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수조-형 소듐냉각고속로의 다공성매질근사법에서 수력학적 저항 모델

Hydraulic Resistance Modeling of the Porous Media Approaches for a Pool-type Sodium-cooled Fast Reactor

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Introduction

❑ SALUS (Small, Advanced, Long-cycled and Ultimate Safe SFR)

- **KAERI is developing a design and analysis technique for a pool-type sodium-cooled fast reactor called SALUS(Small, Advanced, Long-cycled and Ultimate Safe SFR)**
  - **100MWe Power Generation**
  - **A long refueling period more than 20 years.**

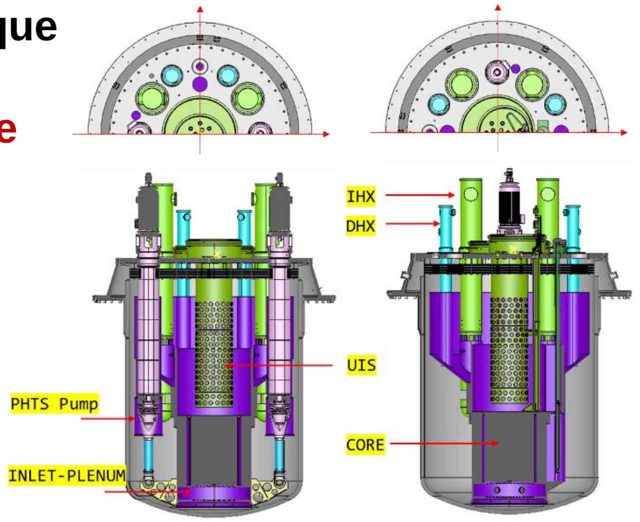


Fig. SALUS PHTS Assembly

❑ CFD (Computational Fluid Dynamics) Analysis for SALUS Design Improvement

- **CFD analysis results (temperature and pressure distribution) would help improving the SALUS design, associated with the structural analysis results (thermal stresses).**
- **Objectives of the CFD analysis:**
  - **PHTS (Primary Heat Transfer System).**
  - **HAA (Head Access Area) and RVCS (Reactor Vault Cooling System), to get the proper BC's (boundary conditions) @ the outermost surfaces of the PHTS.**

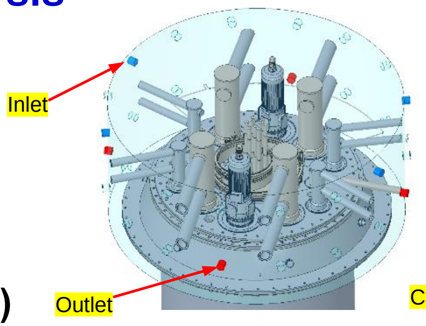


Fig. SALUS HAA

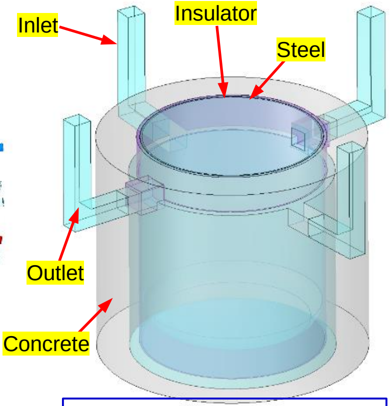


Fig. SALUS RVCS

CFD-Aided Design of SALUS

❑ CFD Models

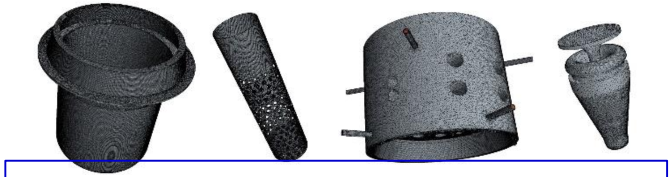
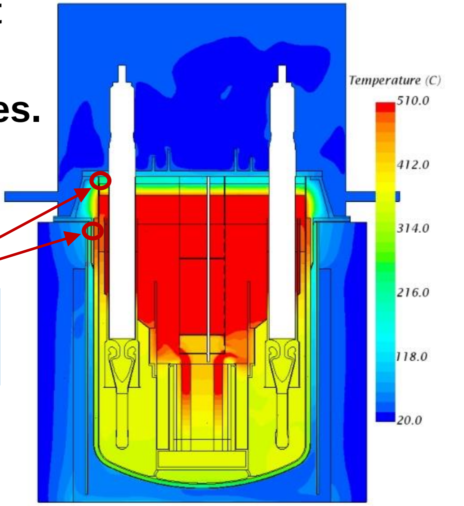


