TIFONE: a design-oriented code for the inter-wrapper flow and heat transfer in liquid metal-cooled reactors

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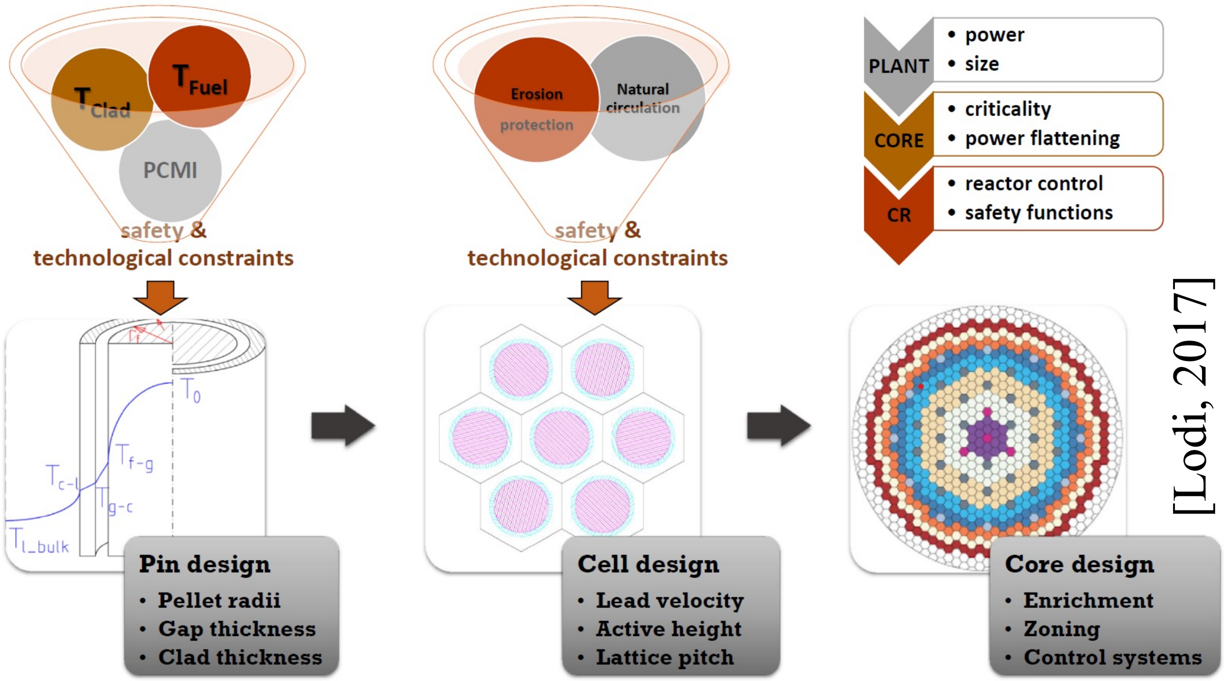
LFR core design - the need for dedicated tools

- A comprehensive approach to core design:
  - Identify **safety and technological constraints** → derive **design guidelines**
  - Design individual components
  - Manage interfaces with other reactor systems
  - **Optimize** performance by **working on available margins**
- Computational tools in support of core design:
  - **Design-Oriented Codes (DOCs):**
    - Target: **equilibrium**
    - Balanced error contributions, fast-running
    - Clear application domain
  - Verification-Oriented Codes (VOCs):
    - Target: **high accuracy**
    - Comprehensive physical treatment
    - Sophisticated models and methods



[Lodi, 2017]

- Three "pillars" for core design:
  - Neutronics (NE)
  - Thermal-hydraulics (TH)
  - Thermo-mechanics (TM)

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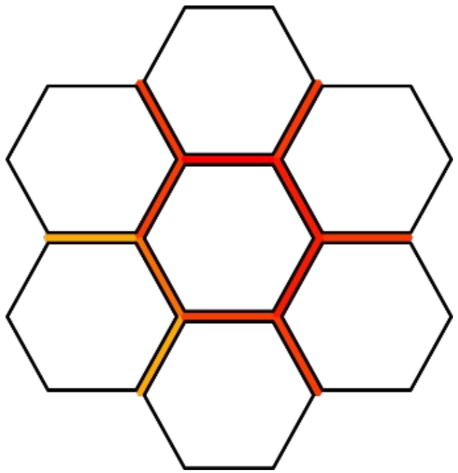
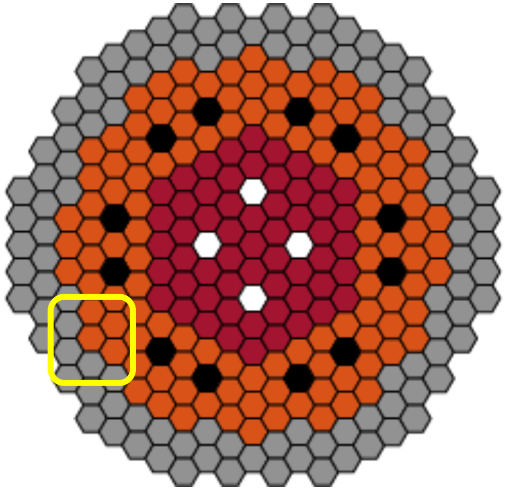
Motivation to develop a new code: TIFONE, a DOC for LFR core TH

- **Inter-Wrapper (IW) region** is inherent in LFR design (width established by core TM design)
  - Among the core TH design goals: to avoid cold by-passes and excessive thermal gradients among opposite faces of the assembly ducts (**bowing**)
  - To be achieved by working on: IW coolant flow
- → Core TH design requires knowledge of:
  - **Full-core** axial and radial coolant temperature distribution
  - Axial and perimetrical wrapper temperature profile for each SA
- Literature review:
  - COBRA-WC, NETFLOW
  - SUPERENERGY-2, SE2-ANL

→ **No available DOC for core TH design** (*)

(*) Note on ANTEO+ and porous medium approach





TIFONE: Termo-**I**draulica delle **F**ughe che **O**ccorrono nel **N**occiolo fra gli **E**lementi
(thermal-hydraulics of the bypass flow occurring in the core among the SAs)

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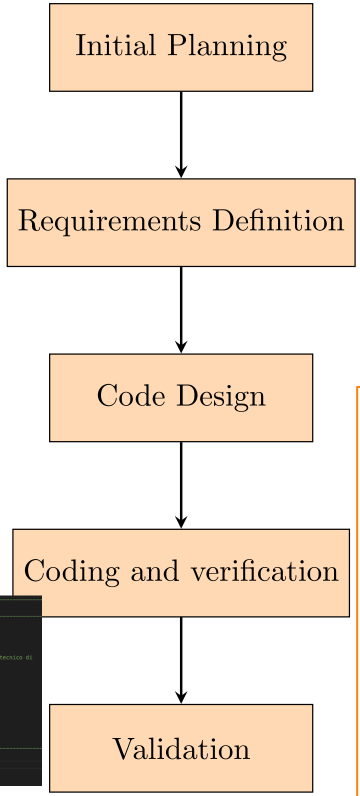
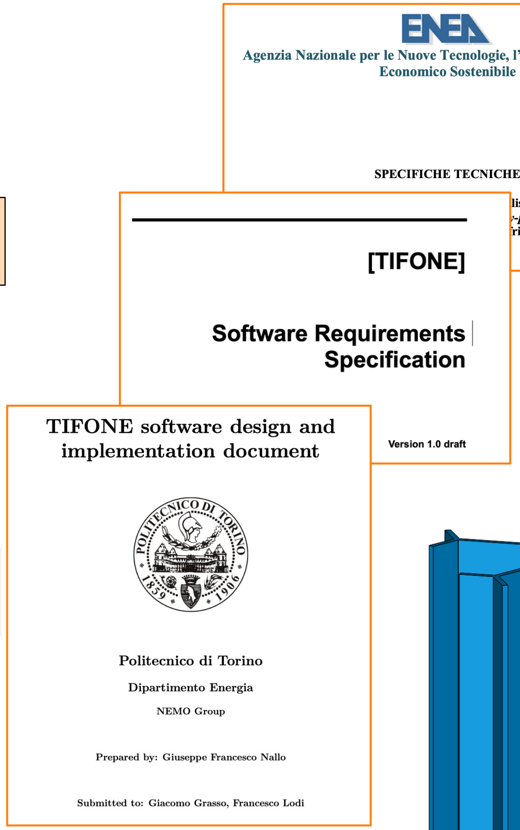
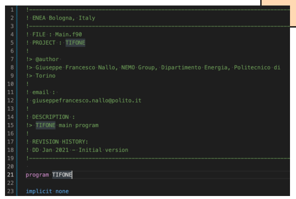
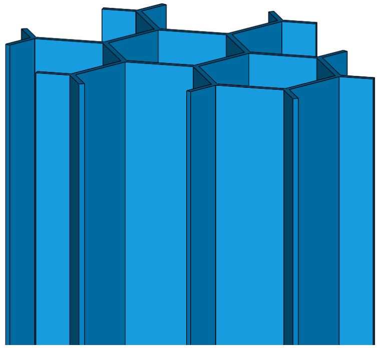
A quality-compliant code design approach for TIFONE

- TIFONE was developed according to ENEA's **Software Quality Management** System → necessary if intend to use the code to support licensing





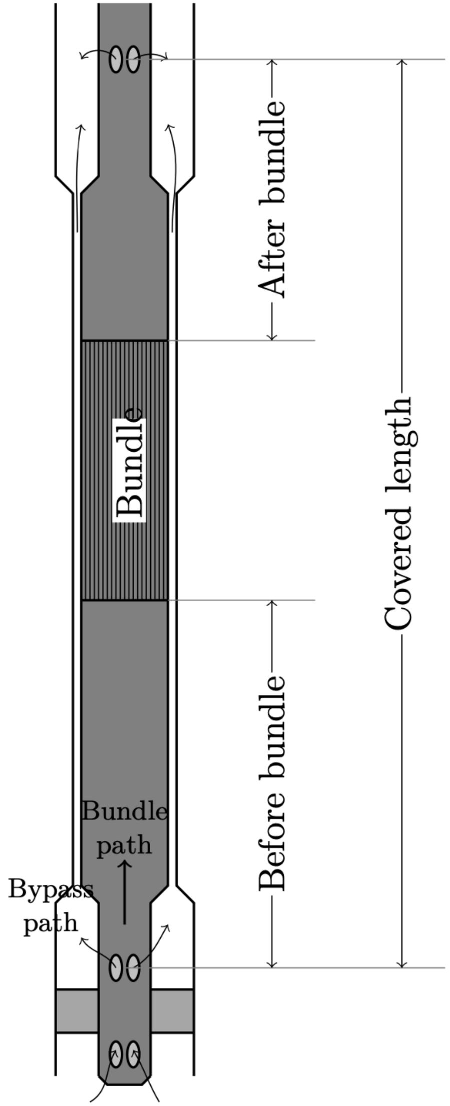




- Application domain:
  - Steady-state
  - Liquid metal coolant (*)
  - Closed, hexagonal SAs
  - Forced and mixed convection regimes (<u>not purely natural circulation</u>)

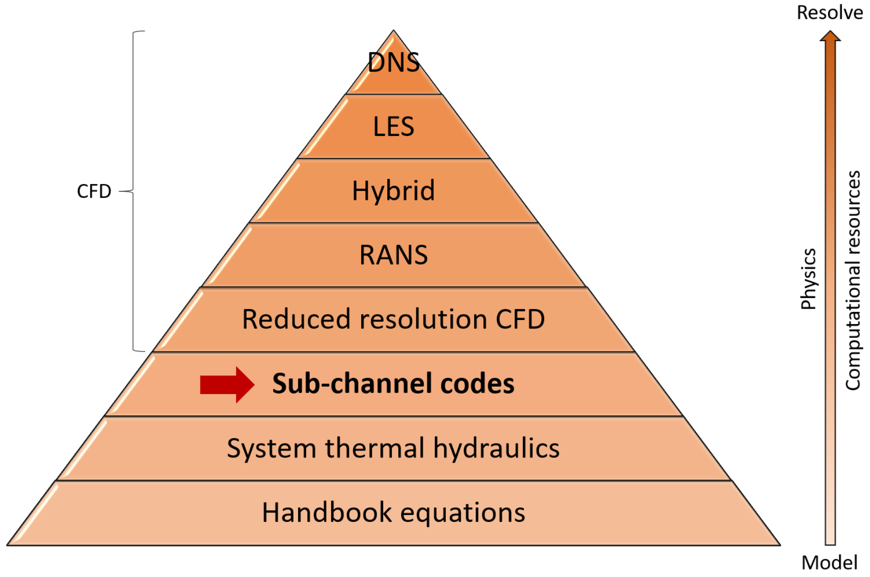
- Calculation domain:
  - Axially: between dividing and merging of inter- and intra-SA flows
  - Radially: IW region of the entire core

(*) Na, Pb or PBE

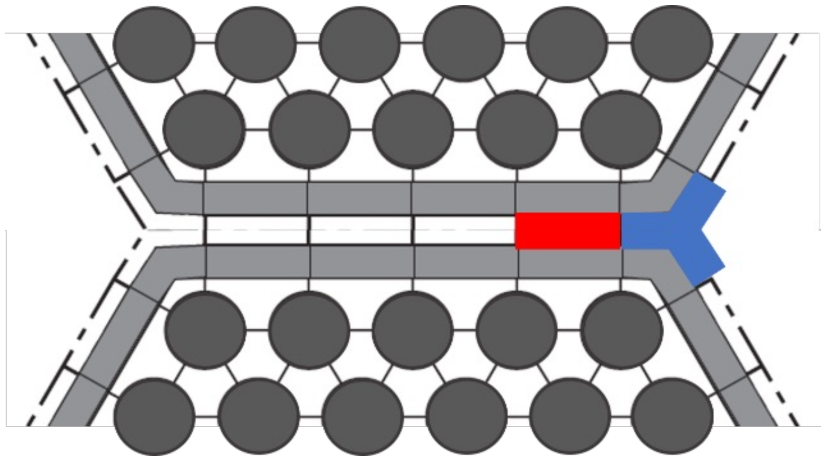


Problem solving approach and spatial discretization

- Based on the requirements specification, need to select the most suitable calculation approach
- The **Sub-Channel (SC)** method was selected → balance between complexity and accuracy



- Spatial discretization:
  – Axial: arbitrary node distribution
  – Radial: arbitrary number of *edge SCs* + one *corner SCs* for each corner.



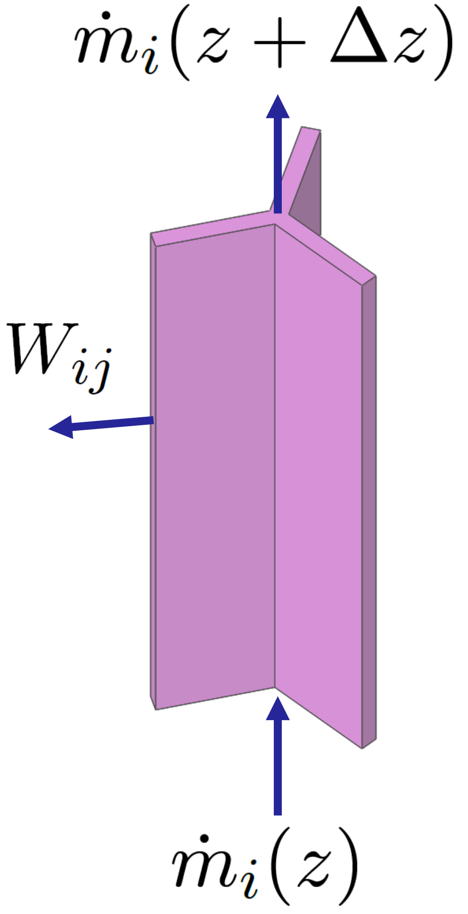
Physico-mathematical model: mass conservation

Problem solving approach | Data modelling | Code functional modelling | Detailed code design | Implementation / Verification | Validation

$$A_i \Delta z \frac{\partial}{\partial t} \langle \rho_i \rangle + \Delta \dot{m}_i = -\Delta z \sum_{j=1}^{N_{nei,i}} W_{ij}$$

$$\frac{\Delta \dot{m}_i}{\Delta z} = -\sum_{j=1}^{N_{nei,i}} W_{ij}$$

- Forced convection: neglect inter-SC mass transfer
- Mixed convection: assume inter-SC mass transfer entirely due to buoyancy effects
- Onset of mixed convection for $Y_{mix} = Gr/Re^2 > 0.002$ [Jackson]



- Boundary condition: $\dot{m}_{in}$. User provides $\dot{m}_{in,core}$ and f_{BP}; repartition among SCs is then computed via *flow split* calculation

Physico-mathematical model: energy conservation

$$A_i \Delta z \frac{\partial}{\partial t}\left[\langle \rho h\rangle_i\right] + \Delta\left[\dot{m}_i\left\{h_i\right\}\right] = A_i \Delta z \dot{q}_{eq,i} - \Delta z \sum_{j=1}^{N_{nei,i}}\left[\left\{W_{ij}^{*D} h_i\right\} - \left\{W_{ji}^{*D} h_j\right\}\right] - \Delta z \sum_{j=1}^{N_{nei,i}} W_{ij}\left\{h^*\right\} + A_i \Delta z \left\langle \frac{dP_i}{dt}\right\rangle$$

$$\frac{\Delta}{\Delta z}\left(\dot{m} h_i\right) = A_i \dot{q}_{eq,i} - \sum_{j=1}^{N_{nei,i}} W_{ij}^{*H}\left(h_j - h_i\right) - \sum_{j=1}^{N_{nei,i}} W_{ij}\left\{h^*\right\}$$

$$H_i^* \sum_{j=1}^{N_{nei}} W_{ij}$$

$$H_i^* = \frac{\sum_{j=1}^{N_{nei}}\left[\left|x_{ij}\right|\left(h_i + h_j\right) - x_{ij}\left(h_i - h_j\right)\right]}{2\sum_{j=1}^{N_{nei}}\left|x_{ij}\right|}$$

$$W_{ij}^{*H}\left(h_i - h_j\right) = q''_{ij} s_{ij}\Big|_{conduction} + q''_{ij} s_{ij}\Big|_{turbulence}$$

$$q''_{ij} s_{ij}\Big|_{turbulence} = W_{ij}^{T,H}\left(h_i - h_j\right)$$

$$W_{ij}^{T,H} = \bar{\rho}_{ij} s_{ij} \cancel{\left(\frac{\bar{\alpha}_{ij}}{\eta_{ij}}\right)}$$

$$q''_{ij} s_{ij}\Big|_{conduction} = \bar{\rho}_{ij} s_{ij} \kappa_{ij}\left(\frac{\bar{\alpha}_{ij}}{\eta_{ij}}\right)\left(h_i - h_j\right)$$

$\kappa \sim 1$

- Boundary condition: T_{in}

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Physico-mathematical model: momentum conservation

Axial

$$\Delta z \frac{\partial}{\partial t}\langle \dot{m}_i \rangle + \Delta\left[\dot{m}_i\{v_i\}\right] = -A_i \Delta z \langle \rho_i \rangle g - A_i \Delta\{P\} - \Delta z \sum_{j=1}^{N_{nei}} \left[\left\{W_{ij}^{*D} v_i\right\} - \left\{W_{ji}^{*D} v_j\right\}\right] - \Delta z \sum_{j=1}^{N_{nei}} W_{ij}\{v^*\} - \Delta z \frac{1}{2} \langle \rho_i \rangle v_i^2 A_i \frac{f_i}{D_{H,i}} - A_i \Delta P_{form,i}$$

$$\frac{\Delta(\dot{m}_i v_i)}{\Delta z} = -A_i \langle \rho_i \rangle g - A_i \frac{\Delta\{P\}}{\Delta z} - \sum_{j=1}^{N_{nei}} W_{ij}^{*M}(v_i - v_j) - \sum_{j=1}^{N_{nei}} W_{ij}\{v^*\} - \frac{1}{2}\langle \rho_i \rangle v_i^2 A_i \frac{f_i}{D_{H,i}} - A_i \frac{\Delta P_{form,i}}{\Delta z}$$

- Boundary condition: p_{in}

Radial

$$\frac{\partial}{\partial t}\langle W_{ij} \rangle + \frac{\Delta}{\Delta x'}[W_{ij}\{u\}] + \frac{\Delta}{\Delta z}[W_{ij}\{v\}] = -\left[s_{ij}\frac{\Delta}{\Delta x}\{P_j\}\right] - \left\{\frac{F_{ix}}{\Delta x' \Delta z}\right\}$$

$$P_i = P_j \quad \forall i, j$$

- Implemented empirical correlations for f:
  - Turbulent: Blasius, Colebrook, Haaland
  - Laminar: Liang

  With correction factor for non-circular geometries from Idelchick handbook

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Physico-mathematical model: flow split and heat transfer to wrapper

Flow split

$$v_i^2 \frac{f_i}{D_{H,i}} L + \xi_i v_i^2 = v_j^2 \frac{f_j}{D_{H,j}} L + \xi_j v_j^2$$

$$\begin{bmatrix} 1 & -K_{21} & 0 & \dots & 0 & 0 \\ 0 & 1 & -K_{32} & & 0 & 0 \\ \vdots & & & \ddots & & \vdots \\ 0 & 0 & 0 & & 1 & -K_{N_{cat}N_{cat}-1} \\ \frac{N_1 A_1}{A_{tot}} & \frac{N_2 A_2}{A_{tot}} & \frac{N_3 A_3}{A_{tot}} & \dots & \frac{N_{N_{cat}-1} A_{N_{cat}-1}}{A_{tot}} & \frac{N_{N_{cat}} A_{N_{cat}}}{A_{tot}} \end{bmatrix} \begin{bmatrix} X_1 \\ X_2 \\ \vdots \\ X_{N_{cat}-1} \\ X_{N_{cat}} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \\ 1 \end{bmatrix}$$

Heat transfer to wrapper

$$T_{w,o,m} = T_{sc} + q''_{w,o,m}/\alpha_o$$

$$T_{w,i,m} = T_{w,o,m} + \frac{q''_{w,o,m} k_w}{s_w}$$

- Implemented empirical correlations for *Nu*:
  - Kays, Duchatelle, Dwyer, Sleicher/Rouse, Paradis

