordinates of interface between the areas, the value and coordinates of the maximum and minimum coolant mass flow rate at the header outlet are variable.

The pattern of coolant distribution at the DHS flow part outlet

(continued)

The considered regularity is due to the following hydrodynamic effects:

- *presence* of eddy and stagnant areas in the header, *presence of free submerged and semi-submerged jets;*

- conversion of free submerged jets into semi-submerged ones and vice versa taking place at the turn in the header main part;

- dependence of the coolant distribution pattern at the header outlet on the header design, coolant flow mode and the location of its supply to the header inlet, correlation between local hydraulic resistance of the flow parts in the header and the outlet element ;

- jet ingress to the header bottom;

- jet contraction at the header inlet with restricted flow area;

- jet deflection at the bottom and at its joint with the side wall;

- enlargement of cross-section and, consequently, reduction of average velocity along the path of the free submerged jet in the header main part and semi-submerged jet at the bottom and side wall due to their slowdown;

…

The pattern of coolant distribution at the outlet of DHS

POCATOM

…

- change of the location of the velocity profile maximum in the semi-submerged jet caused by its deflection in the header as a result of contact with structural elements;
- location and area of the jet and outlet element meeting point;
- jet landing in the outlet element at the right angle;
- coincidence of the location of maximum coolant flow rate at the header outlet with the location of the maximum velocity in the jet at the place of its meeting with the outlet element;
- direct proportion between the maximum coolant flow rate inside the outlet element channels and average jet velocity at the location of its meeting with the outlet element;
- higher coolant mass flow rates in the outlet element channels located at the place of its meeting with the falling jet compared to the coolant mass flow rates in the remaining channels of this element;
- movement of the coolant along the outlet element with mass flow rate distribution along the path outside of the location of its meeting with the jet;
- direct proportion between the maximum non-uniformity of coolant mass flow rate distribution at the header outlet and the ratio of local hydraulic resistances of the outlet element and the header flow part.

Conclusion

1. The features of hydrodynamics of flow parts of cylindrical and flat axisymmetric DHS with coolant reversing are revealed for various combinations of coolant inlet and outlet locations.

2. Previously unknown properties of hydrodynamics similarity of the flow parts for the indicated DHS and the regularity of the coolant distribution at the outlet from them are established.

3. Information about the hydrodynamic features of the DHS flow paths allows, with relatively high accuracy, the nature of coolant flow in the header flow path to be predicted, and semi-empirical relationships for coolant mass flow (velocity) distribution calculation at the DHS outlet to be obtained.

Thank you for your attention