Fig. Meshes for SALUS CFD simulation

- ~30,000,000 unstructured polyhedral meshes
  - Overall basic mesh size of ~7 cm
  - Prizm layers in the fluid region near structural surfaces for the wall functions
- Conjugate heat transfer: conduction + convection + radiation
  - S2S Gray Thermal radiation model
  - k-ω SST(Shear Stress transport) turbulence model
- Component models
  - Core model is based on a conceptual core design.
  - HXs are approximated as porous media, with a proper volumetric heat source/sink.
  - Pumps are modeled as (P+T) inlet boundary conditions without modeling any moving turbomachinery.
  - Air inlet BCs for HAA and RVCS are modeled by design analyses.
  - USHS(Upper Shielding Structure) are modeled as a solid block.

❑ Thermal Stress Analysis for SALUS Design

- For checking if the design requirements of the containment vessel (CV) are satisfied, thermal stress analysis was conducted.
- CFD + structural analyses proved that the thermal stresses on the critical locations(red marks) met the design requirements.



Critical Locations

Fig. SALUS PHTS Temperature

Purposes & Contents

Ultimate Goal: **Improvement in the SALUS design, by using CFD technology associate with structural analysis**

Purpose of this study: **The hydraulic resistance models of the porous media approaches for the SALUS IHXs, DHXs, and UIS shall be established, and verified by using experiment and calculation results.**

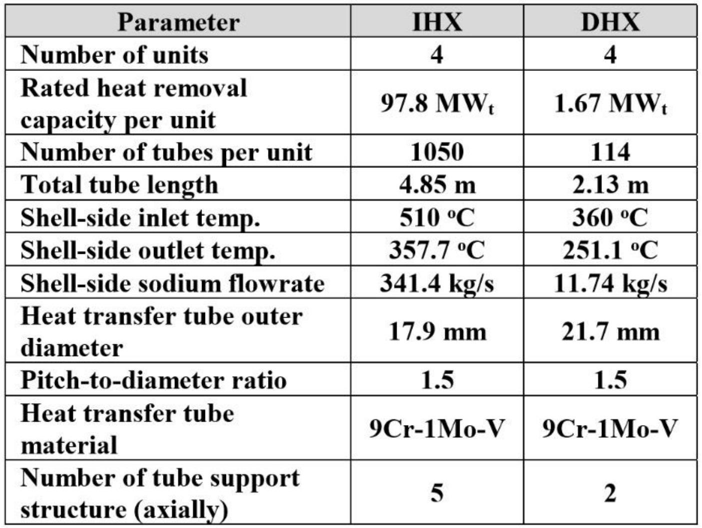
CONTENTS :

Porous Media Approaches for SALUS HXs

CFD Models for the SALUS HXs

- Two types of HXs(Heat Exchangers) in PHTS
  - 4 IHXs (Intermediate Heat Exchangers)
  - 4 DHXs (Decay Heat Exchangers)
- Porous Media Approaches for the SALUS HXs
  1) Cylindrical-shaped IHXs and DHXs are counter-current flow type sodium-to-sodium heat exchangers with a shell and straight tubes.
  2) The shell-side, where the primary sodium flow through to transfer heat to the secondary sodium, are approximated as porous media.
  3) The secondary sodium flow circulations were omitted, and the heat transfer rates to the secondary sodium were modelled as volumetric heat removal rates in the porous media.
  4) The hydraulic resistances in the shell-side (porous media) should be modelled appropriately by using iHELP(intermediate Heat Exchanger test Loop for PGSFR) experimental data.
  5) IHXs and DHXs have the same configuration such as pitch-to-diameter ratio, support plate, and triangular tube array, which are similar to those of the PGSFR.