Data modelling

- Identify the needed input and output quantities, based on:
  - Requirements stated in the SRS
  - Specific needs of the selected problem-solving approach
- Identify the quantities to be treated by the code
  - Based on the selected problem-solving approach
  - Include user inputs to modify code behavior as needed

Numerics			
Column	**Data type**	**Description**	**Notes**
nAxNod	int	Number of axial nodes	
zAxNod	float (nAxNod+1)	Axial coordinates of node boundaries	
cRadDiscr	string	Label identifying the selected approach for the ra-	

in case ='default'.
ch SA
in case ='manual',
defined radial
n
in case ='manual'

Materials			
Column	**Data type**	**Description**	**Notes**
cLm	string	Label identifying the coolant type	
cWrap	string	Label identifying the wrapper material	
cLmDens	string	Label identifying the selected correlation for coolant density	

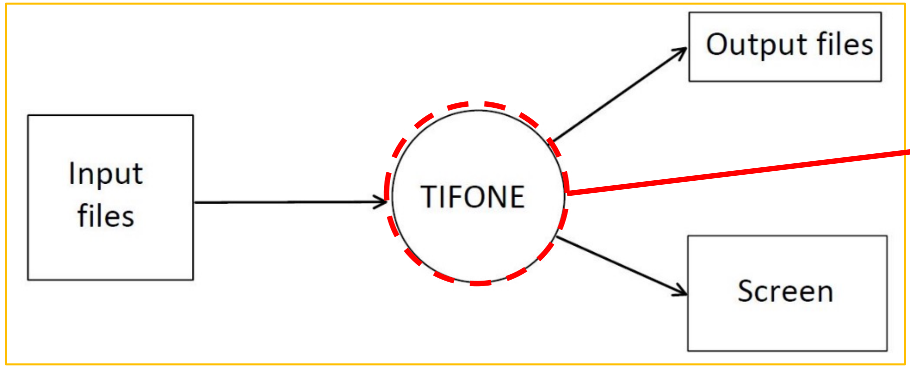
SC TH data			
Column	**Data type**	**Description**	**Notes**
temp	float(nSc, nAxNod)	Temperature	
velc	float(nSc, nAxNod)	Flow velocity	
dens	float(nSc, nAxNod)	Coolant density	
enth	float(nSc, nAxNod)	Enthalpy	

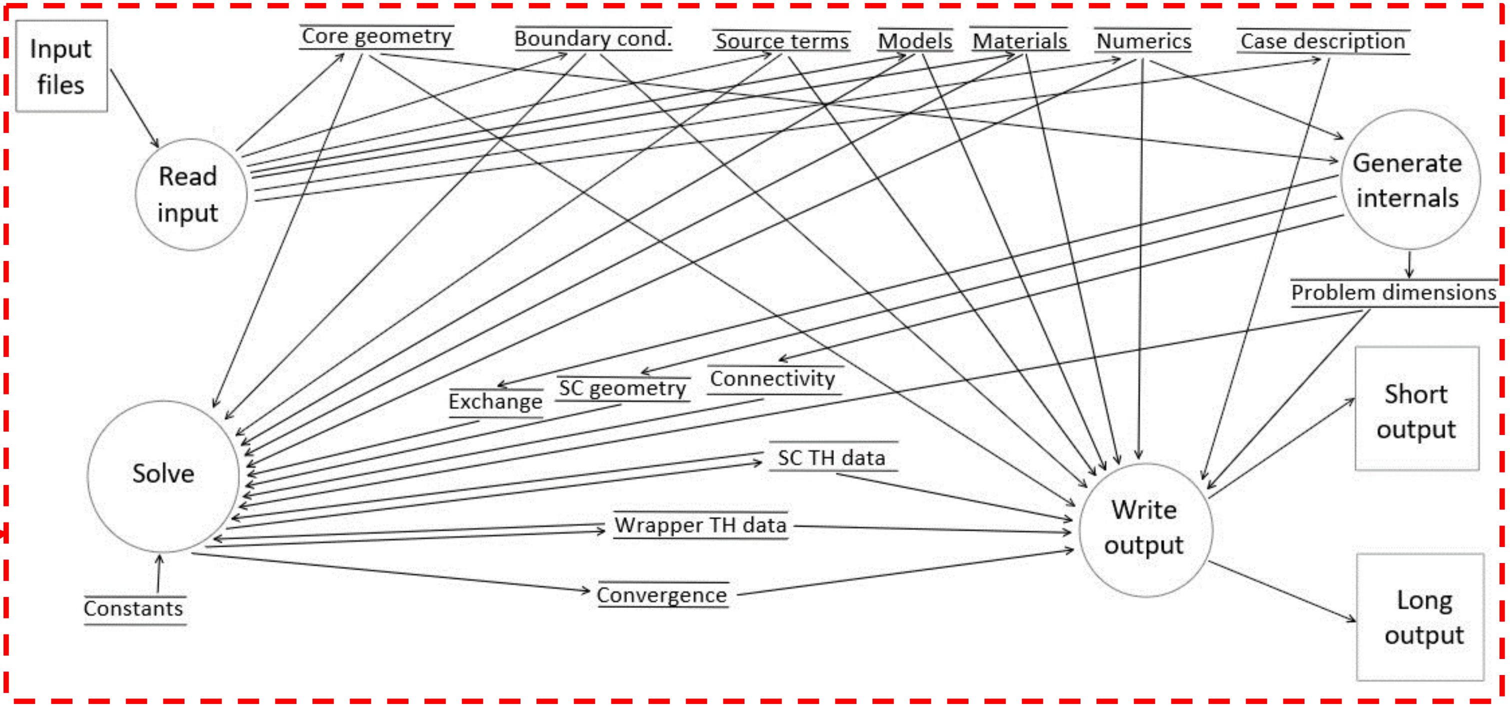
Boundary conditions			
Column	**Data type**	**Description**	**Notes**
tempInlet	float	Core inlet temperature	
mdotIn	float	Total core mass flow rate	
iwFrac	float	Fraction of the core mass flow rate flowing in the IW region	The IW flow rate is then distributed among the SCs based on the flow split calculation
presInlet	float	Core inlet pressure	Defaults to 0.0 Pa

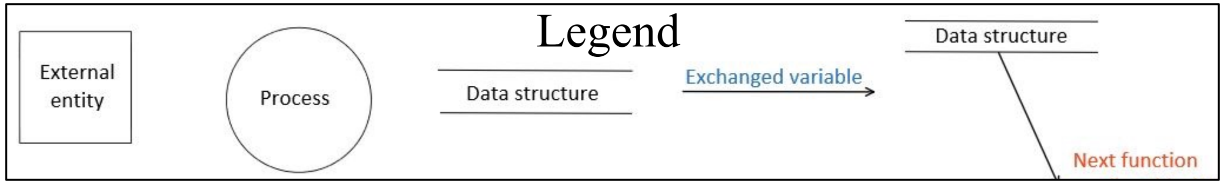
ass
for pressure
for velocity
for temperature

Functional modelling (I)

- Aim: identify the transformations undergone by data contained in data structures.
- Increase level of detail until functions are highly *consistent*
- Graphical representation: DFDs

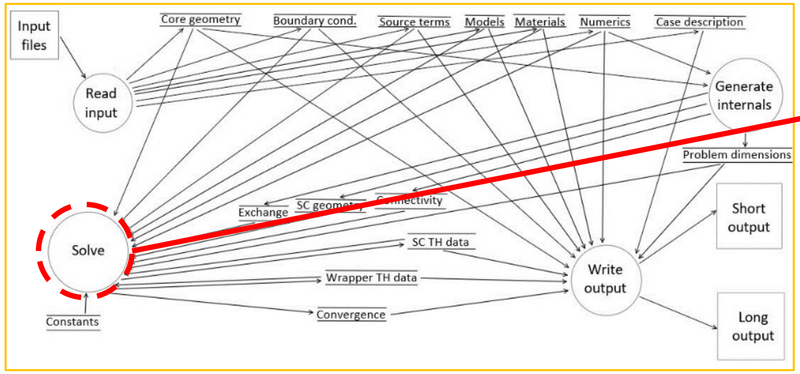


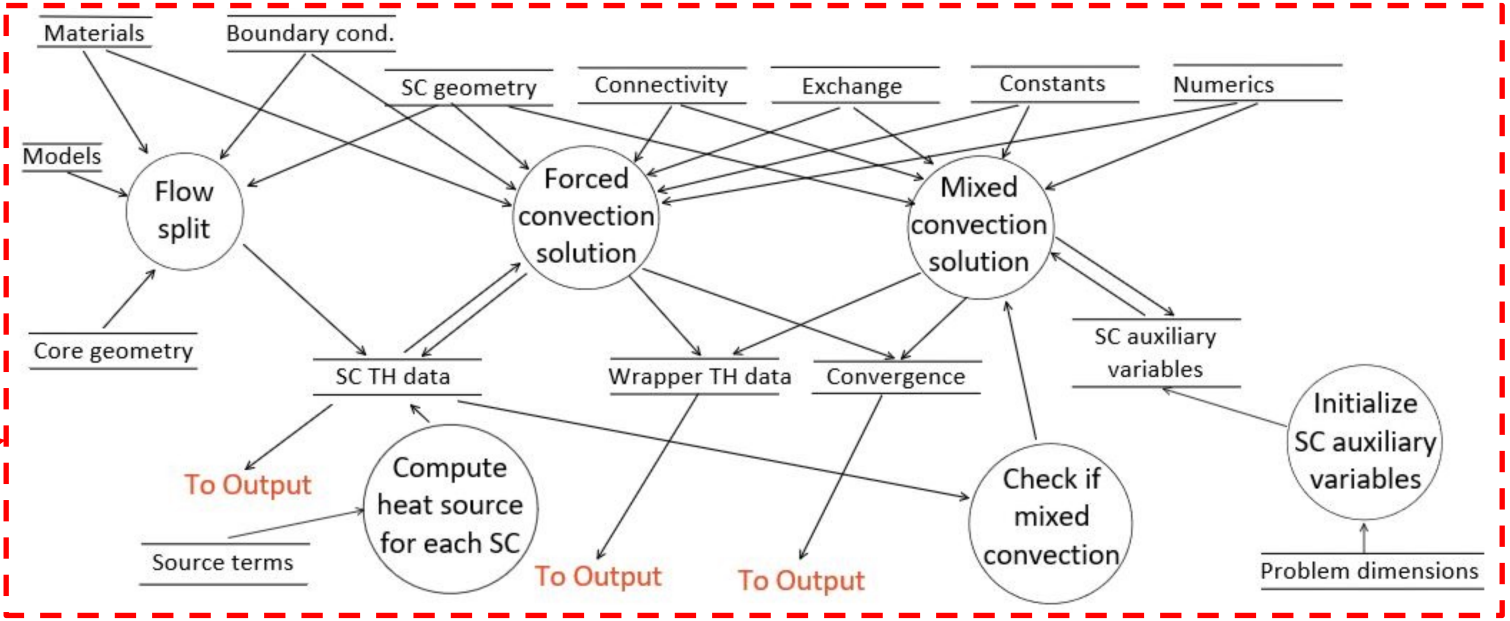


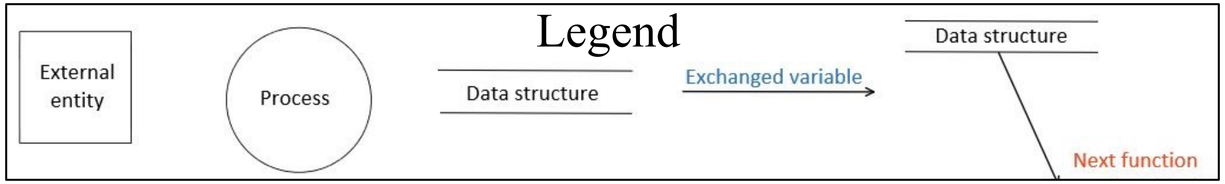


Functional modelling (II)

- Aim: identify the transformations undergone by data contained in data structures.
- Increase level of detail until functions are highly *consistent*
- Graphical representation: DFDs



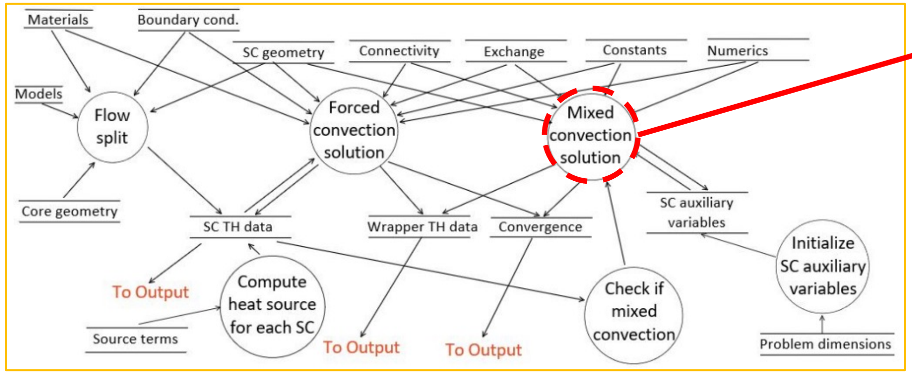


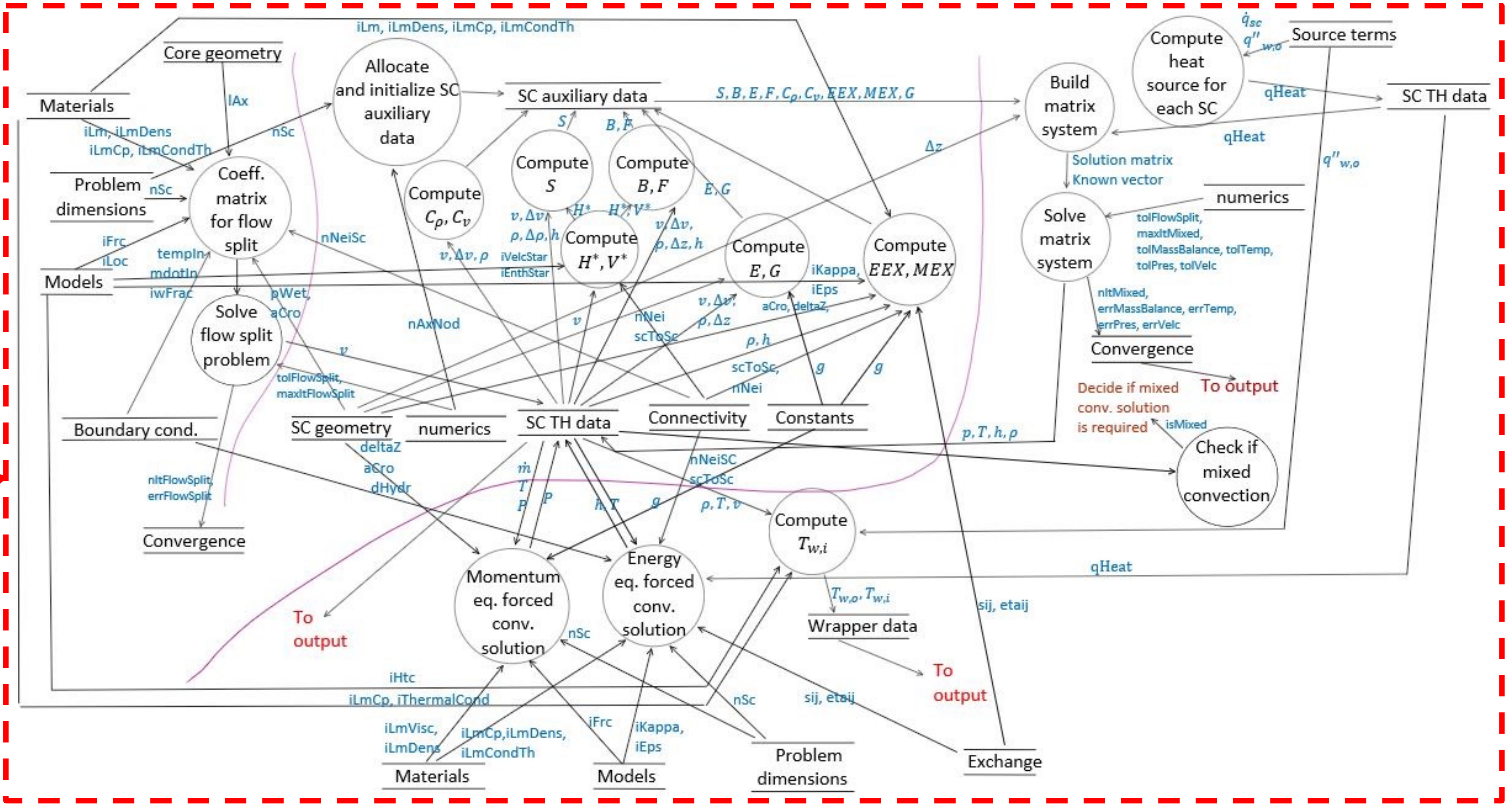


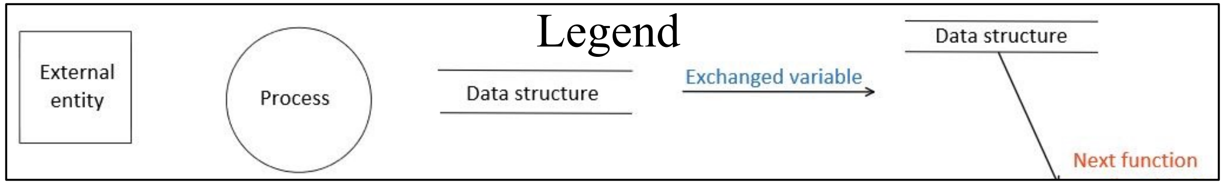
Functional modelling (III)

Problem solving approach | Data modelling | **Code functional modelling** | Detailed code design | Implementation / Verification | Validation

- Aim: identify the transformations undergone by data contained in data structures.
- Increase level of detail until functions are highly *consistent*
- Graphical representation: DFDs







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KALLA IW flow experiments

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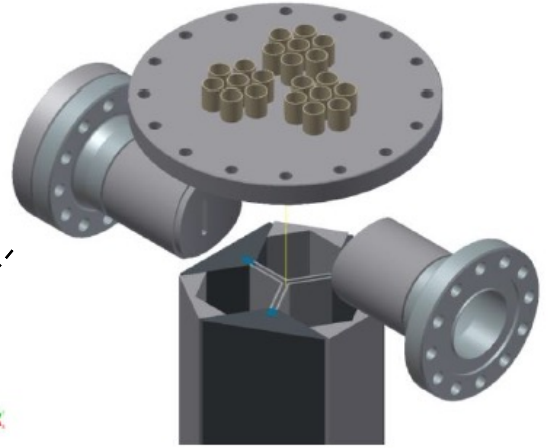
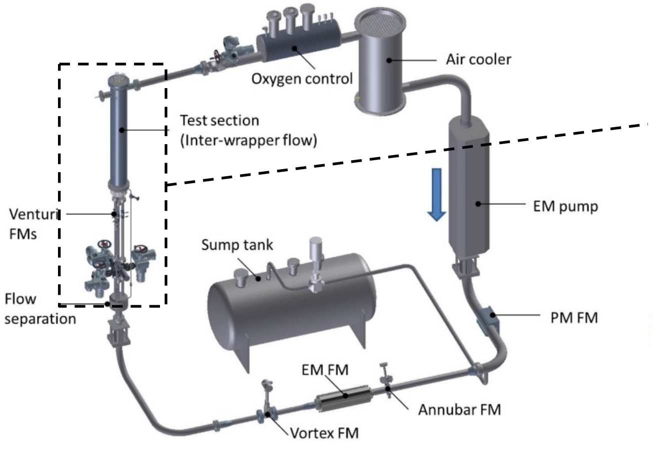
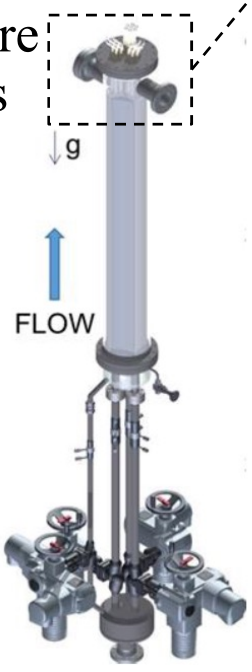
Problem solving approach | Data modelling | Code functional modelling | Detailed code design | Implementation / Verification | **Validation**

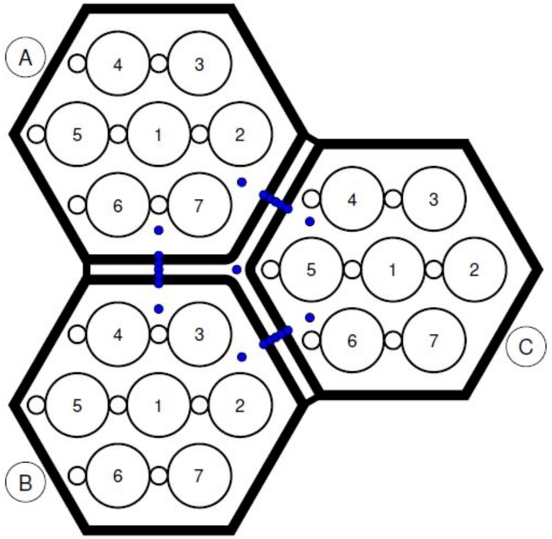
Quantity	Unit	Value	Meaning
Outer dimensions			
FF	mm	65.00	Outer flat-to-flat distance
w	mm	2.0	Wall thickness
δ	mm	3.0	Gap width
Bundle dimensions			
D	mm	16.0	Rod diameter
L_{heat}	mm	600.0	Rod heated length
L_{tot}	mm	1400.0	Rod total length
P	mm	20.50	Rod pitch
d	mm	4.40	Wire diameter
H	mm	262.0	Wire pitch
W	mm	20.75	Wall distance
Ratios			
P/D	-	1.281	Pitch-to-diameter
H/D	-	16.375	Wire pitch-to-diameter
W/D	-	1.297	Wall-distance-to-diameter
Flow areas			
A_{bdl}	mm^2	1704.2	Bundle cnannels (A-C)
A_{int}	mm^2	73.6	Bundle internal sub-channels
A_{edge}	mm^2	152.9	Bundle edge sub-channels
A_{corner}	mm^2	57.5	Bundle internal sub-channels
A_{gap}	mm^2	331.9	Gap channel (D)
Hydraulic diameters			
$d_{h,bdl}$	mm	10.31	Bundle channels (A-C)
$d_{h,int}$	mm	9.1	Bundle internal sub-channels
$d_{h,edge}$	mm	11.6	Bundle edge sub-channels
$d_{h,corner}$	mm	9.1	Bundle internal sub-channels
$d_{h,gap}$	mm	5.85	Gap channel (D)

- KALLA inter-wrapper flow experiment in SESAME project
- Three 7-pin bundles including inter-wrapper channels
- Axial and radial temperature and velocity measurements available









Overview on validation dataset

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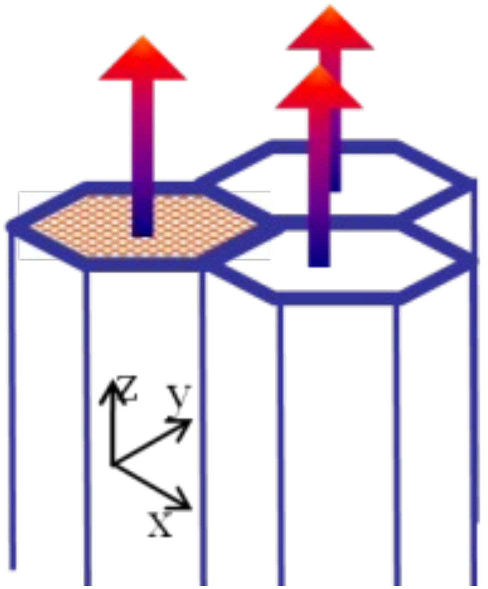
Problem solving approach | Data modelling | Code functional modelling | Detailed code design | Implementation / Verification | **Validation**

- Both **symmetric** and **asymmetric** cases performed
- Flow conditions: laminar/turbulent
- Heat flux boundary conditions: from **three standalone ANTEO+runs** (one for each FA) with total power to IW rescaled to match measured power
- Mixed convection solution

Nominal conditions:

Quantity	Unit	Value	Meaning	Notes
$\dot{m}$	kg/s	0.686	Inlet mass flow rate	
T_{in}	°C	199.25	Inlet LBE temperature	
q_{tot}	kW	3.700	Total power to IW flow	
q''	kW/m^2	$f(z)$	Surface heat flux	From ANTEO+

Note: the code can simulate also other LMs (e.g. Na), therefore other validation cases considering these fluids can be considered in the future.