Table. Thermal Design Parameters of the SALUS HXs



Parameter	IHX	DHX
Number of units	4	4
Rated heat removal capacity per unit	97.8 MW_t	1.67 MW_t
Number of tubes per unit	1050	114
Total tube length	4.85 m	2.13 m
Shell-side inlet temp.	510 °C	360 °C
Shell-side outlet temp.	357.7 °C	251.1 °C
Shell-side sodium flowrate	341.4 kg/s	11.74 kg/s
Heat transfer tube outer diameter	17.9 mm	21.7 mm
Pitch-to-diameter ratio	1.5	1.5
Heat transfer tube material	9Cr-1Mo-V	9Cr-1Mo-V
Number of tube support structure (axially)	5	2

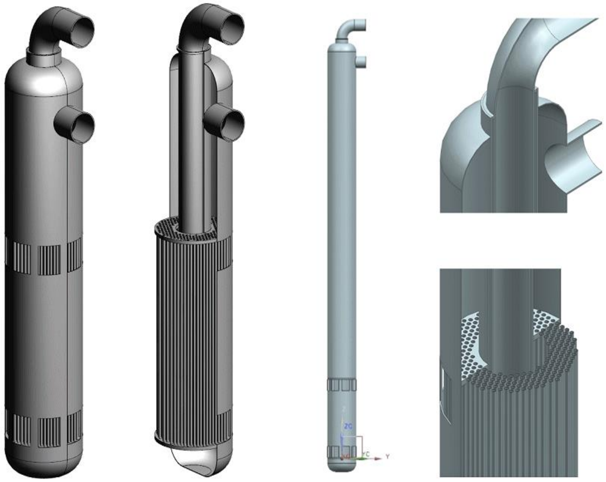


Fig. Schematic design of the SALUS DHX

Governing Equations in the Porous Region (1/2)

❑ For Flow inside the Assumed Porous Media

- **Assumptions:**
  - **The control volumes and the control surfaces are large relative to the interstitial spacing of the porous medium**
  - **The given control cells and control surfaces are assumed to contain both the fluid and the distributed solids.**
- **Definition of Terms**
  - **Volume porosity:** $\boxed{\gamma \equiv \frac{\mathrm{Vol_f}}{\mathrm{Vol_T}}}$
  - **Area Porosity:** $\boxed{\gamma_A \equiv \frac{A_\mathrm{f}}{A_T}}$
- **Governing Equations**

$$\frac{\partial(\rho\gamma)}{\partial t}+\frac{\partial\left(\rho\gamma_A u_j\right)}{\partial x_j}=0$$

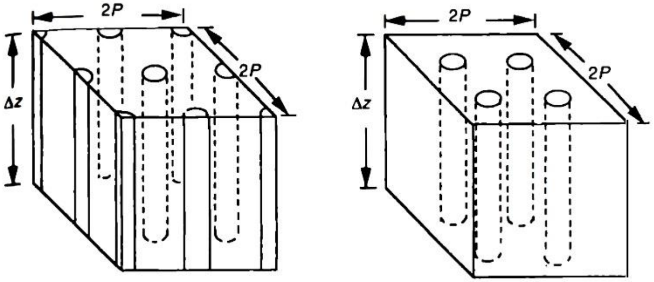
$$\frac{\partial(\rho\gamma u_i)}{\partial t}+\frac{\partial\left(\rho\gamma_A u_j u_i\right)}{\partial x_j}=-\gamma_A\frac{\partial p}{\partial x_i}+\frac{\partial}{\partial x_j}\left[\mu_e\gamma_A\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)\right]+B_i-R_i$$

$$\frac{\partial(\rho\gamma H)}{\partial t}+\frac{\partial\left(\rho\gamma_A u_j H\right)}{\partial x_j}=\frac{\partial}{\partial x_j}\left(\Gamma_e\gamma_A\frac{\partial H}{\partial x_j}\right)+\gamma\, Q$$

NOMENCLATURE

ρ	density [kg/m^3]
u	velocity component [m/s]
t	time [sec]
x	distance [m]
H	total energy [J/kg]
μ_e	effective viscosity [Pa·s]
Γ_e	effective diffusivity [m^2/s]
B	body force
R	resistance to the flows
Q	heat source or sink

Governing Equations in the Porous Region (2/2)