<u>Acknowledgement</u>: access to SESAME dataset courtesy of Dr. M. Tarantino, access to full dataset courtesy of Dr. J. Pacio.

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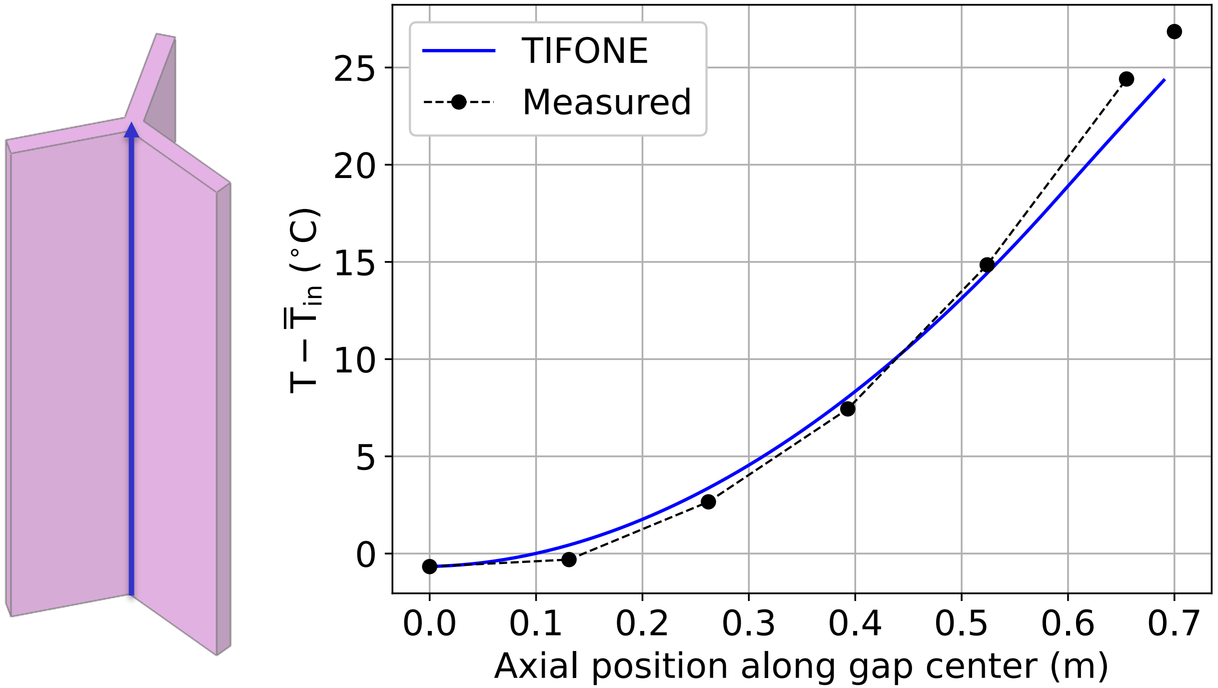
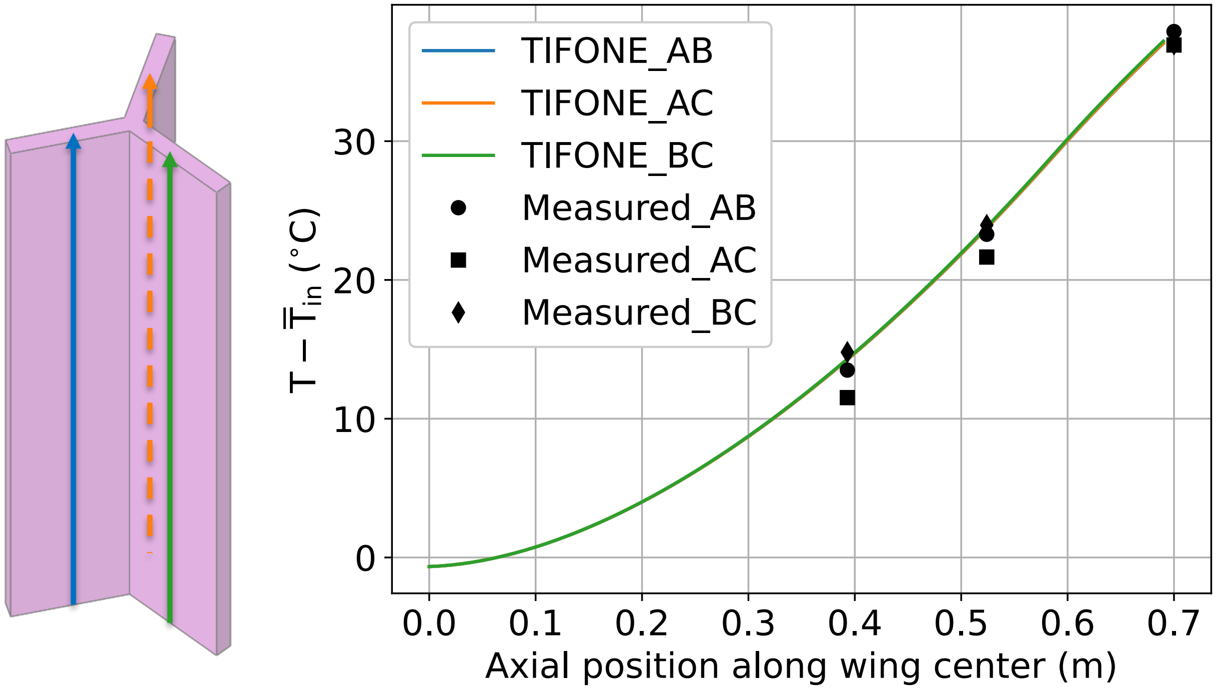
Symmetric validation cases

Quantity	Unit	Case 1	Case 3	Case 6	Case 8
$\dot{m}$ – **IW mass flow rate**	kg/s	**0.686**	**0.517**	**0.342**	**0.17**
$\dot{m}_A \sim \dot{m}_B \sim \dot{m}_C$	kg/s	3.55	3.55	3.55	3.55
q_{tot} – **Total power to IW flux**	kW	3.700	3.010	2.160	1.170
$q_A \sim q_B \sim q_C$	kW	30.00	30.00	30.00	30.00
T_{in} – **Inlet LBE temperature**	˚C	199.25	199.20	199.10	199.10

Note: here and thereafter, uncertainties on measured quantities are not indicated for the sake of clarity

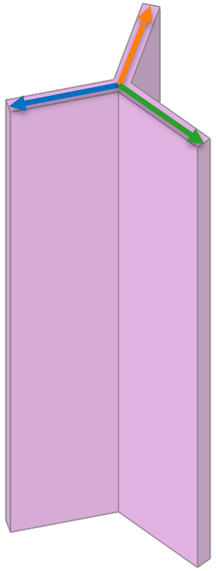
Symmetric case #1: axial temperature profiles

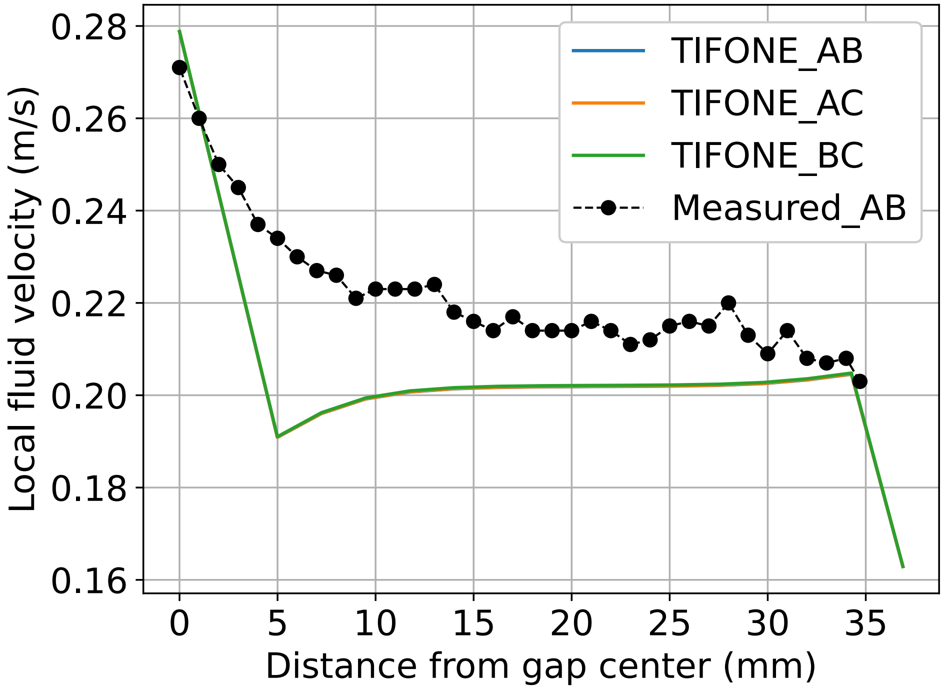


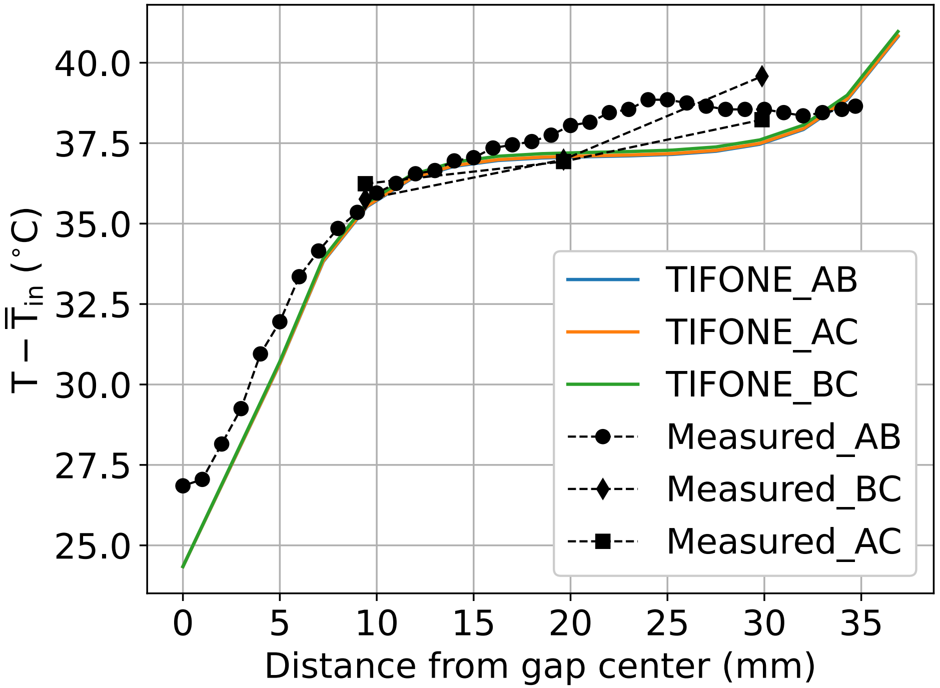


Symmetric case #1: radial temperature profiles

- Satisfactory agreement on velocity profile
  - To be assessed: local measurements, but averaged quantities per SC computed
- Very good agreement on radial coolant temperature distribution
- To be confirmed by considering a case with larger number of SAs







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Symmetric case #1: wrapper temperatures

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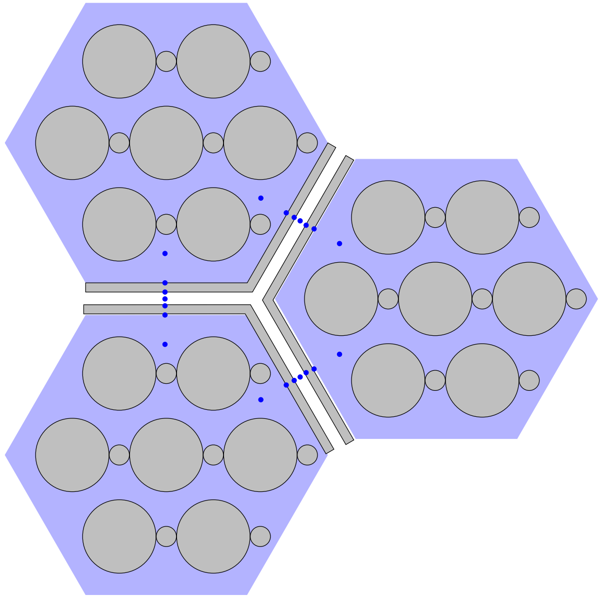
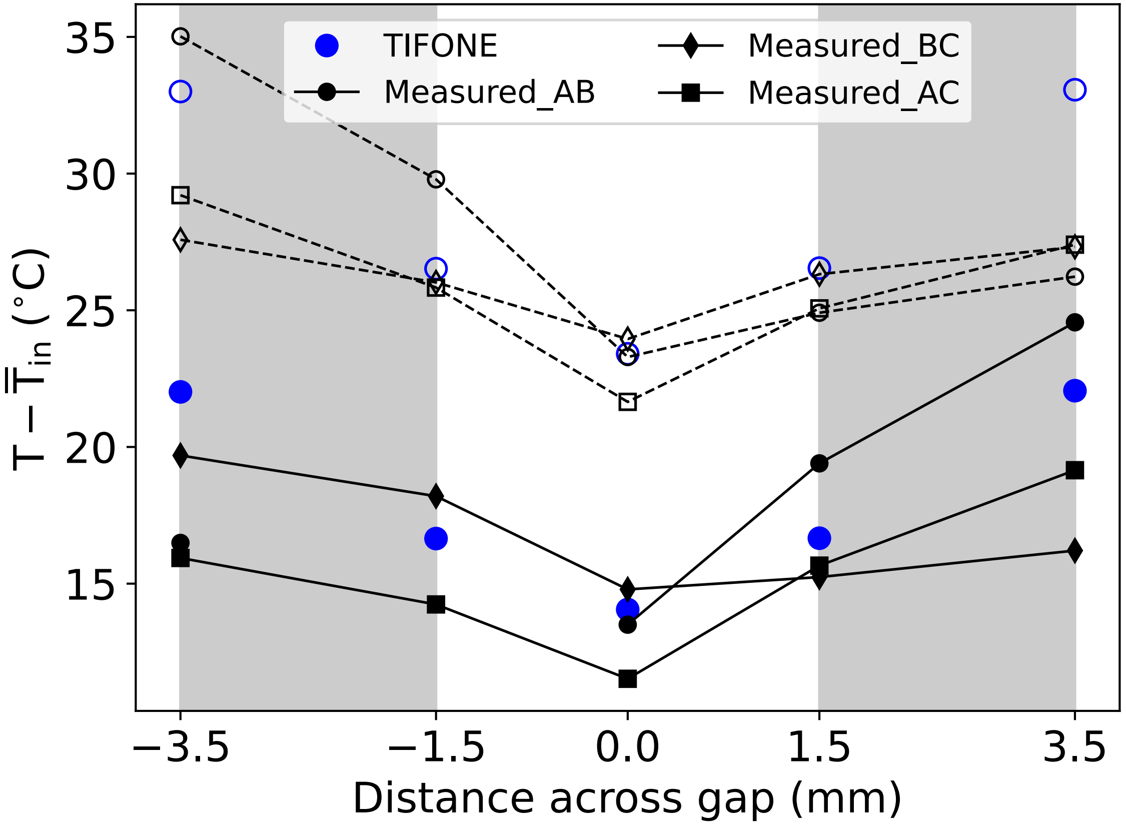
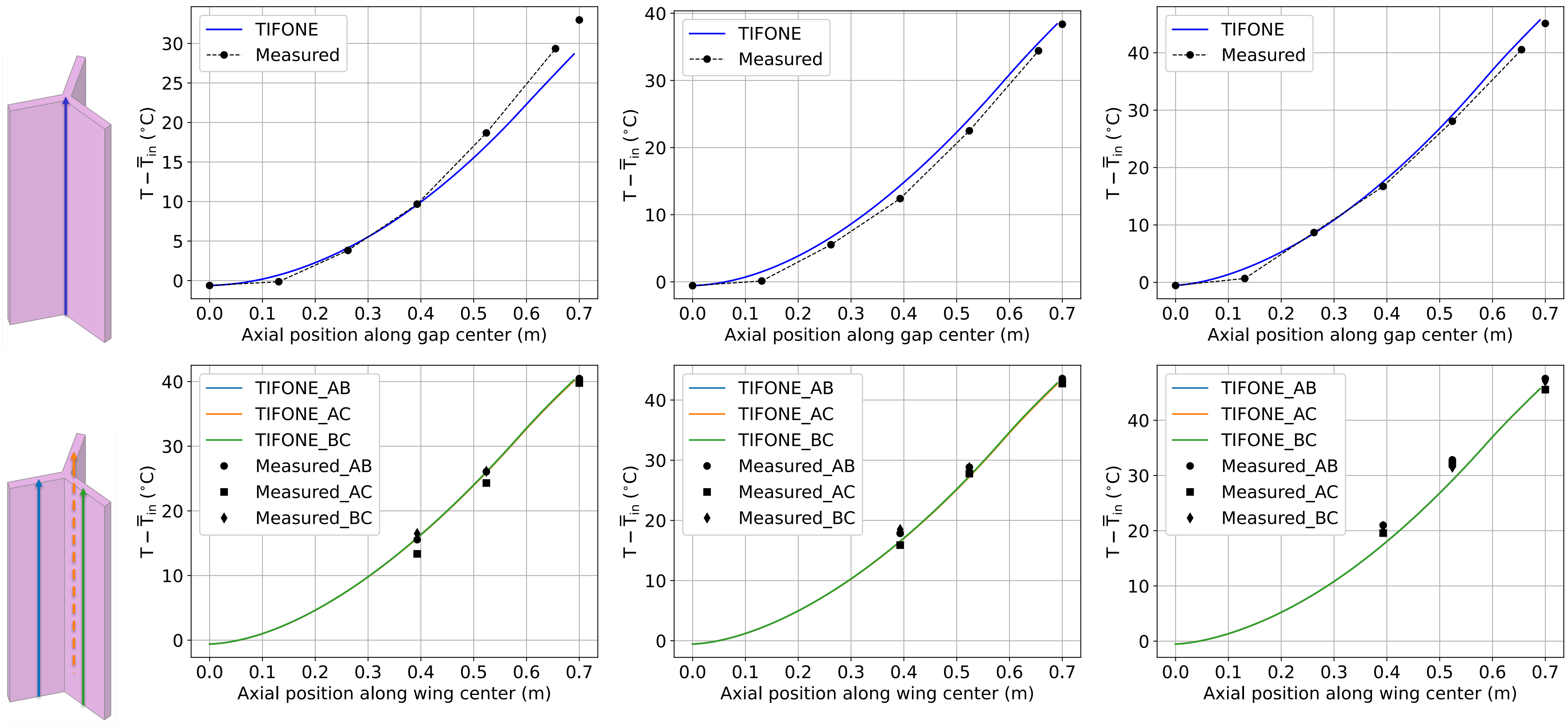




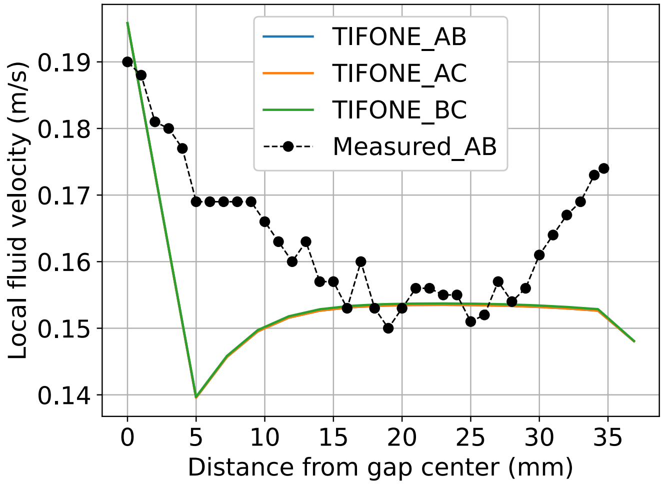
Symmetric cases #3,6,8: axial temperature profiles

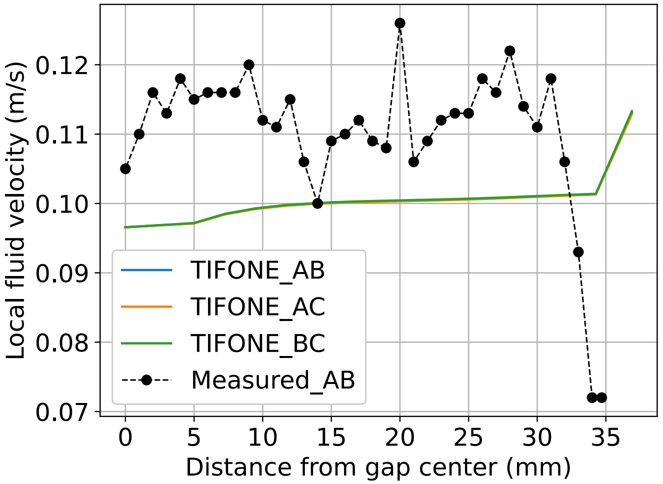


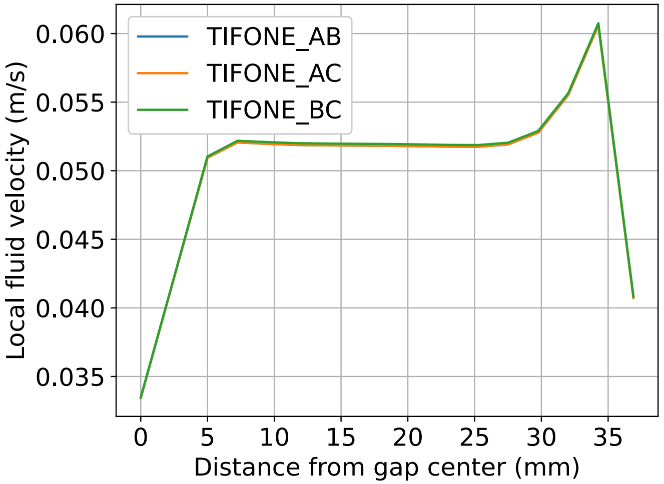
Symmetric cases #3,6,8: radial velocity and temperature profiles

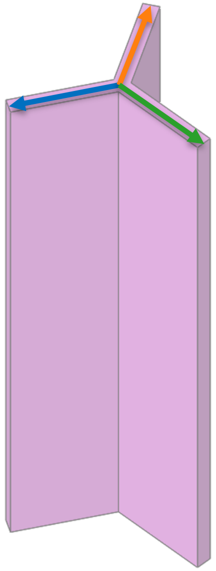
$\dot{m}_{IW}$ reduced

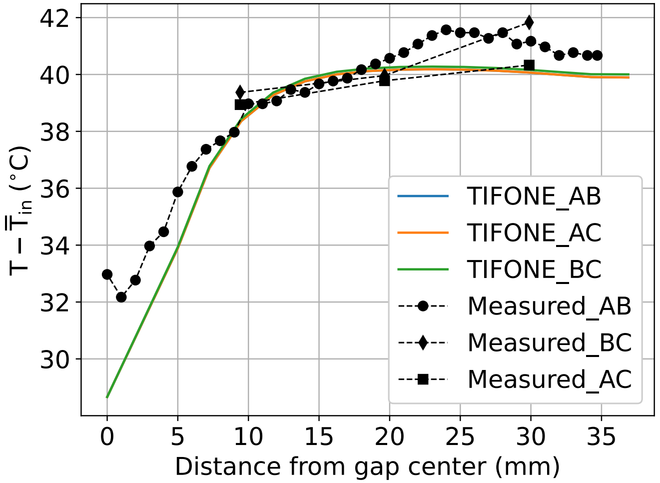
#3: $Y_{mix} = 0.0031$ | #6: $Y_{mix} = 0.0045$ | #8: $Y_{mix} = 0.0087$

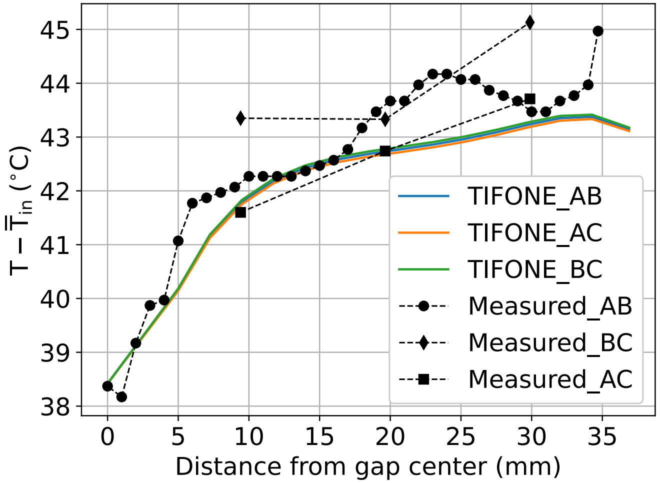


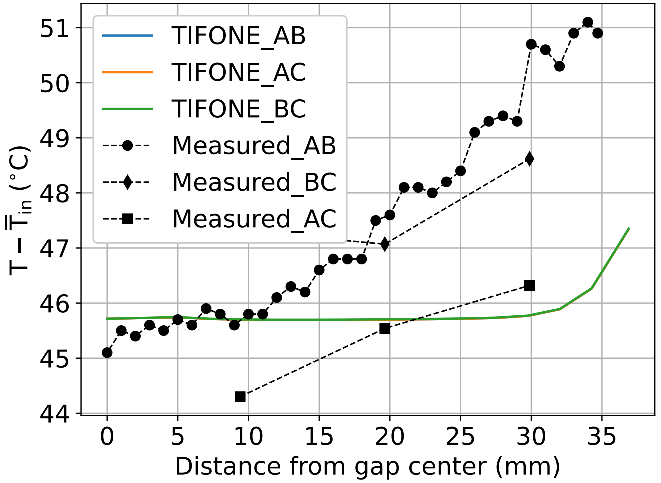












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Aymmetric validation cases: reduced flow rate in C by 20%

Quantity	Unit	Case 1	Case 3	Case 6	Case 8
$\dot{m}$ – IW mass flow rate	kg/s	**0.686**	**0.517**	**0.342**	**0.17**
$\dot{m}_A \sim \dot{m}_B$	kg/s	3.55	3.55	3.55	3.55
$\dot{m}_C$	kg/s	**2.86**	**2.86**	**2.86**	**2.86**
q_{tot} – Total power to IW flux	kW	3.700	3.010	2.160	1.170
$q_A \sim q_B \sim q_C$	kW	30.00	30.00	30.00	30.00
T_{in} – Inlet LBE temperature	˚C	199.25	199.20	199.10	199.10

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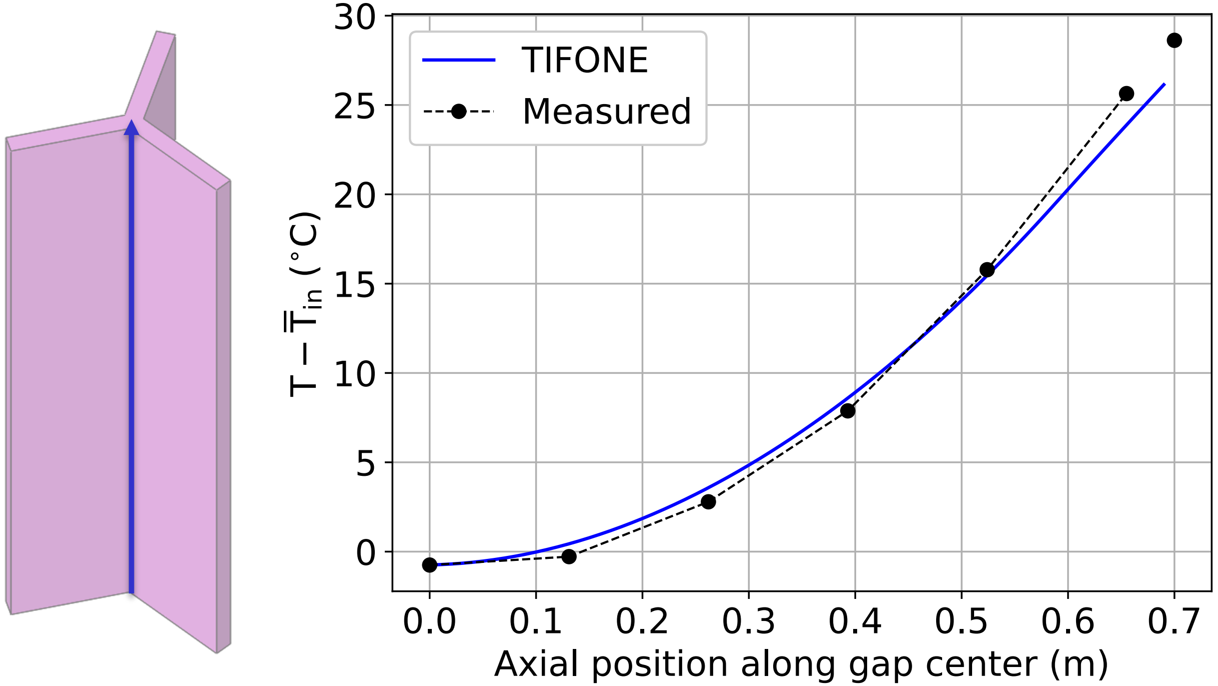
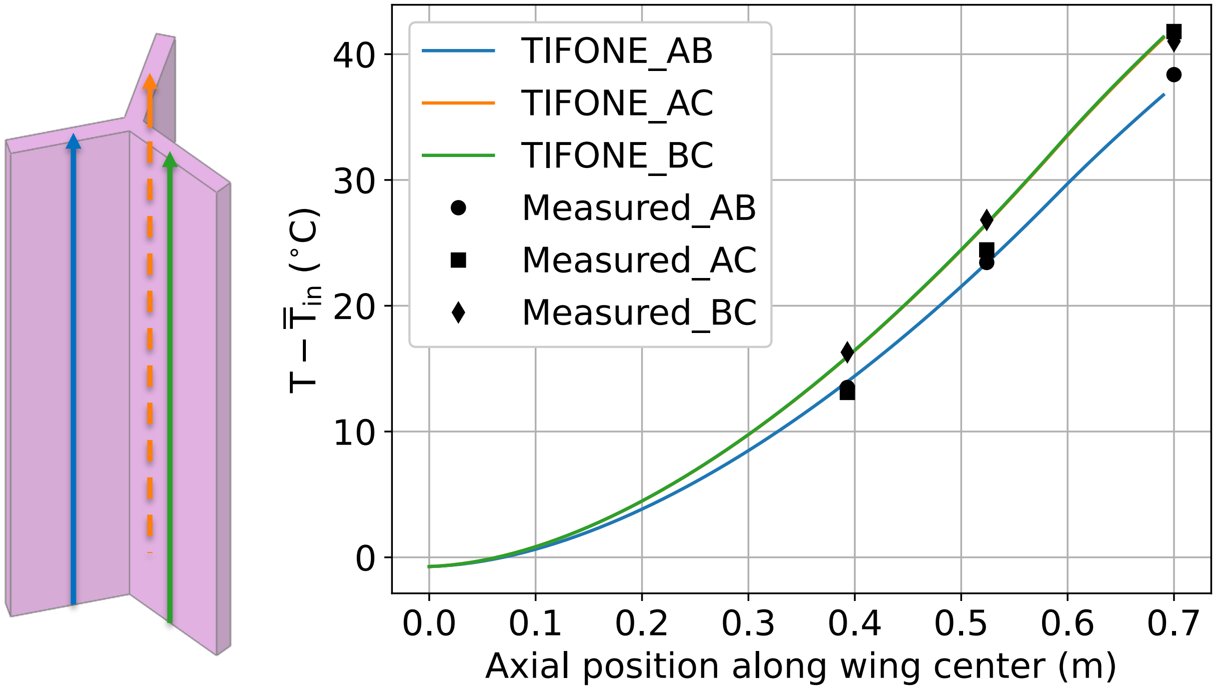
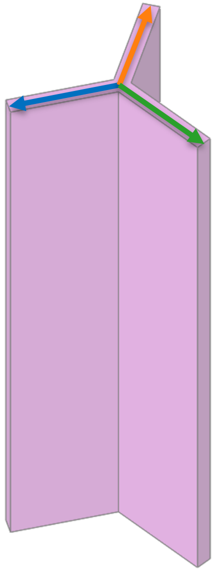
Asymmetric case #42: axial temperature profiles

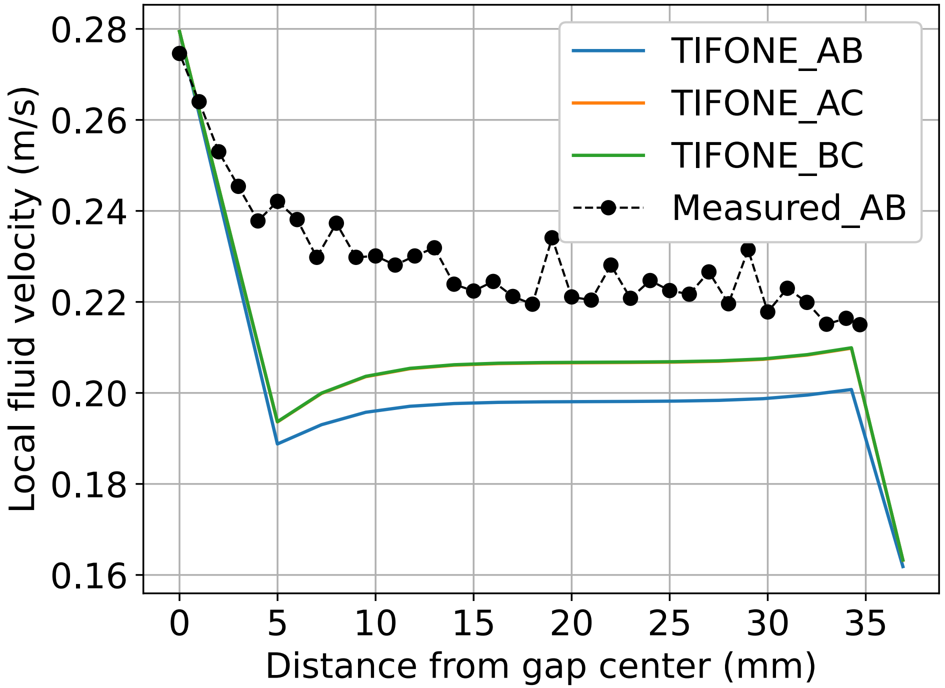


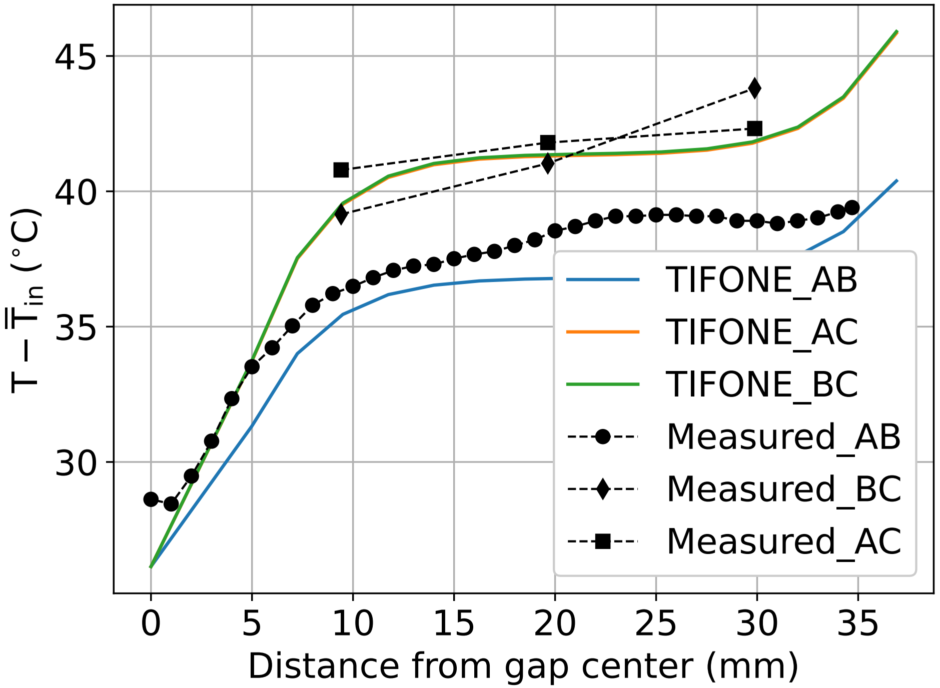


Asymmetric case #42: radial temperature profiles

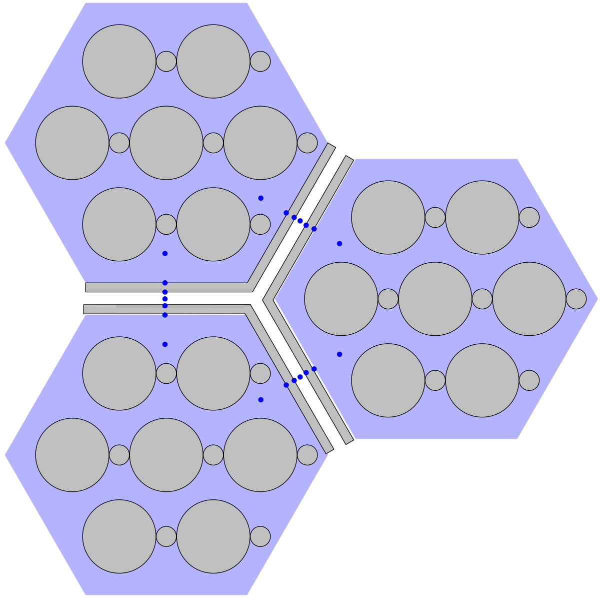
- Satisfactory agreement on velocity profile
  - To be assessed: local measurements, but averaged quantities per SC computed
- Very good agreement on radial coolant temperature distribution
- To be confirmed by considering a case with larger number of SAs