❑ Introducing 'Superficial Velocity'

- ❍ **Assuming** $\boxed{\gamma \equiv \gamma_A}$
- ❍ **Definitions:**
  - ⏩ **Superficial velocity, u^S ($=\gamma \cdot u$) = an artificial flow velocity that assumes that only fluid passes the cross-sectional area and neglects the solid portion of the porous medium.**
  - ⏩ **Physical velocity, u**
- ❍ **Be careful when entering the hydraulic resistance of the porous region into the momentum source terms.**
  - ⏩ **For the "Porous Inertial Resistance" in STAR-CCM+, the required input value is a coefficient(multiplier) to a square of the superficial velocity in the unit of kg/m^4.**

❑ Advantages and disadvantages of using porous media approaches

- ⏩ **Less mesh density → efficient calculation (relatively correct average velocity fields)**
- ⏩ **The turbulence transport equations are not solved in the porous regions.**
  → If turbulent properties are required in the porous region, users must specify directly turbulent parameters such as turbulence intensity and length scale, etc.
- ⏩ **Heat transfer in the porous media are not solved in detail.**
  → volumetric heat source/sink

Hydraulic Resistance Model for Cross Flows (1/2)

Pressure Drop Correlation by Zukauskas and Ulinskas

- **Pressure drop through a tube banks by the Euler number, Eu :**

$$\Delta P = Eu \frac{\rho u^2}{2} z$$

Where z is the number of tube rows.

$$\boxed{\frac{\Delta P}{\Delta L} = Eu \frac{\rho u^2}{2} \frac{z}{\Delta L} = \frac{Eu}{pitch} \cdot \frac{\rho u^2}{2}}$$

The equations of Eu for in-line tube banks with a pitch to diameter ratio (P/D) of 1.5 : ($k_1 \approx 1.0$)

$$\frac{Eu}{k_1} = \begin{cases} 0.263 + \dfrac{0.867\times10^2}{\mathrm{Re}} - \dfrac{0.202\times10}{\mathrm{Re}^2} & \text{for } 3 < \mathrm{Re} < 2\times10^3 \\ 0.235 + \dfrac{0.197\times10^4}{\mathrm{Re}} - \dfrac{0.124\times10^8}{\mathrm{Re}^2} & \\ \quad + \dfrac{0.312\times10^{11}}{\mathrm{Re}^3} - \dfrac{0.274\times10^{14}}{\mathrm{Re}^4} & \text{for } 2\times10^3 < \mathrm{Re} < 2\times10^6 \end{cases}$$

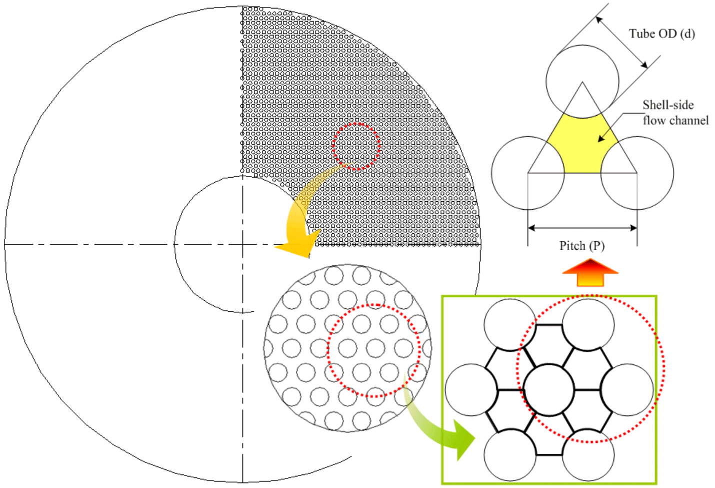


Fig. Configuration of heat transfer tube array for the SALUS IHXs and DHXs

Verification of the Implemented Pressure Drop Correlation

- **Experimental study by Derek B. Ebeling-Koning :**
  - **Test section: cross section of 142.875 x 28.575mm, length of 914.4mm**
  - **Pitch to diameter ratio (P/D) = 1.5 & Tube diameter = 6.35mm → $h_D = 10.3$mm**
  - **Test Reynolds number range = 1 x 10^3 ~ 2.0 x 10^4**