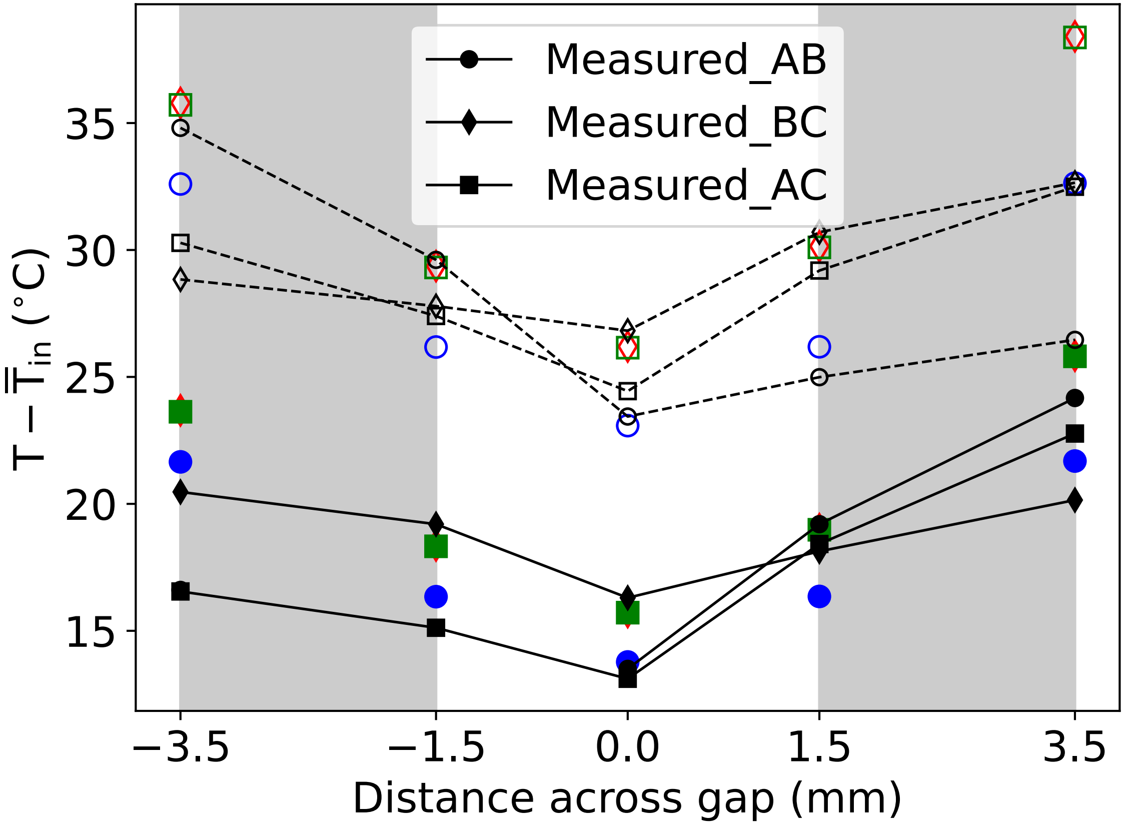






Asymmetric case #42: wrapper temperatures





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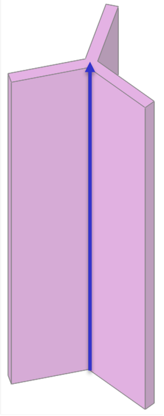
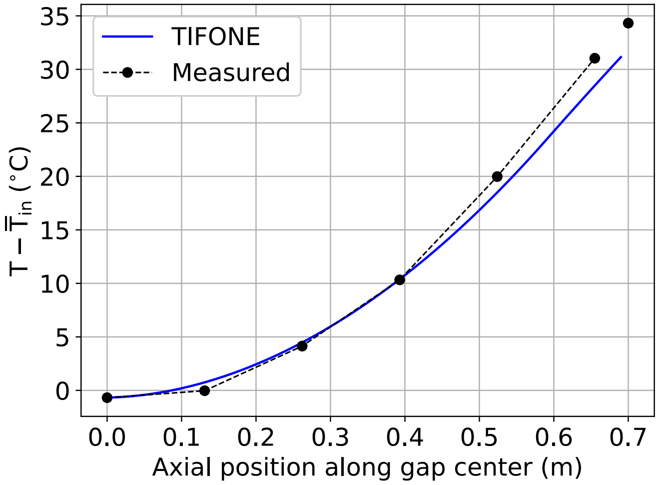
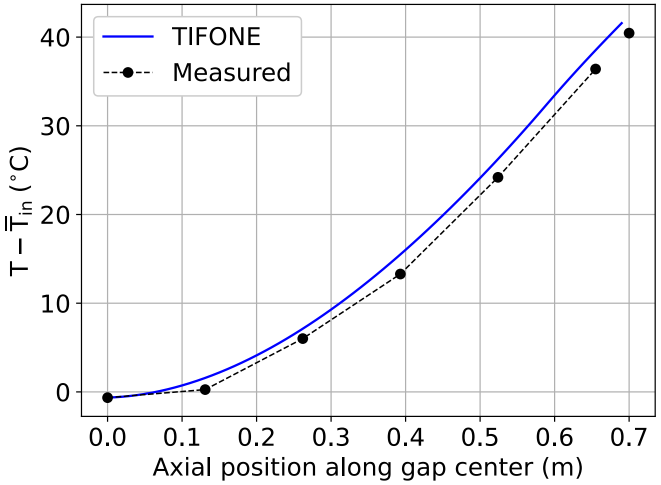
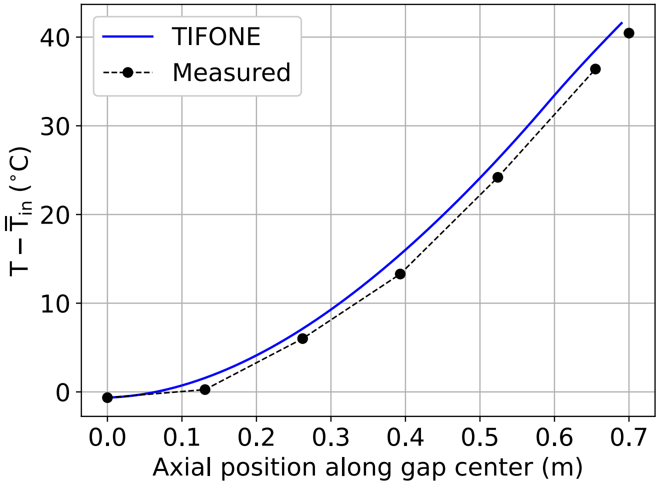
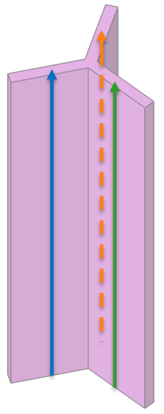
Asymmetric cases # 45,48,51: axial temperature profiles

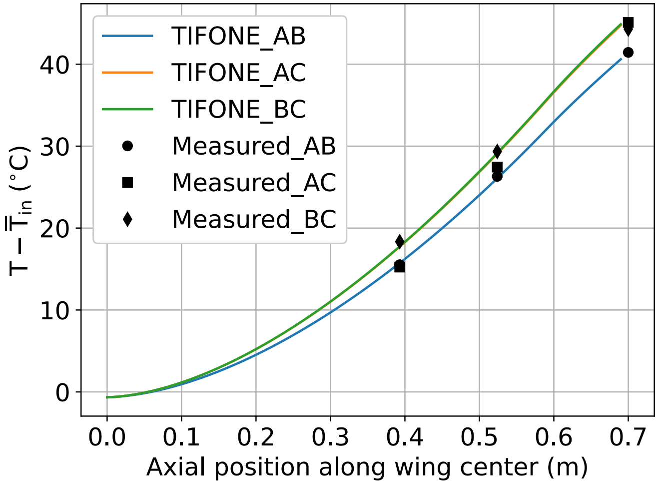


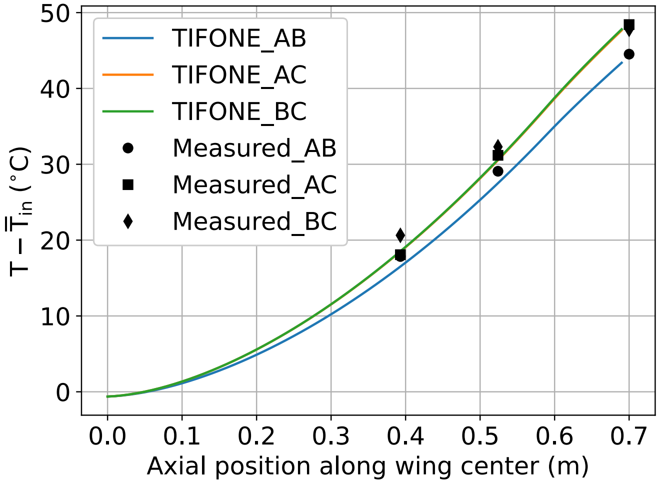


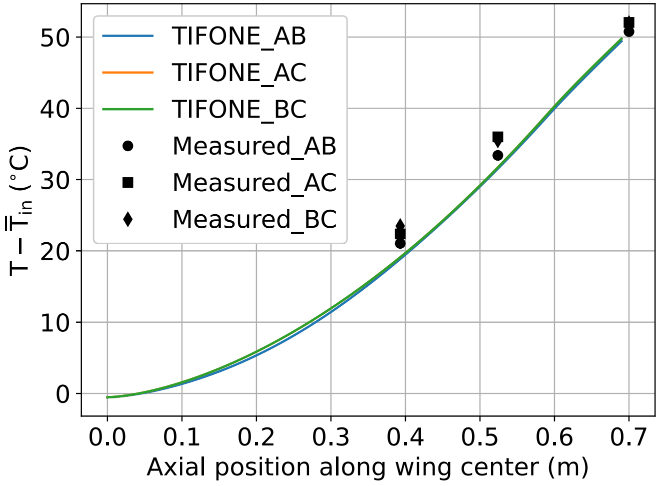












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Asymmetric cases # 45,48,51: axial temperature profiles

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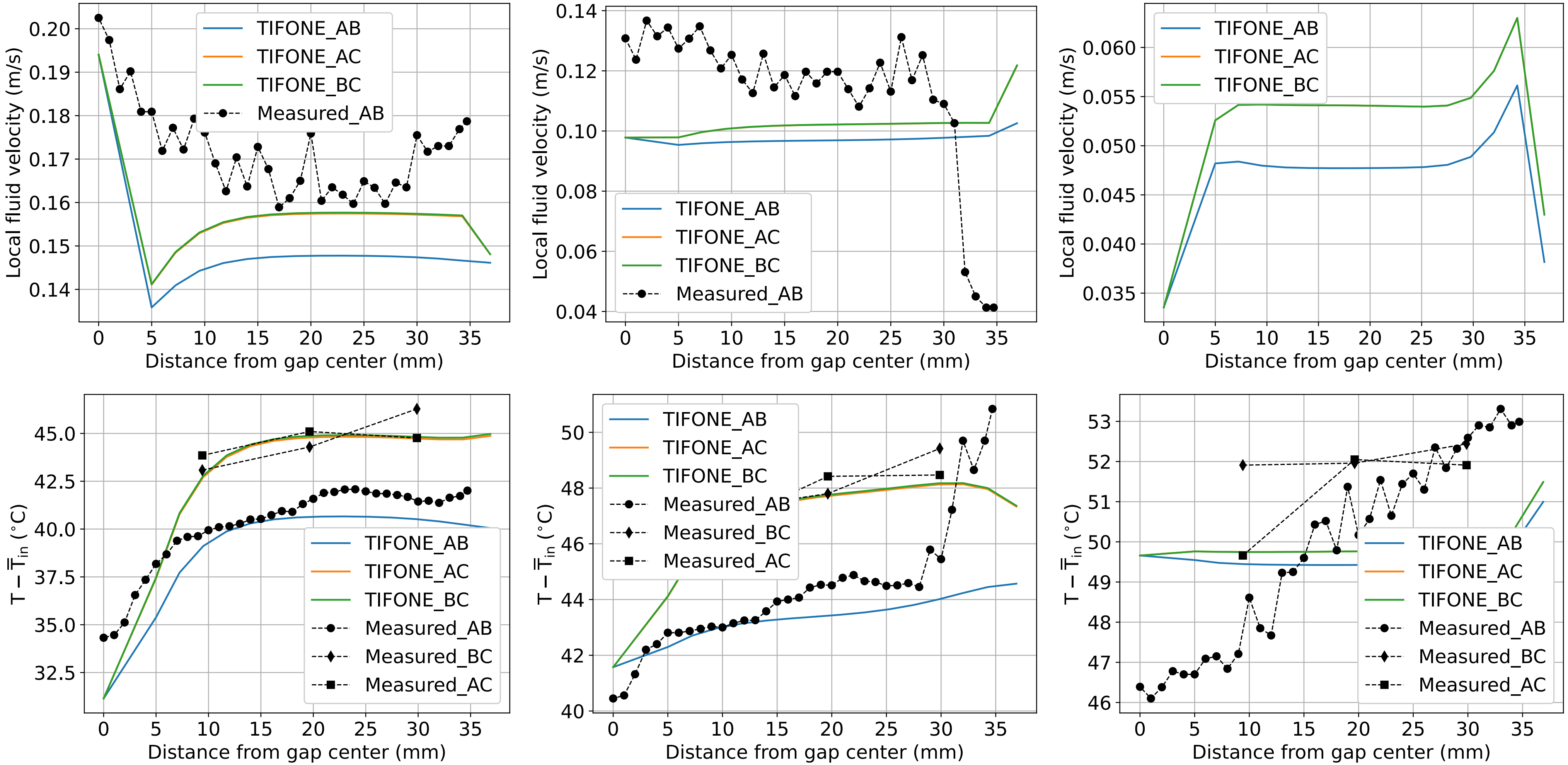
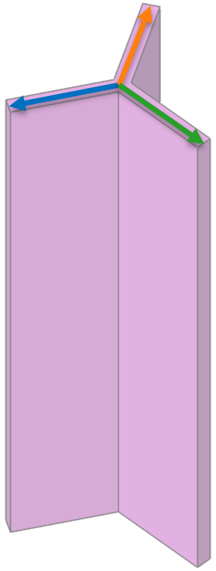
$\dot{m}_{IW}$ reduced

#3: $Y_{mix} = 0.0038$ | #6: $Y_{mix} = 0.0056$ | #8: $Y_{mix} = 0.010$





Conclusions and perspective

- Conclusions:
  - A new DOC, TIFONE, was developed for the SC analysis of the IW flow and heat transfer in (H)LMCRs
  - Code development was performed according to ENEA Software Quality Assurance Procedures
  - Validation against KALLA experimental data shows promising results, which degrade towards the free convection

- Ongoing activities:
  - Benchmark against CFD (porous medium approach) for ATHENA core simulator
  - Inclusion in the ENEA DOC suite (e.g. to be coupled with ANTEO+)
- In perspective:
  - More validation data are needed to qualify the capabilities of the code in more reactor-relevant scenarios (e.g. ATHENA, CLEAR-S)
  - Empirical correlations for ε_{ij} and κ_{ij} might be derived from CFD calculations

Thanks for your kind attention

Backup slides

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Nuclear fission reactors generations

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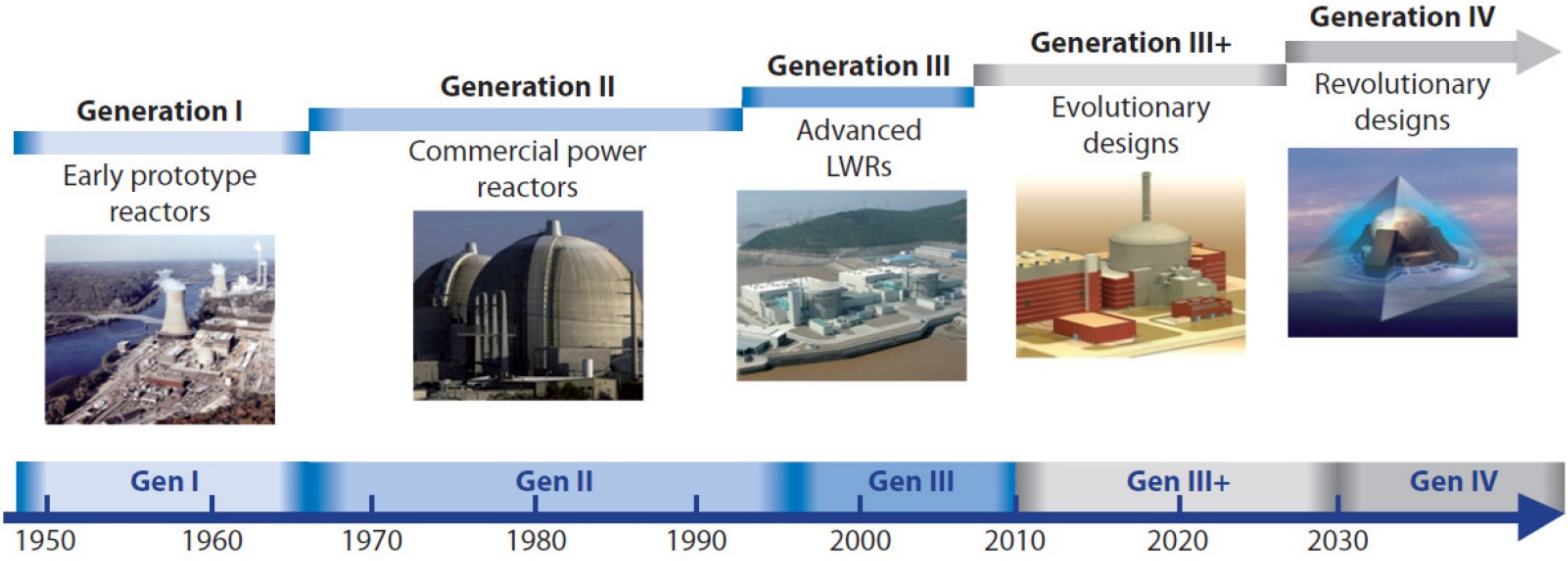

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Generation-IV fission reactors

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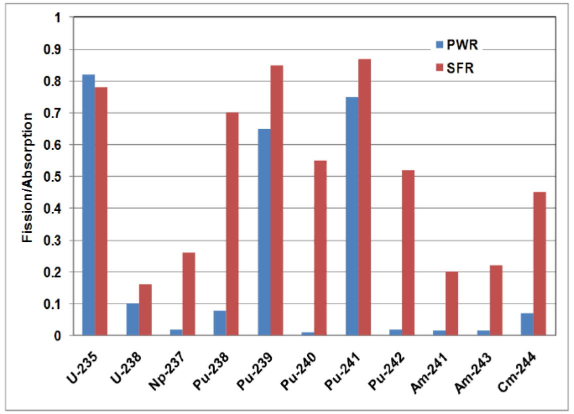
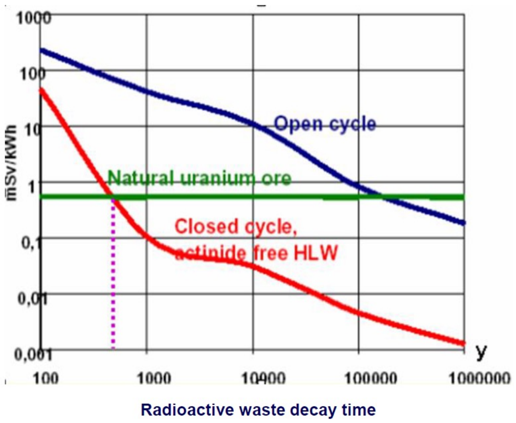
- GIF objectives:
  - Sustainability
    - Improve **fuel utilization**
    - **Minimize long-term waste**
  - Economics
    - Reduce life cycle costs
    - Minimize financial risks
  - Safety and reliability:
    - Operational **safety** and reliability
    - Reduced core damage probability
    - Eliminate need for off-site power response
  - Proliferation resistance
- 6 potential reactor designs being considered

$$\frac{\int \sigma_f(E)\Phi(E)dE}{\int \Phi(E)dE} \Big/ \frac{\int \sigma_a(E)\Phi(E)dE}{\int \Phi(E)dE}$$





- Fast reactors:
  - Burn **MAs** → reduce long-term radiotoxicity
  - Breed fuel → fuel utilization efficiency
  - Low moderation → need large fissile inventory
  - Harsh neutron damage (higher burnup, harder spectrum)

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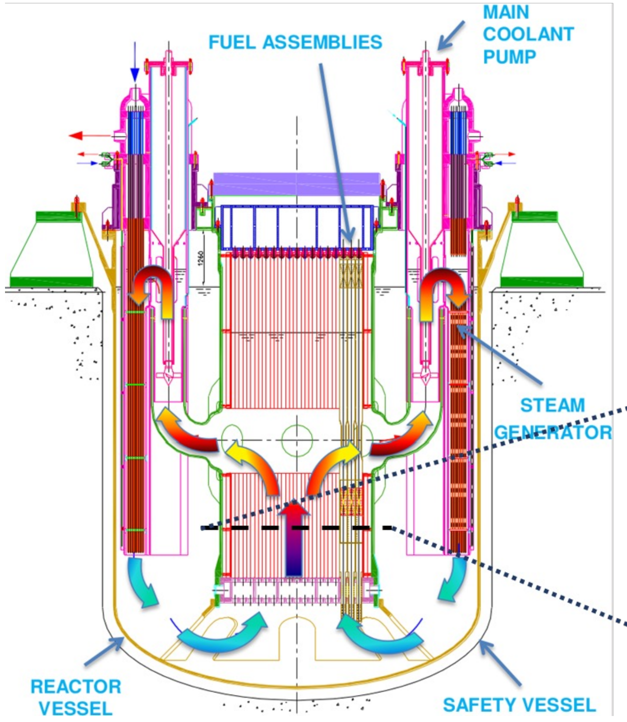
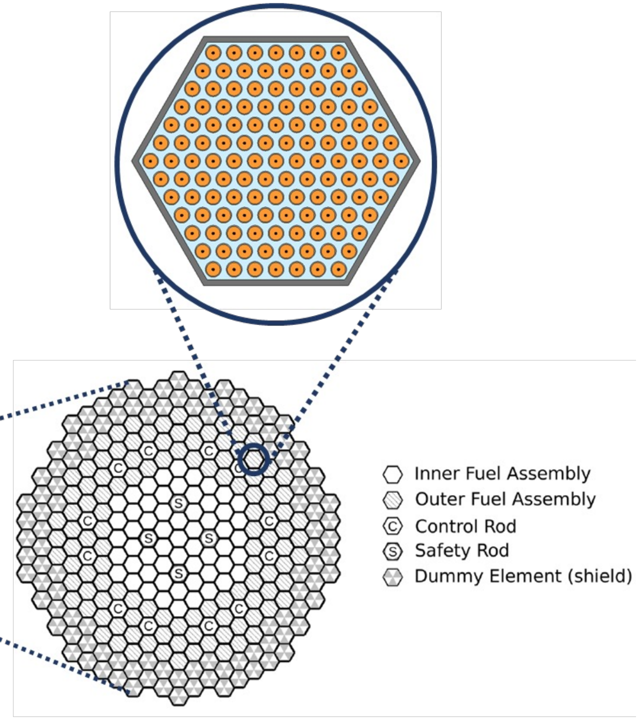
HLMCRs: advantages and challenges

- Features of HLMCRs:
  - High core outlet temperature: thermal efficiency ↑
  - Large **margin to boiling**:
    - No need for pressurization
    - No core voiding
  - Low reactivity with air and water (vs. SFR)
  - High heat transfer capability
  - High coolant density
    - **natural circulation** for decay heat removal
    - Strong coolant-structure interactions
  - Corrosion/erosion of structures
  - Risk of coolant freezing
  - Difficult inspection (coolant opacity)





- Advanced Lead-cooled Fast Reactor European Demonstrator (ALFRED)

Coolant inlet T	673 K
Maximum fuel T	~2270 K
Maximum core Δp	100 kPa
Total electric power	~120 MWe
System efficiency	~40 %

Asymmetric validation cases: unheated bundle A

011	199.2 ± 0.2	3.58 ± 0.07	3.58 ± 0.07	3.56 ± 0.07	0.69 ± 0.01	0.00 ± 0.00	30.00 ± 0.30	30.00 ± 0.30	232.1 ± 0.2
012	199.2 ± 0.2	3.58 ± 0.07	3.58 ± 0.07	3.56 ± 0.07	0.69 ± 0.01	0.00 ± 0.00	30.00 ± 0.30	30.00 ± 0.30	231.9 ± 0.2
013	199.2 ± 0.2	3.59 ± 0.07	3.60 ± 0.07	3.57 ± 0.07	0.52 ± 0.01	0.00 ± 0.00	30.00 ± 0.30	30.00 ± 0.30	232.6 ± 0.2
014	199.2 ± 0.2	3.59 ± 0.07	3.60 ± 0.07	3.57 ± 0.07	0.52 ± 0.01	0.00 ± 0.00	30.00 ± 0.30	30.00 ± 0.30	232.7 ± 0.2
015	199.1 ± 0.2	3.59 ± 0.07	3.59 ± 0.07	3.57 ± 0.07	0.34 ± 0.01	0.00 ± 0.00	30.00 ± 0.30	30.00 ± 0.30	233.4 ± 0.2
016	199.1 ± 0.2	3.59 ± 0.07	3.59 ± 0.07	3.57 ± 0.07	0.34 ± 0.01	0.00 ± 0.00	30.00 ± 0.30	30.00 ± 0.30	233.4 ± 0.2
017	199.1 ± 0.2	3.60 ± 0.07	3.60 ± 0.07	3.57 ± 0.07	0.17 ± 0.00	0.00 ± 0.00	30.00 ± 0.30	30.00 ± 0.30	233.8 ± 0.2
018	199.1 ± 0.2	3.60 ± 0.07	3.60 ± 0.07	3.57 ± 0.07	0.17 ± 0.00	0.00 ± 0.00	30.00 ± 0.30	30.00 ± 0.30	233.6 ± 0.2