Hydraulic Resistance Model for Cross Flows (2/2)

❑ Verification of the Implemented Pressure Drop Correlation

- **Implementing hydraulic resistance correlation into STAR-CCM+:**
  - **Entering values for the "Porous Inertial Resistance" in the form of a coefficient(multiplier) to the square of the superficial velocity in the unit of kg/m^4.**
  - **User Field Function:**

$$\frac{\Delta P}{\Delta L} = \frac{Eu}{pitch} \cdot \frac{\rho \cancel{u}^2}{2}$$

```
FrictionPressLoss = ${EulerNo}*${Density}/(2*${Pitch}*${Porosity}*${Porosity})
EulerNo = (${ReynoldsNo}<2000? ${k_1}*(0.263+86.7/${ReynoldsNo}-2.02/(${ReynoldsNo}*${ReynoldsNo})):
             ${k_1}*(0.235+1970/${ReynoldsNo}-12400000/(${ReynoldsNo}*${ReynoldsNo})
             +31200000000/(${ReynoldsNo}*${ReynoldsNo}*${ReynoldsNo})-
             27400000000000/(${ReynoldsNo}*${ReynoldsNo}*${ReynoldsNo}*${ReynoldsNo})))
```

Eu

Table. Experimental and Simulation Results for the Pressure Drop Measurements in 90° Inclined Tube Bundles

Tube Arrangement	Reynolds Number (Experiment)	CFD Simulation			Normalized Flow Resistance (Experiment), B	Error = (A-B)/B
		Inlet Velocity [m/s]	ΔP/ΔL @ Mid Position [Pa/m]	Normalized Flow Resistance (Eq. (*)), A		
In-line (Square) $\theta = 0°$ (Cross flow) $T_{avg} = 27.8$ °C $\rho = 998.0$ kg/m^3 $\beta = 0.650935$ (porosity) $D_h = 0.0103$ m $A_{channel} = 0.004083$ m^2	4280	0.378993	6100.7	2936.7	2860	2.7%
	10200	0.893624	33733.0	6530.7	5410	20.7%
	19100	1.65586	90281.0	9449.1	8930	5.8%

Normalized flow resistance components defined by D. B. Ebeling-Koning:

$$R_x^* \triangleq \frac{D_h^2}{\mu\left|\langle \underline{u} \rangle\right|} \frac{\Delta P_x}{L_x} \quad (*)$$

$$\left|\langle \underline{u} \rangle\right| = \frac{\text{volumetric flow rate}}{\text{flow area}}$$

$$\left(= u^S\right)$$

Hydraulic Resistance for Axial Flows through the Tube Bundle of Smooth Straight Pipes (1/2)

Darcy friction factor correlations for axial flows

- Shell-side axial pressure losses of the straight tube bundle are mainly caused by the frictional loss on the tube outer surfaces.
- The pressure loss can be expressed as a function of Reynolds numbers for an internal pipe flow (Darcy correlations).

$$f_z = \begin{cases} \dfrac{64}{\mathrm{Re}} & \text{for Re} < 2{,}000 \\ \dfrac{1}{\left[1.8\log\left(\mathrm{Re}\right)-1.64\right]^2} & \text{for Re} > 4{,}000 \end{cases} \qquad (\bigstar)$$

Hydraulic Diameter:

$$A_f = \frac{\sqrt{3}}{4}P^2 - \frac{1}{2}\times\frac{\pi}{4}d_{o,w}^2$$

$$D_h = \frac{4A_f}{\pi d_{o,w}/2}$$

- The axial frictional pressure drop

$$\boxed{\Delta P_{axial} = f_z\frac{L}{D_h}\cdot\frac{1}{2}\rho u_{axial}^2} \qquad (^{**})$$

where A_f, P, $d_{o,w}$ and D_h denote flow channel area, pitch between tube centers, tube outer diameter, and shell-side hydraulic diameter, respectively.