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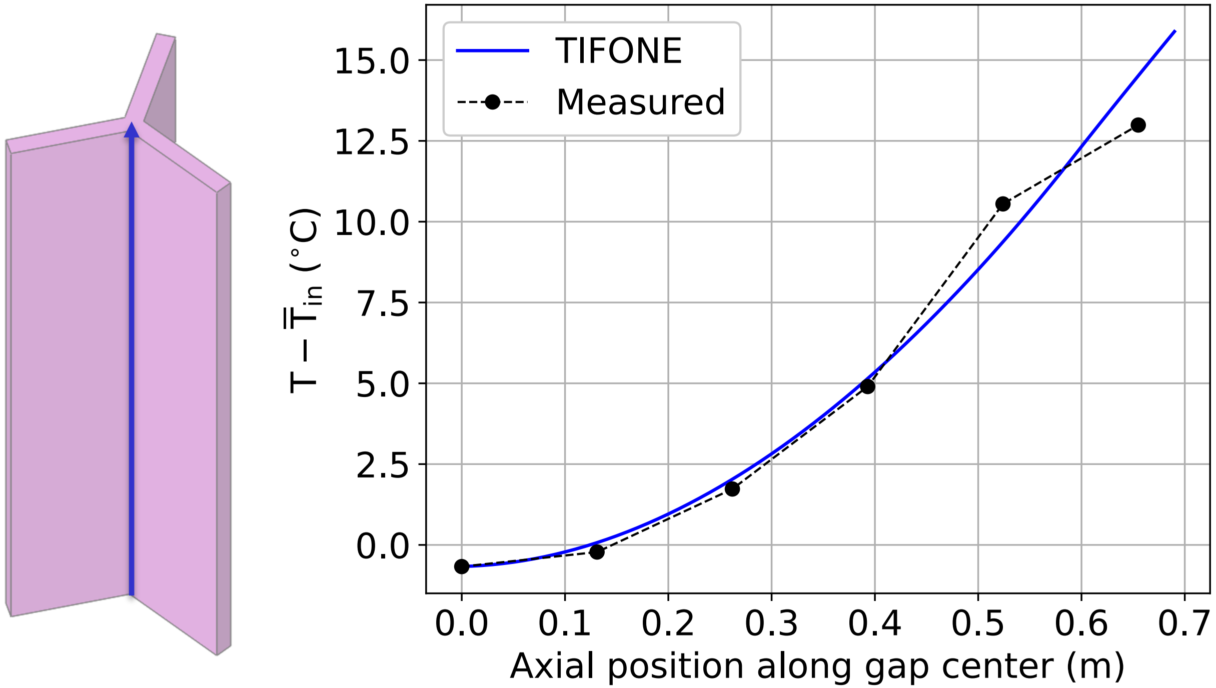
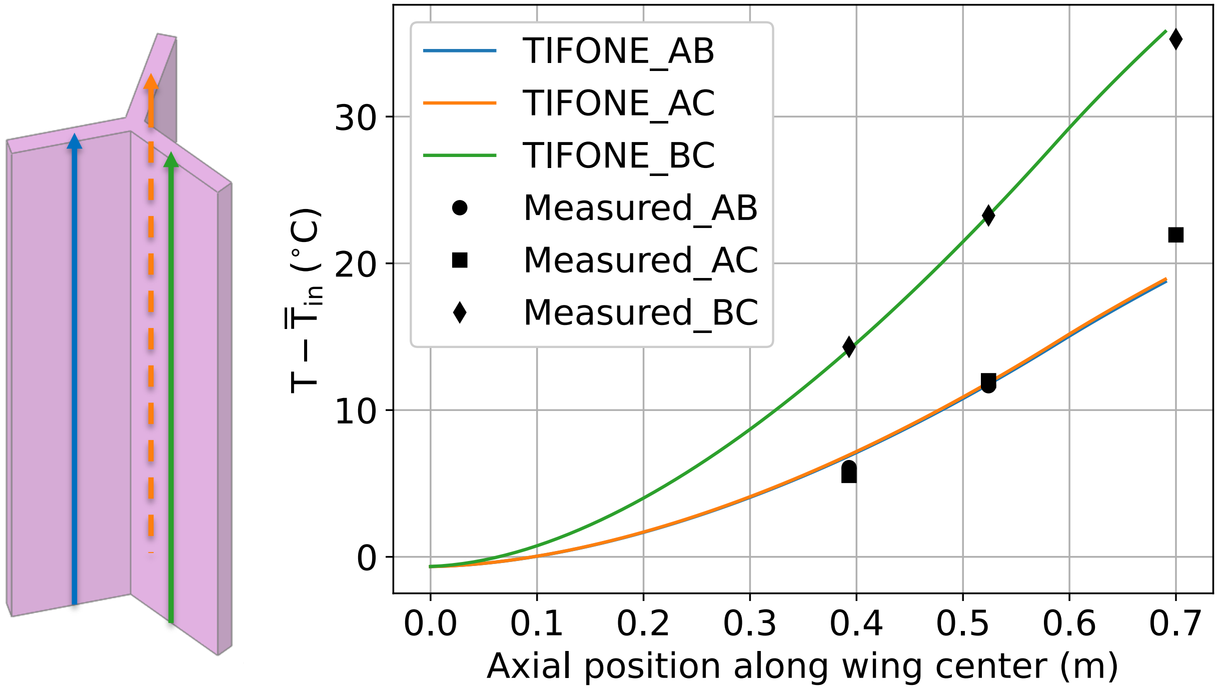
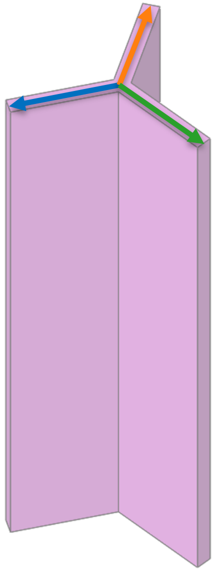
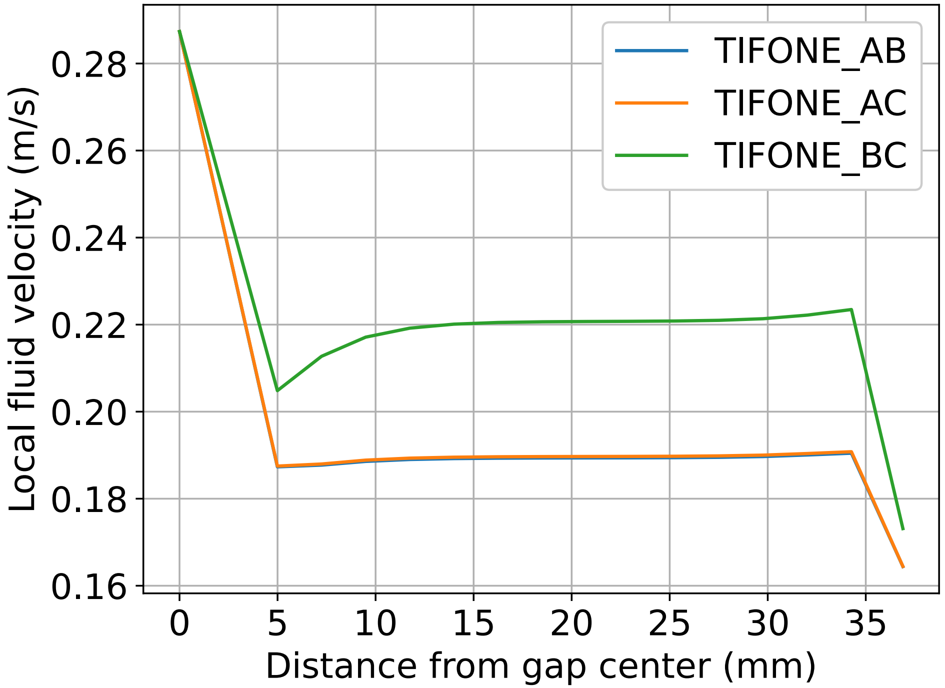
Asymmetric case #11: axial temperature profiles

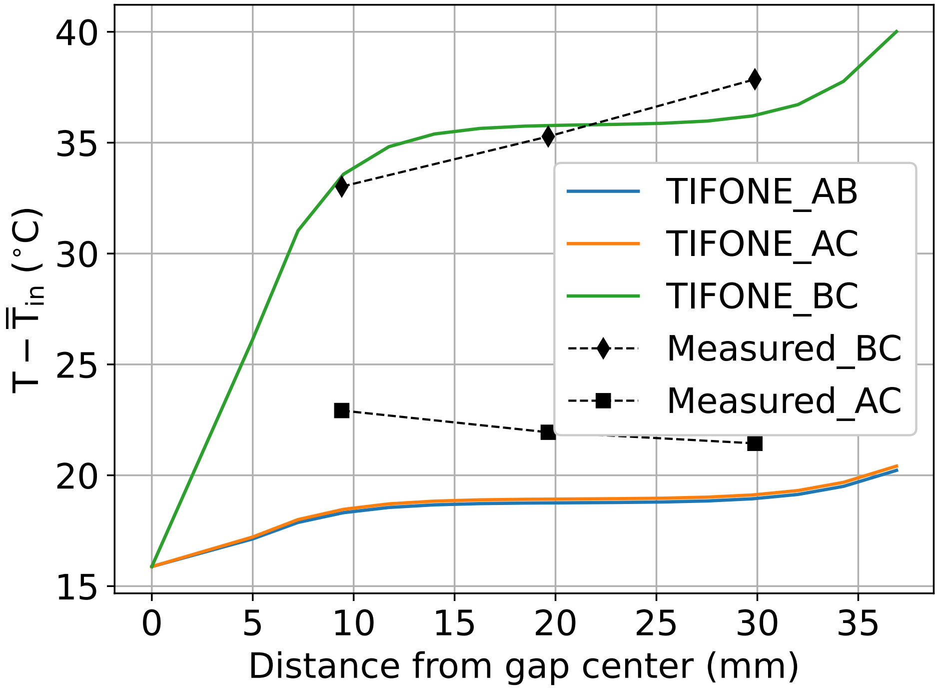




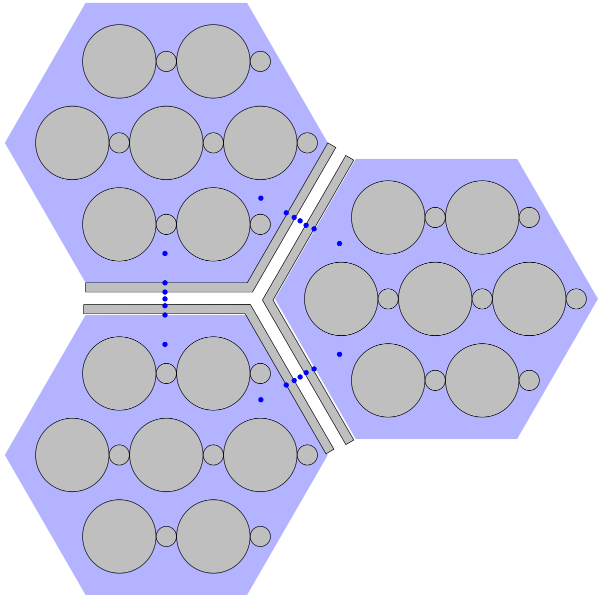
Asymmetric case #11: radial temperature profiles

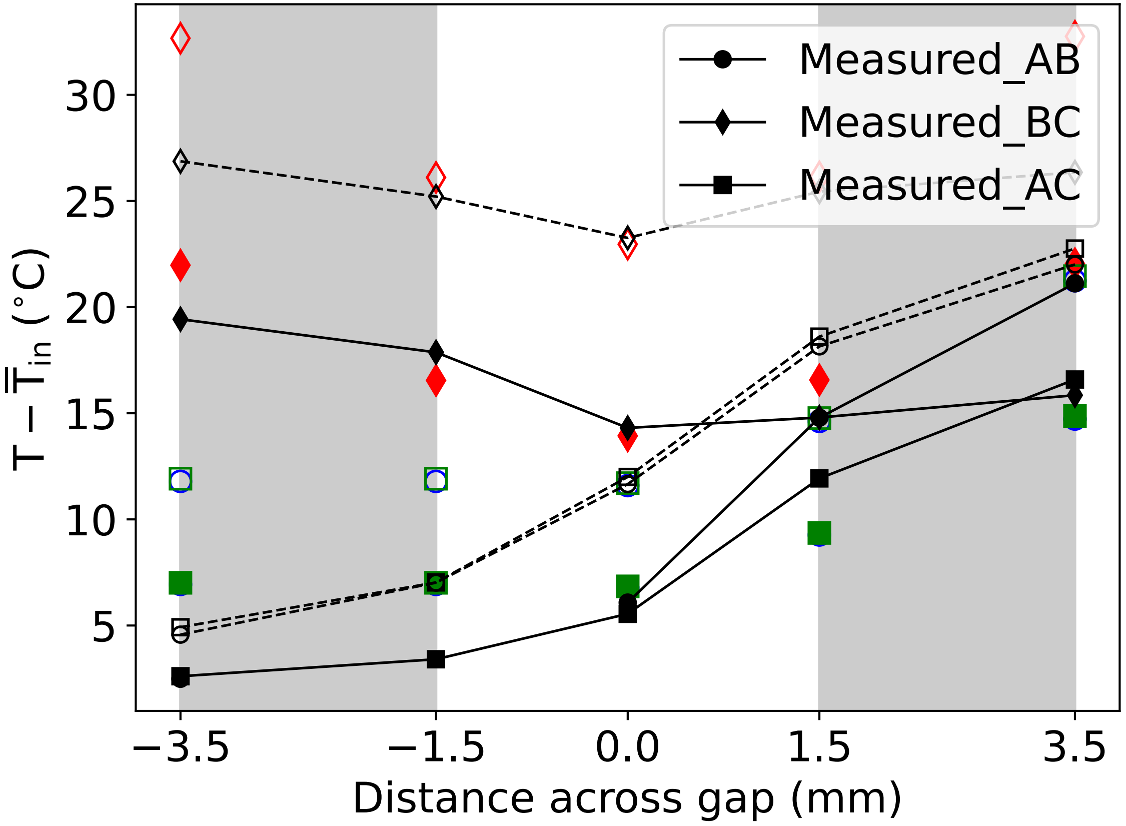




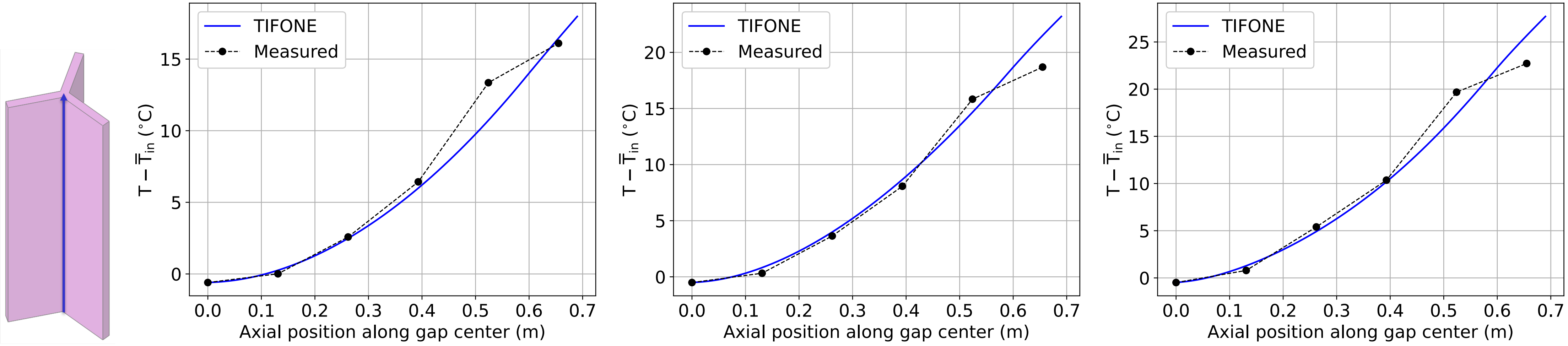


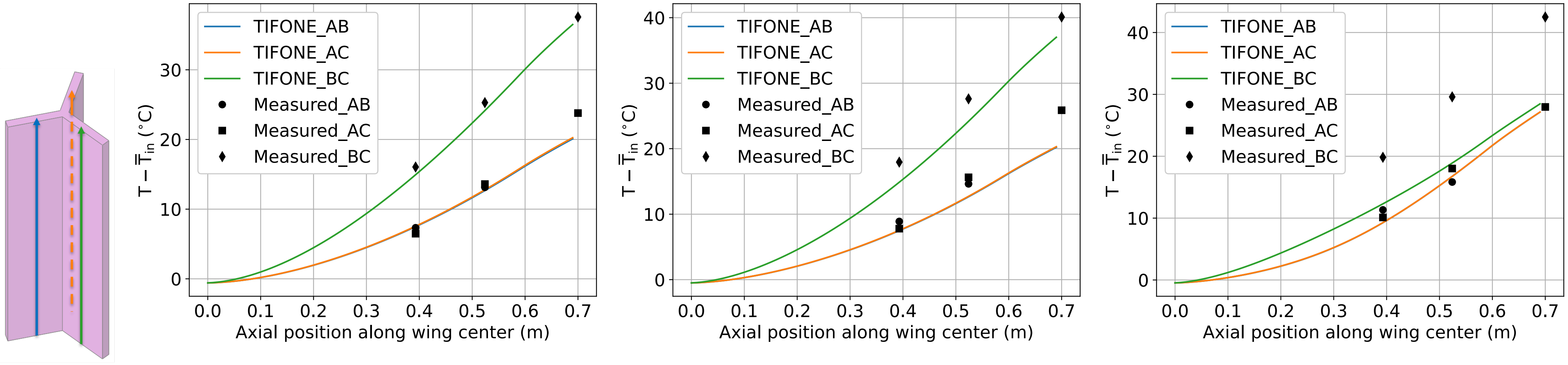
Asymmetric case #11: wrapper temperatures





Asymmetric cases # 13,15,17: axial temperature profiles





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Asymmetric cases # 13,15,17: radial velocity and temperature profiles

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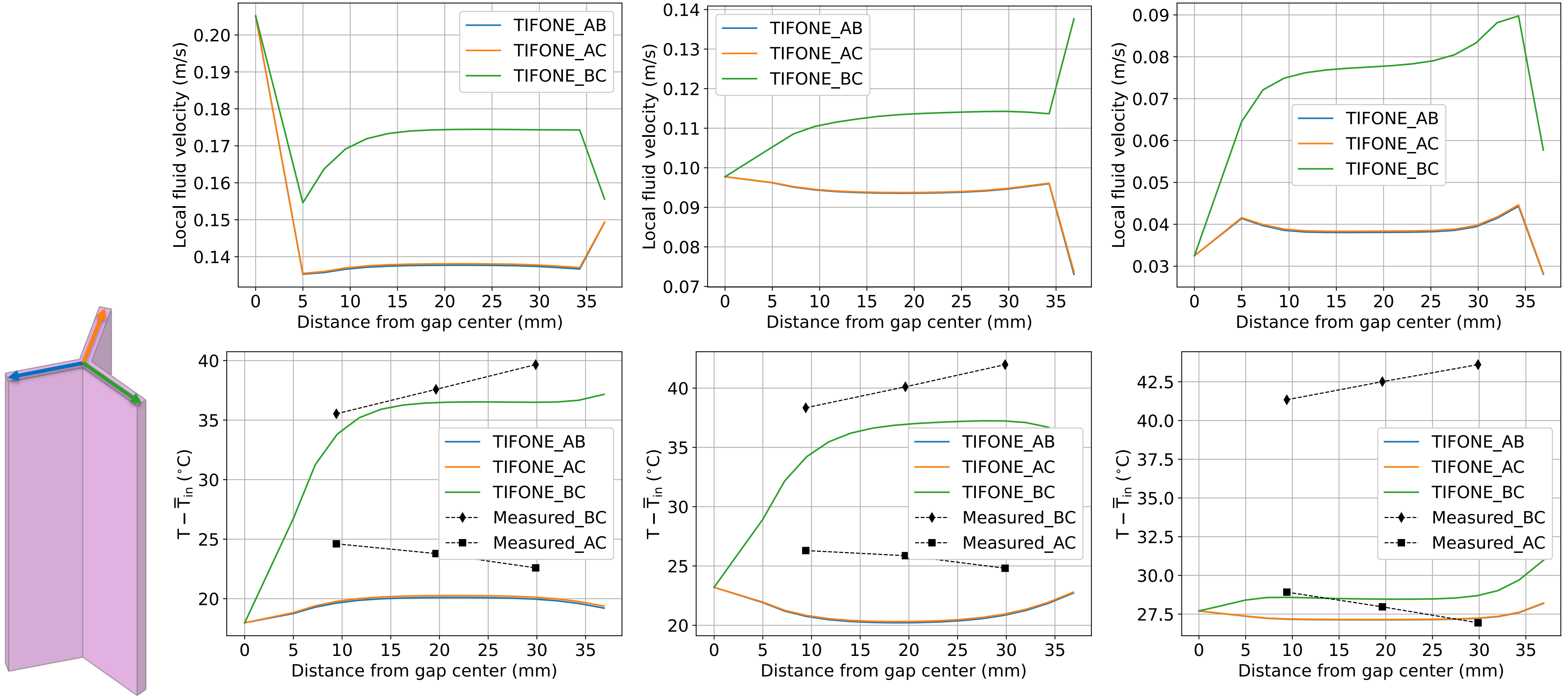
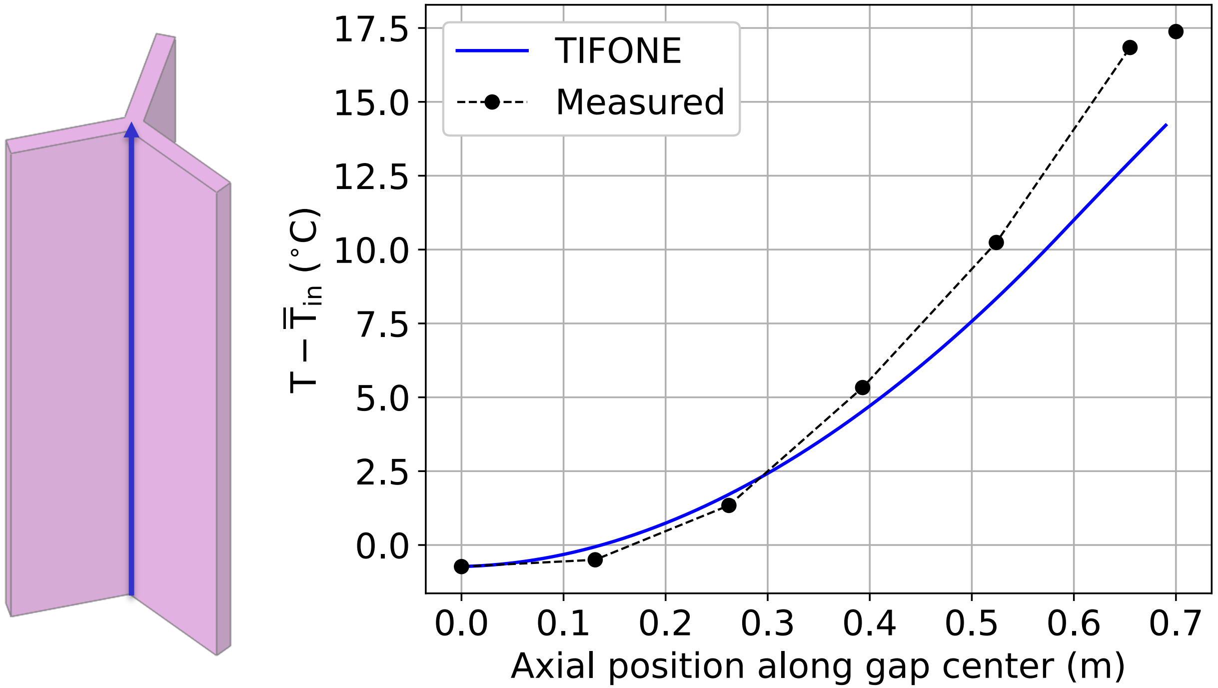