Verification of the Implemented Darcy Correlation

- Rectangular channel flow with axial hydraulic resistances :
  - Axial velocity of the HX shell side = ~1.05m/s (IHX) or ~0.214m/s (DHX) @ full power
  - CFD simulations were performed on three sample axial velocities less than 1.0m/s.
  - Sodium properties: density = 847.4kg/m^3 & dynamic viscosity = 5.99E-4Pa·s @400^{o}C

Hydraulic Resistance for Axial Flows through the Tube Bundle of Smooth Straight Pipes (2/2)

❑ Verification of the Implemented Pressure Drop Correlation

- **Implementing hydraulic resistance correlation into STAR-CCM+:**
  - **Entering values for the “Porous Inertial Resistance” in the form of a coefficient(multiplier) to the square of the superficial velocity in the unit of kg/m⁴.**
  - **User Field Function:**

$$\frac{\Delta P_{axial}}{\Delta L} = f_z \frac{1}{D_h} \cdot \frac{1}{2} \rho \cancel{u}^2_{axial}$$

```
FrictionPresLoss = ${FrictionLossCoef}*${Density}/(2*${HydraulicDiameter(in meter)})

FrictionLossCoef = (${ReynoldsNo}<3000? 64/${ReynoldsNo}:
                         1/((1.8*log10(${ReynoldsNo})-1.64)*(1.8*log10(${ReynoldsNo})-1.64)))
```

f_z

Table. Verification for the Axial Hydraulic Resistance

Case	Inlet Velocity (Upstream)	Actual Velocity at the Mid Position in Porous Region	Estimated Reynolds No. in the Porous Region	Friction Loss Coefficient (f_z in Eq. (★))	Pressure Drop Ratio (ΔP/ΔL)	
					Simulation Result	Estimation* (Eq. (**))
1	0.12774 m/s	0.13191 m/s	4947.9	0.03984	11.145 Pa/m	11.081 Pa/m
2	0.41783 m/s	0.42703 m/s	16016.3	0.02846	83.592 Pa/m	82.931 Pa/m
3	0.71628 m/s	0.72964 m/s	27360.5	0.02482	209.861 Pa/m	211.215 Pa/m

*** The estimated pressure drop ratios are calculated based on the actual velocity (u) in the porous region from the simulation result, which is not a superficial velocity.**

Hydraulic Resistance for the Flows through the UIS Lowest Support Plate (1/2)

UIS(Upper Internal Structure) Support Plate

- used To guide and support several kinds of guide tubes such as CR(Control Rod), DM (Direct lifting Machine), sensing and T/C guide tubes
- To guide the core exit sodium to the IHXs for uniform temperature distribution by mixing
- Configuration:
  - Thickness = 30 mm
  - Equal-spacing 172 flow holes with a diameter of 82.4 mm

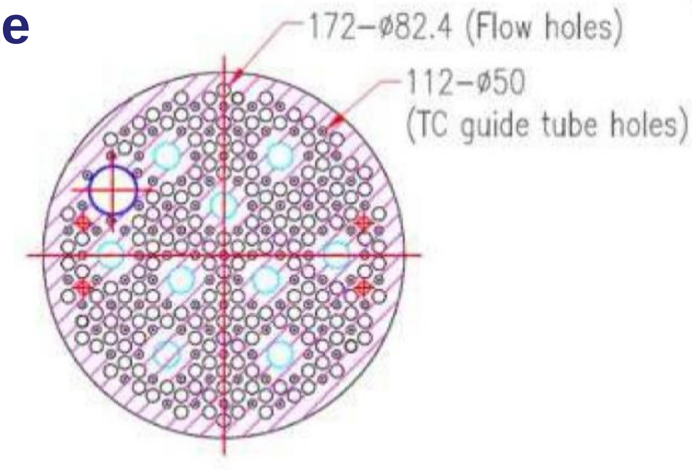


Fig. Top view of the SALUS UIS lowest support plate

Pressure Drop Correlation across a Grid Plate

- Diagram 3-12 in Idelchik's 'Handbook of Hydraulic Resistance'

$$\boxed{\Delta P_{Grid} = K_i \frac{1}{2}\rho u^2 + \xi_{fr}}$$

Here, $K_i = \frac{\Delta P}{\rho u_0^2/2} = \left(1.707 - \bar{f}\right)^2 \cdot \frac{1}{\bar{f}^2}$

where ξ_{fr} = potential friction loss passing through the grid plate

$\bar{f}$ = (actual flow area) to (frontal flow area) ratio, and

u_o = flow velocity upstream

Hydraulic Resistance for the Flows through the UIS Lowest Support Plate (2/2)