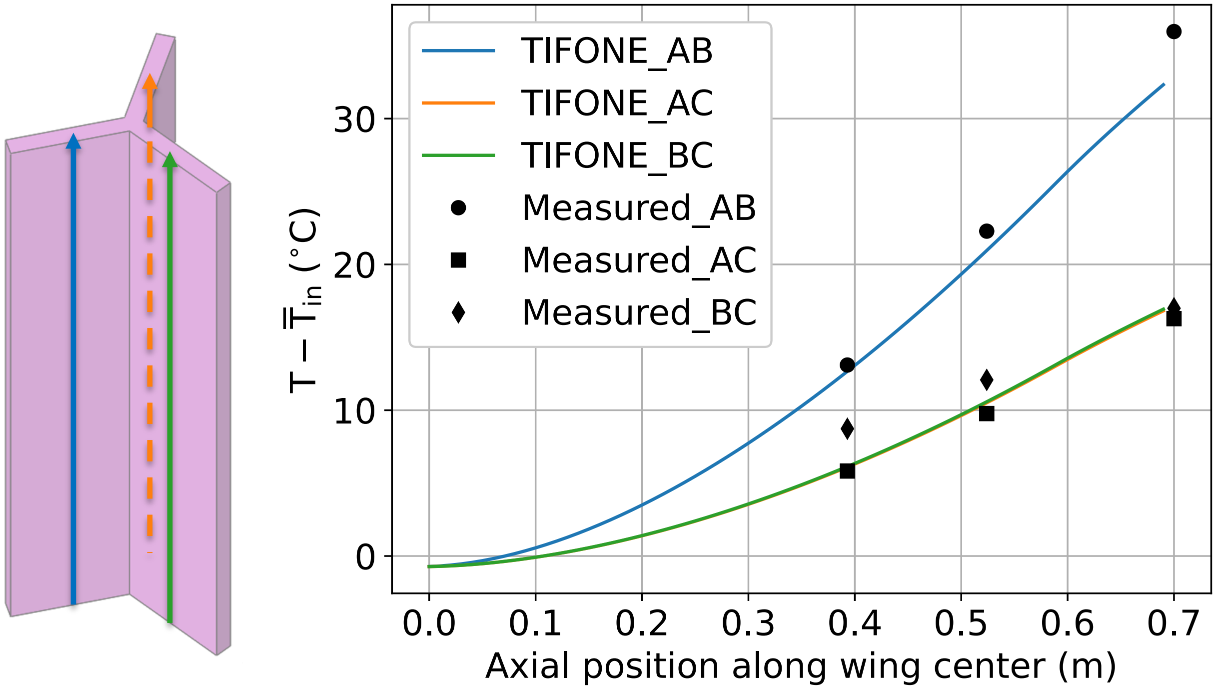
Aymmetric validation cases: unheated bundle C

031	199.2 ± 0.2	3.59 ± 0.07	3.58 ± 0.07	3.55 ± 0.07	0.69 ± 0.01	30.00 ± 0.30	30.00 ± 0.30	0.00 ± 0.00	231.8 ± 0.2
032	199.2 ± 0.2	3.60 ± 0.07	3.58 ± 0.07	3.55 ± 0.07	0.69 ± 0.01	30.00 ± 0.30	30.00 ± 0.30	0.00 ± 0.00	231.8 ± 0.2
033	199.1 ± 0.2	3.59 ± 0.07	3.59 ± 0.07	3.57 ± 0.07	0.52 ± 0.01	30.00 ± 0.30	30.00 ± 0.30	0.00 ± 0.00	232.1 ± 0.2
034	199.1 ± 0.2	3.59 ± 0.07	3.59 ± 0.07	3.57 ± 0.07	0.52 ± 0.01	30.00 ± 0.30	30.00 ± 0.30	0.00 ± 0.00	232.2 ± 0.2
035	199.1 ± 0.2	3.60 ± 0.07	3.59 ± 0.07	3.60 ± 0.07	0.34 ± 0.01	30.00 ± 0.30	30.00 ± 0.30	0.00 ± 0.00	232.2 ± 0.2
036	199.1 ± 0.2	3.60 ± 0.07	3.59 ± 0.07	3.60 ± 0.07	0.34 ± 0.01	30.00 ± 0.30	30.00 ± 0.30	0.00 ± 0.00	232.4 ± 0.2
037	199.1 ± 0.2	3.57 ± 0.07	3.57 ± 0.07	3.58 ± 0.07	0.17 ± 0.00	30.00 ± 0.30	30.00 ± 0.30	0.00 ± 0.00	233.1 ± 0.2
038	199.0 ± 0.2	3.57 ± 0.07	3.57 ± 0.07	3.58 ± 0.07	0.17 ± 0.00	30.00 ± 0.30	30.00 ± 0.30	0.00 ± 0.00	232.9 ± 0.2

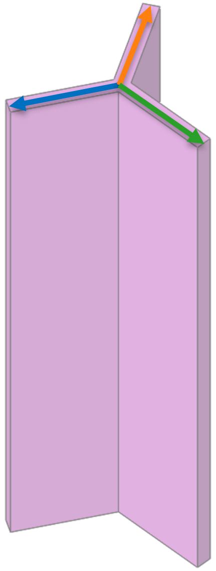
Note: in this case calorimetric measurements were unavailable → use q_{tot} as computed by ANTEO+

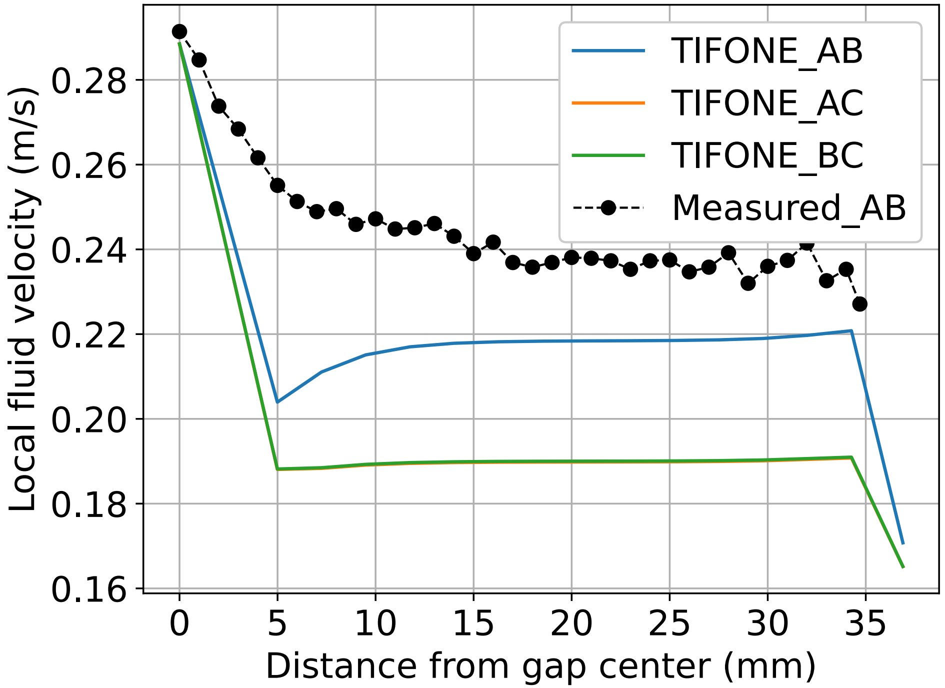
Asymmetric case #32: axial temperature profiles

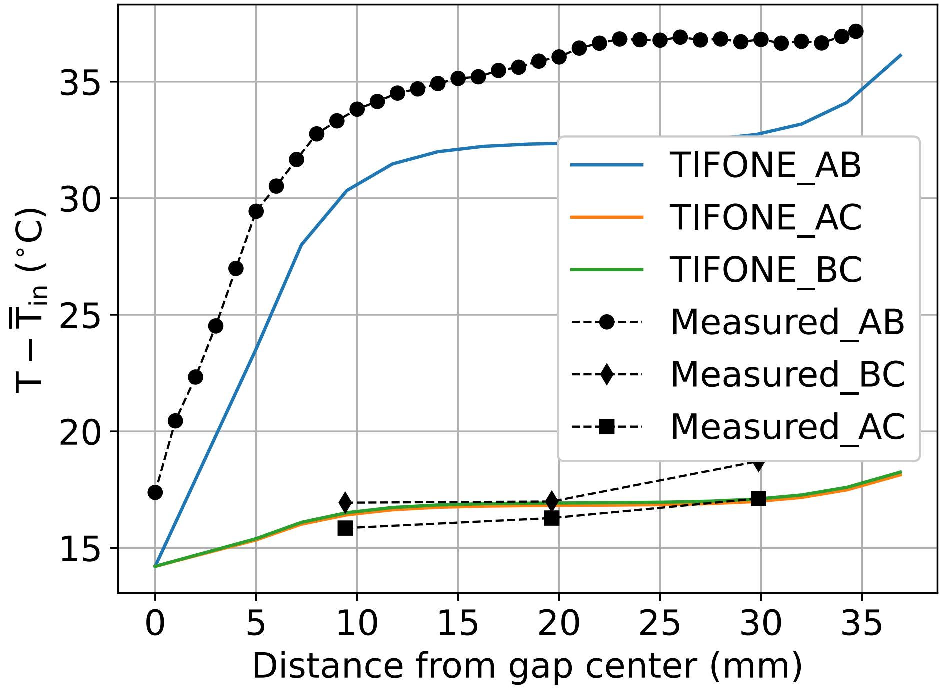




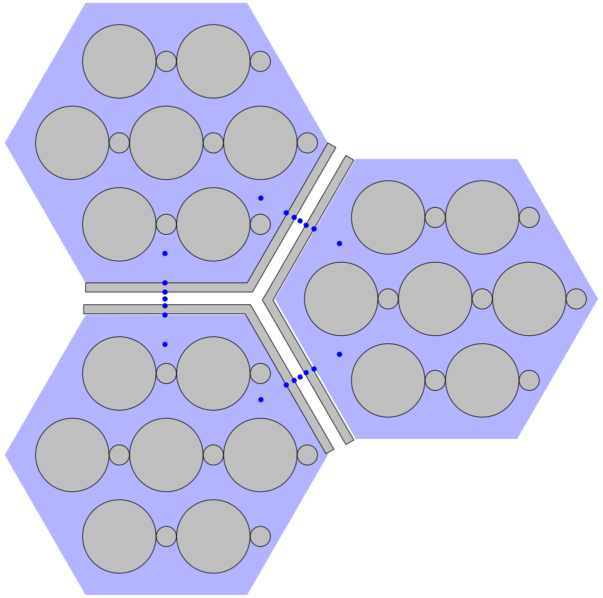
Asymmetric case #32: radial temperature profiles

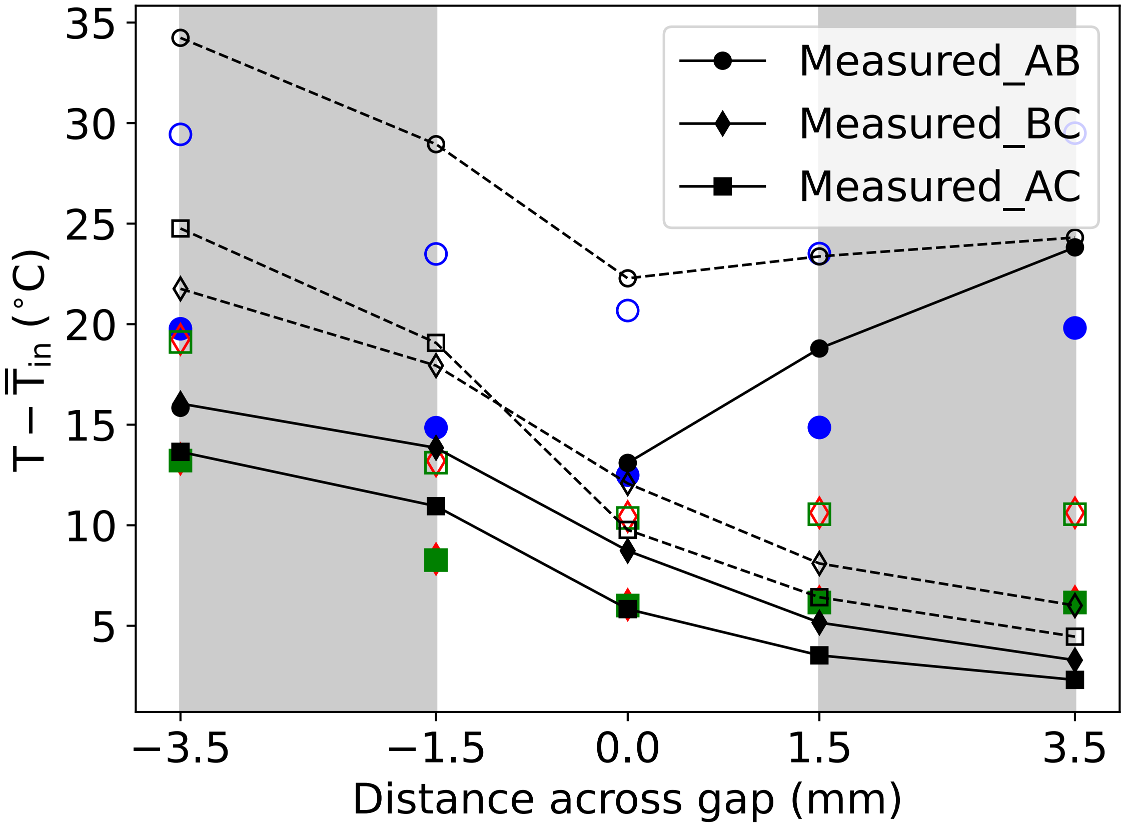




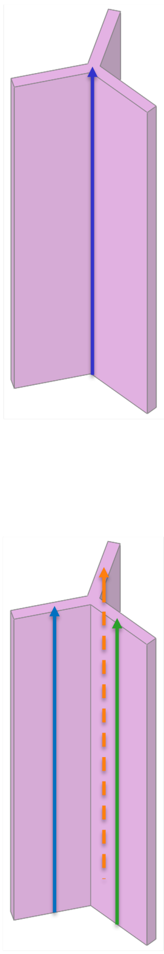


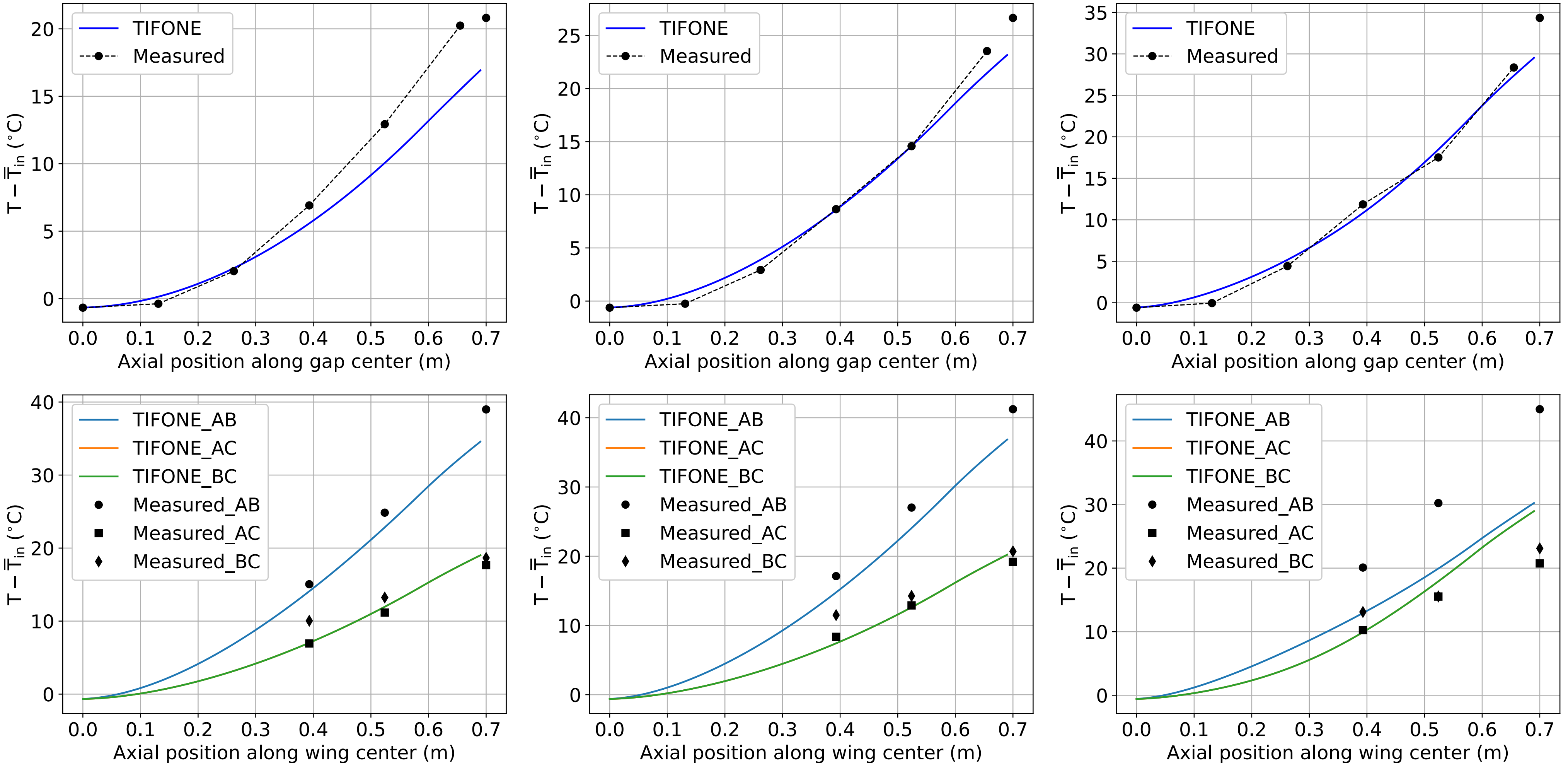
Asymmetric case #32: wrapper temperatures