❑ CFD Simulation for Verification

- A **conceptual geometry** was generated, which is a circular flow passage containing a porous grid plate region in the middle of the passage.
- Hydraulic resistance in the porous grid plate was implemented by using Eq. (4).
- Hand calculation: (β = porosity)

$$K_i = \frac{\Delta P}{\rho u_0^2 / 2} = (1.707 - 0.228)^2 \cdot \frac{1}{0.228^2} = 42.07912$$

$$-R_Y = \frac{\Delta P_{Grid}}{\Delta L} = K \frac{\rho}{2\Delta L} (\beta V)^2 = 42.079 \frac{830kg/m^3}{2(0.03m)} (\beta V)^2$$

Finally, $$\Delta P_{Grid} = K_i \frac{1}{2} \rho u_0{}^2 = \frac{42.079}{2} (830kg/m^3)(1.0m/s)^2 = 17.4628kPa$$

Well matched with simulation result !

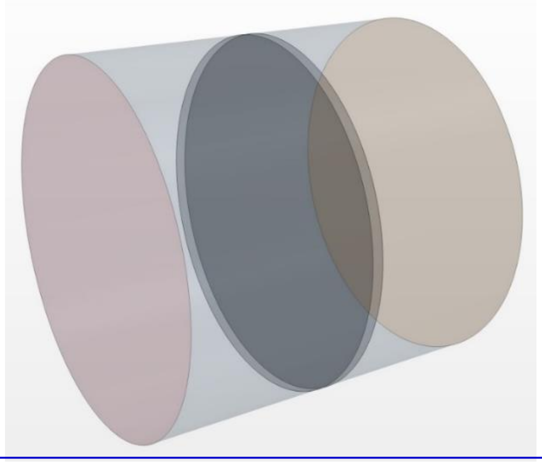


Fig. Simple conceptual geometry for the CFD simulation

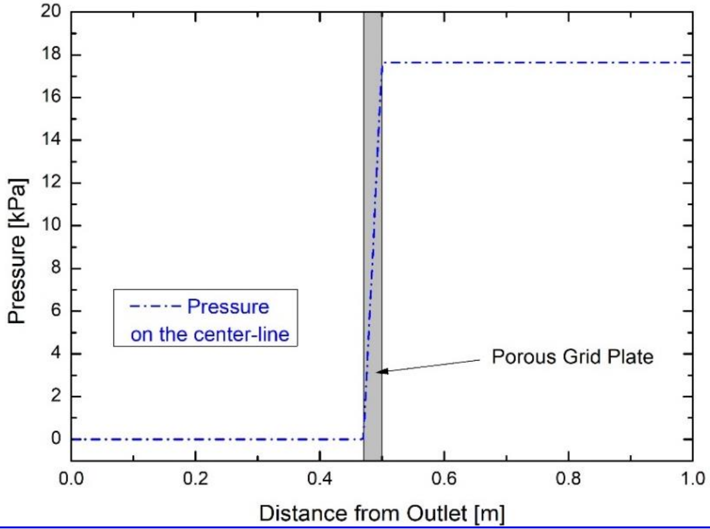


Fig. Resultant pressure profile on the channel center line

Table. Input Values for the Simulation

Input Parameter	Value
Inlet Velocity	1.0 m/s
Porosity	0.228
Y-Dir. Hydraulic Resistance	582092.8 kg/m⁴
X- & Z-Dir. Hydraulic Resistance	1.0E+10 kg/m⁴

Application: Estimating Hydraulic Resistance Correlations for SALUS HXs

❑ iHELP(intermediate Heat Exchanger test Loop for PGSFR)

- ❍ **iHELP was designed to develop and validate the pressure drop correlations used in a design code.**
- ❍ **Based on the hydraulic resistance correlations for the axial flows and the flows across a grid plate, the hydraulic resistance correlations of the SALUS IHXs and DHXs will be derived and implemented into the CFD tool.**