Asymmetric cases # 34,36,38: axial temperature profiles





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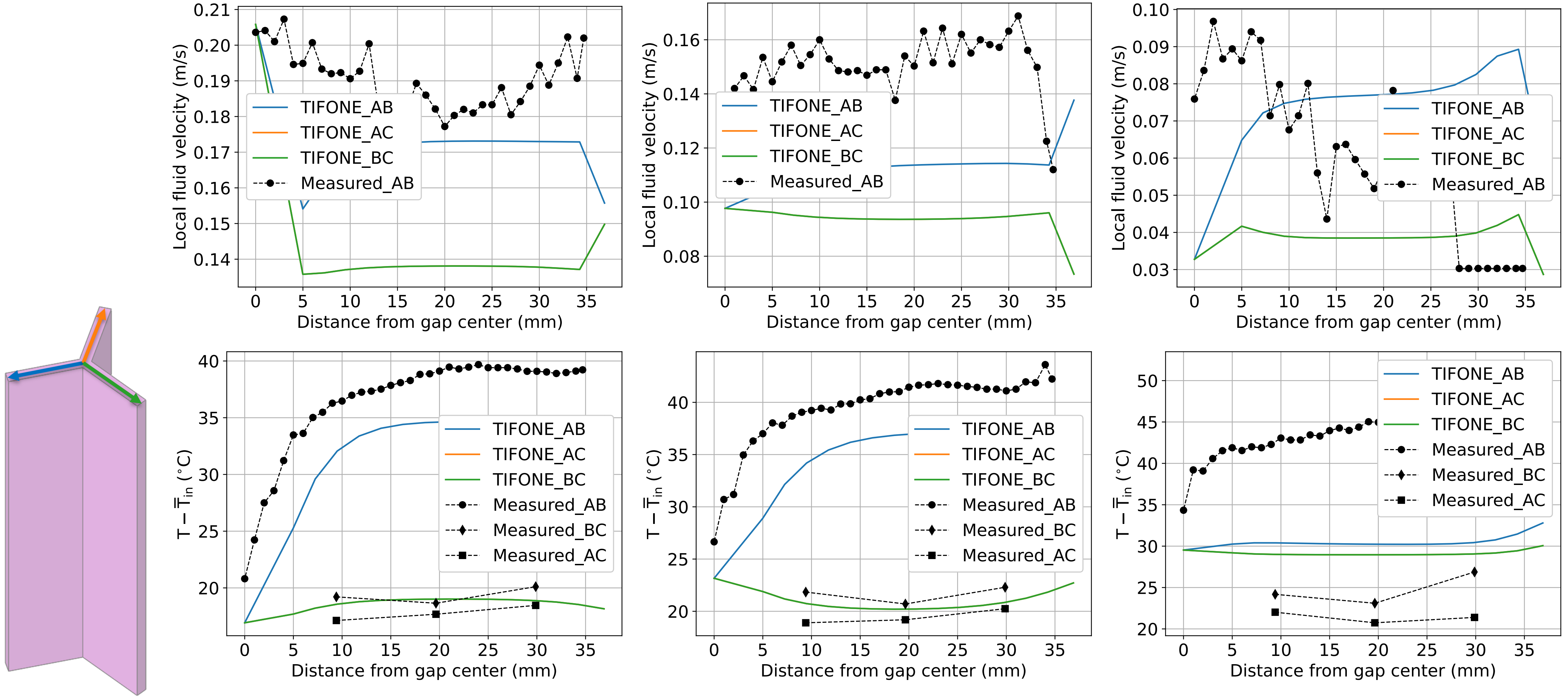
Asymmetric cases # 34,36,38: radial temperature profiles



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Aymmetric validation cases: reduced flow rate in C by 40%

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054	199.1 ± 0.2	3.60 ± 0.07	3.58 ± 0.07	2.22 ± 0.04	0.69 ± 0.01	30.00 ± 0.30	30.00 ± 0.30	30.00 ± 0.30	255.0 ± 0.2
055	199.1 ± 0.2	3.60 ± 0.07	3.58 ± 0.07	2.21 ± 0.04	0.69 ± 0.01	30.00 ± 0.30	30.00 ± 0.30	30.00 ± 0.30	255.0 ± 0.2
056	199.1 ± 0.2	3.59 ± 0.07	3.58 ± 0.07	2.15 ± 0.04	0.51 ± 0.01	30.00 ± 0.30	30.00 ± 0.30	30.00 ± 0.30	256.9 ± 0.2
057	199.1 ± 0.2	3.58 ± 0.07	3.58 ± 0.07	2.15 ± 0.04	0.51 ± 0.01	30.00 ± 0.30	30.00 ± 0.30	30.00 ± 0.30	256.9 ± 0.2
058	199.1 ± 0.2	3.59 ± 0.07	3.58 ± 0.07	2.15 ± 0.04	0.34 ± 0.01	30.00 ± 0.30	30.00 ± 0.30	30.00 ± 0.30	257.8 ± 0.2
059	199.0 ± 0.2	3.58 ± 0.07	3.58 ± 0.07	2.15 ± 0.04	0.34 ± 0.01	30.00 ± 0.30	30.00 ± 0.30	30.00 ± 0.30	257.8 ± 0.2
060	199.0 ± 0.2	3.58 ± 0.07	3.57 ± 0.07	2.15 ± 0.04	0.17 ± 0.00	30.00 ± 0.30	30.00 ± 0.30	30.00 ± 0.30	259.0 ± 0.2
061	199.0 ± 0.2	3.58 ± 0.07	3.57 ± 0.07	2.15 ± 0.04	0.17 ± 0.00	30.00 ± 0.30	30.00 ± 0.30	30.00 ± 0.30	259.0 ± 0.2

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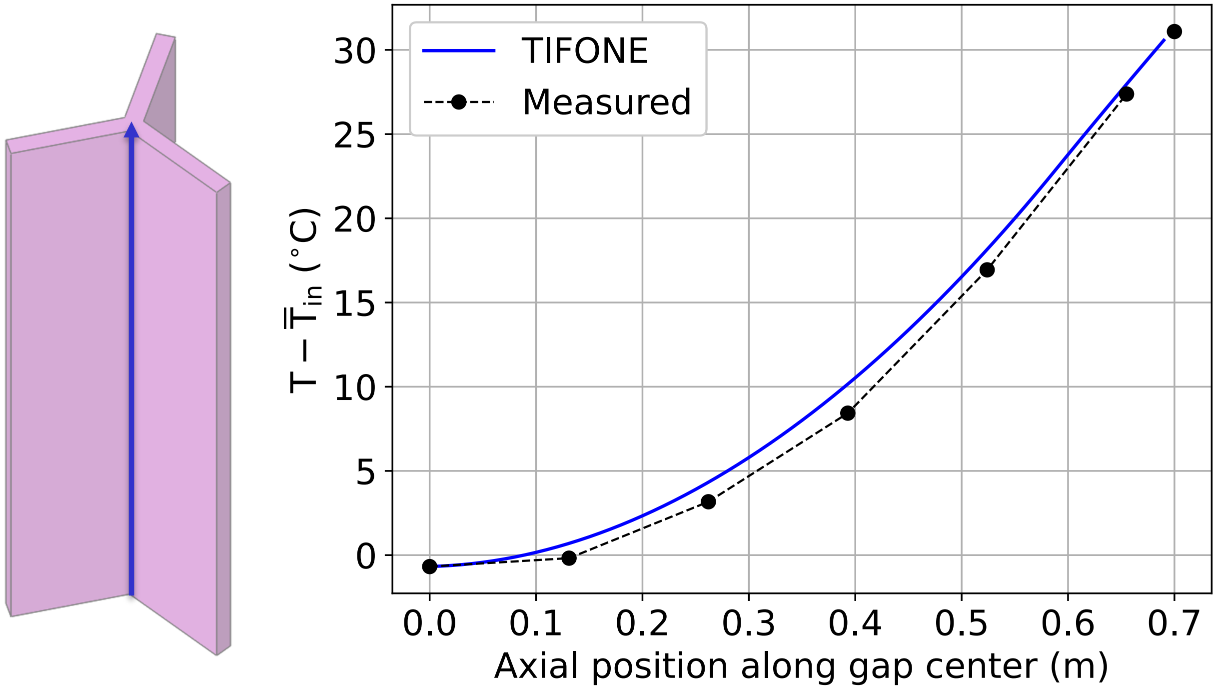
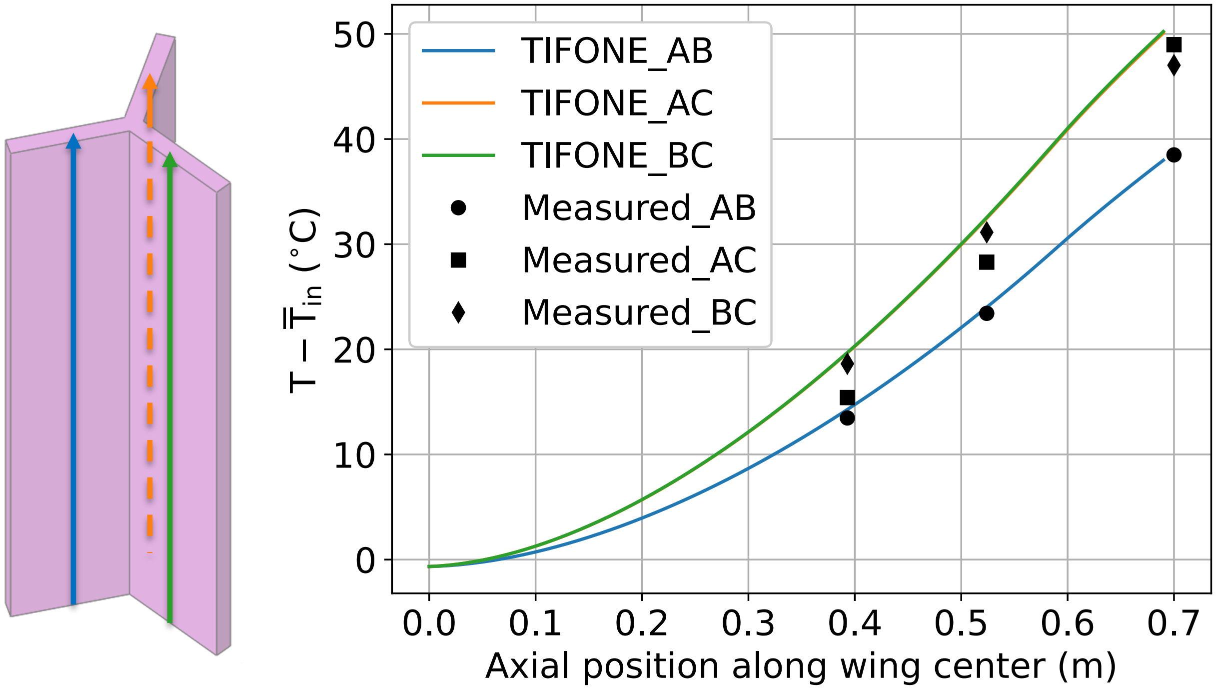
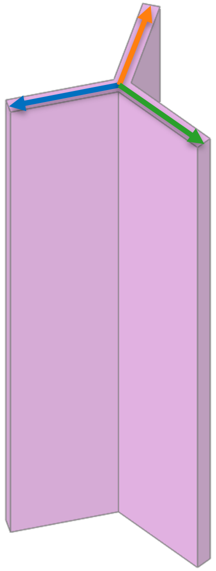
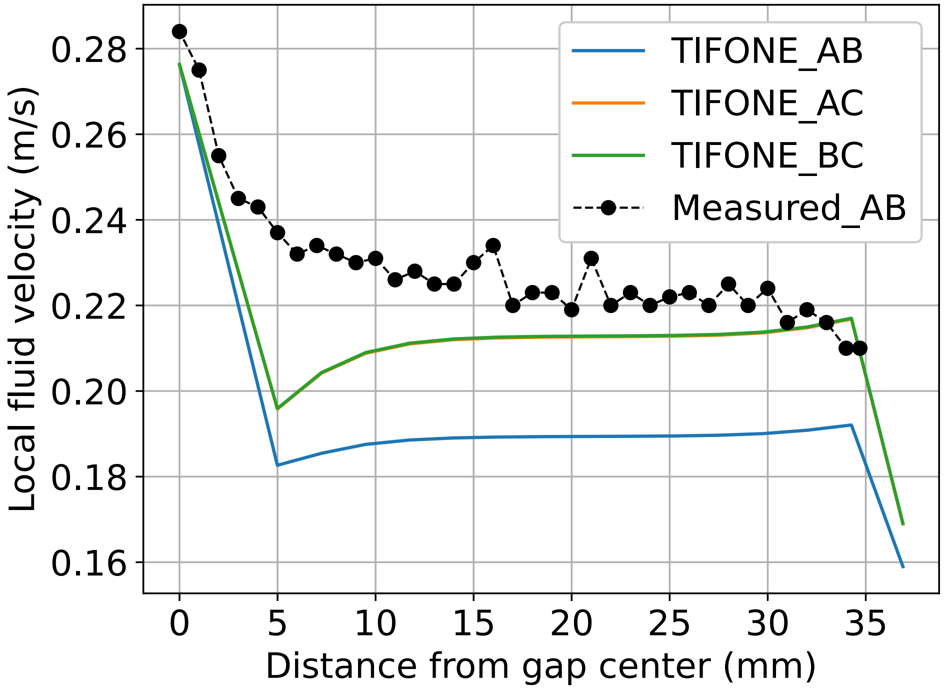
Aymmetric case #55: axial temperature profiles

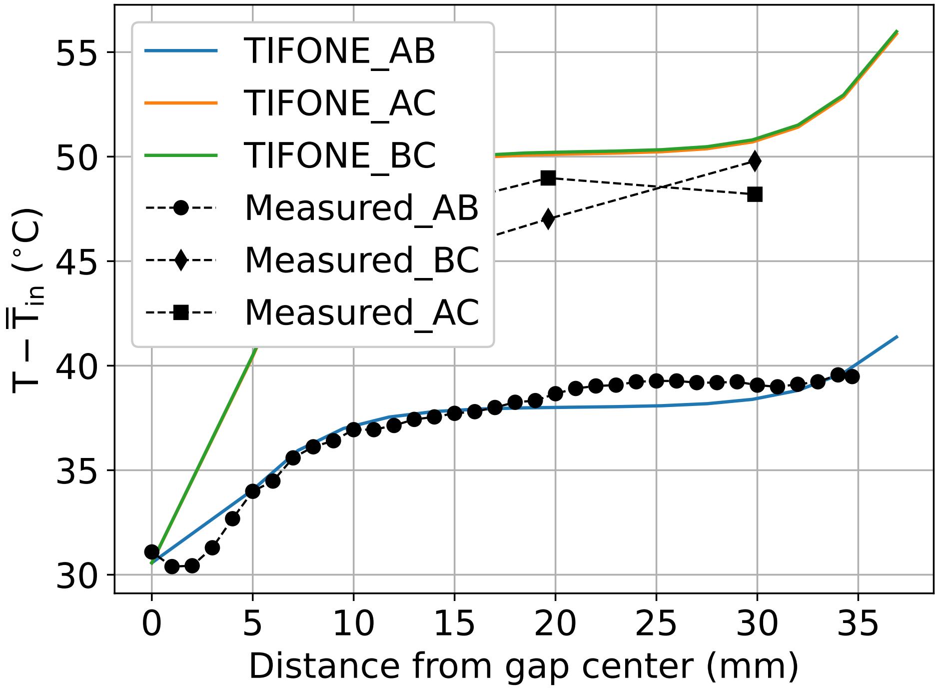




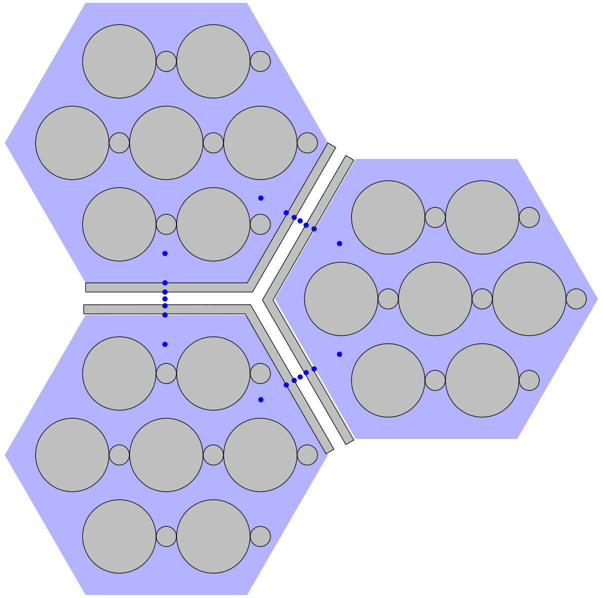
Aymmetric case #55: radial temperature profiles

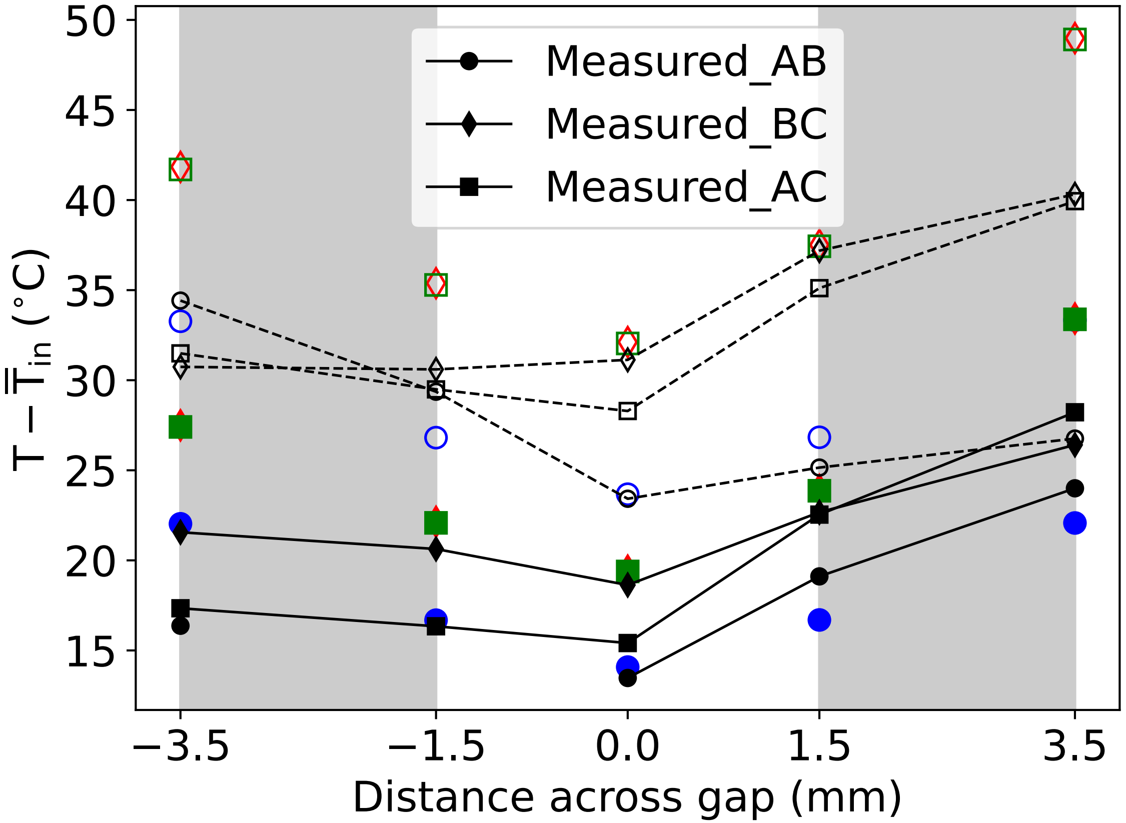




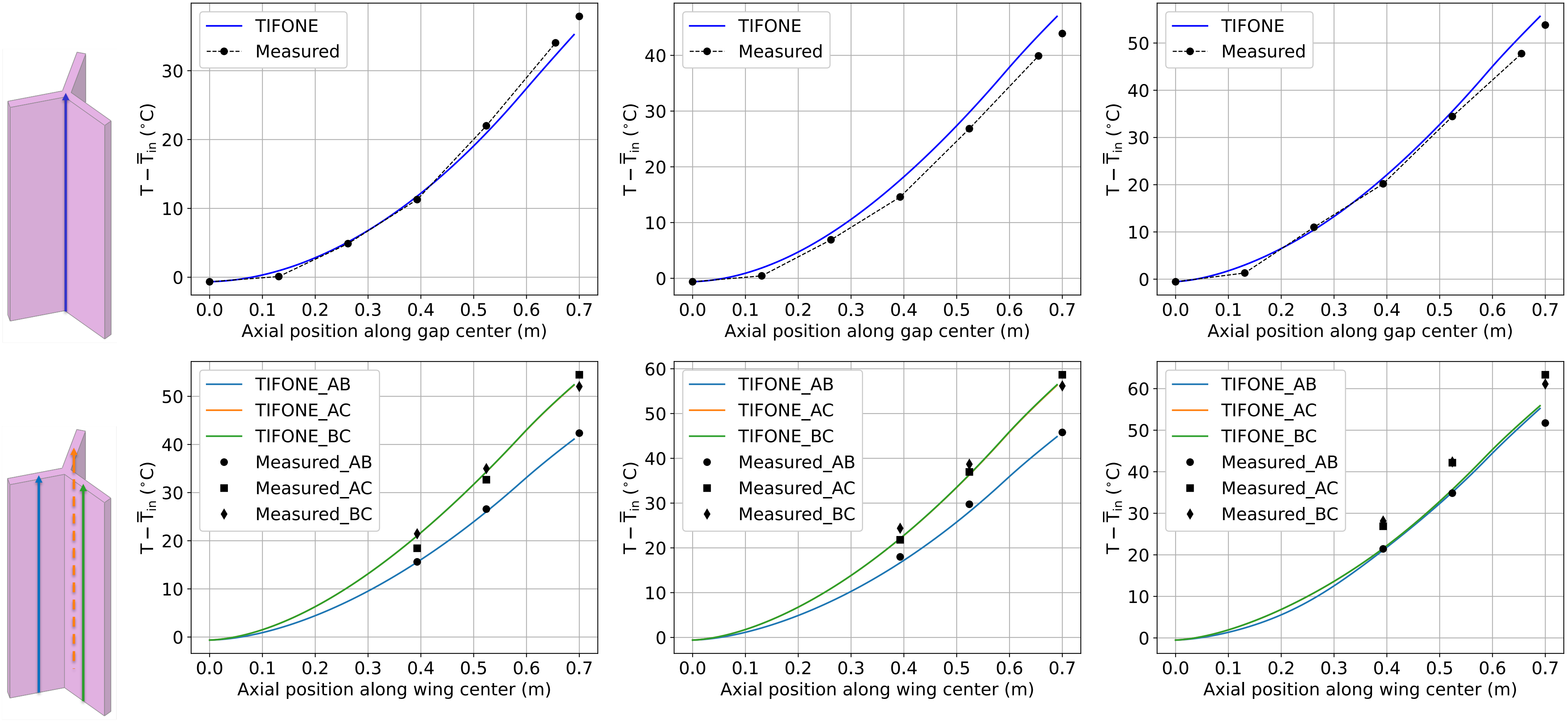


Aymmetric case #55: radial temperature profiles





Asymmetric cases # 57,59,61: axial temperature profiles



Asymmetric cases # 57,59,61: radial temperature profiles