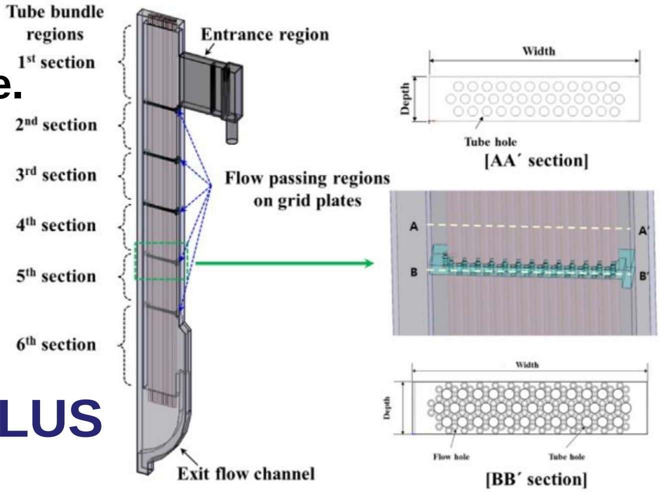


Fig. iHELP Test Section

❑ Next Task of the CFD-aided Design for SALUS

- ❍ **In current SALUS design, DHX inlets are located deep inside the internal structure (Redan).**
  → need sensitivity study on DHX level !!

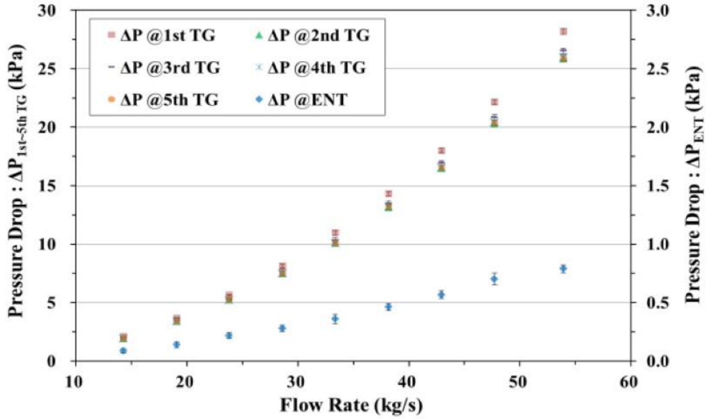


Fig. Pressure drops at the tube bundle regions with grid plates

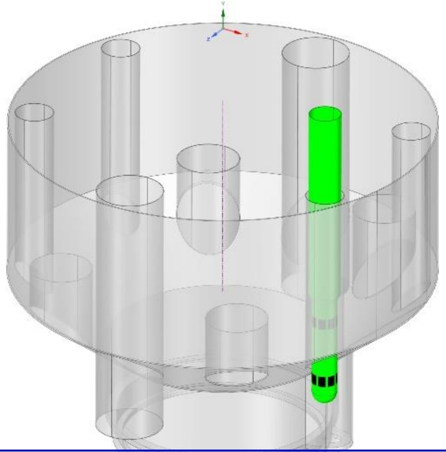


Fig. SALUS Internal Structure and DHX locations

Conclusions

❑ CONCLUSIONS

- **From the verification of the lateral (cross) flow to a in-line tube bank,**
  - **The hydraulic resistance correlation based on Euler number was implemented into the Siemens STAR-CCM+ CFD tool as a function of the local Reynolds number.**
  - **It was found that the STAR-CCM+ users should enter the input values for the "Porous Inertial Resistance" as a form of the coefficient (multiplier) to a square of the superficial velocity.**
- **For the verification of the axial flows along smooth straight tube bundle,**
  - **the hydraulic resistance in axial direction was implemented into the CFD tool by well-known Darcy friction factor correlations.**
  - **The implemented hydraulic resistances were well verified by comparing the resultant pressure losses with the calculations.**
- **For the pressure drop across a grid plate with equally-spaced flow holes,**
  - **A correlation from Idelchik's handbook was adapted.**
  - **A conceptual problem was set for the CFD simulation for verification, and the simulation gave exactly the same value as the hand-calculated.**

❑ Future Works

- **Based on the verified hydraulic resistance correlations for the axial flows and the flows across a grid plate, the hydraulic resistance correlation for the SALUS IHXs and DHXs will be derived by using iHELP experimental data.**

Thank You for Your Attention !!

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