Coupling fluid flow, heat transfer and food product transformation in a tubular heat exchanger, including the influence of curved sections

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Coupling Fluid Flow, Heat Transfer and Food Product Transformation in a Tubular Heat Exchanger, including the Influence of Curved Sections

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Ingénierie Procédés Aliments
(Food & Process Engineering)

AgroParisTech
INSTITUT DES SCIENCES ET INDUSTRIES DU VIVANT ET DE L'ENVIRONNEMENT
PARIS INSTITUTE OF TECHNOLOGY FOR LIFE, FOOD AND ENVIRONMENTAL SCIENCES

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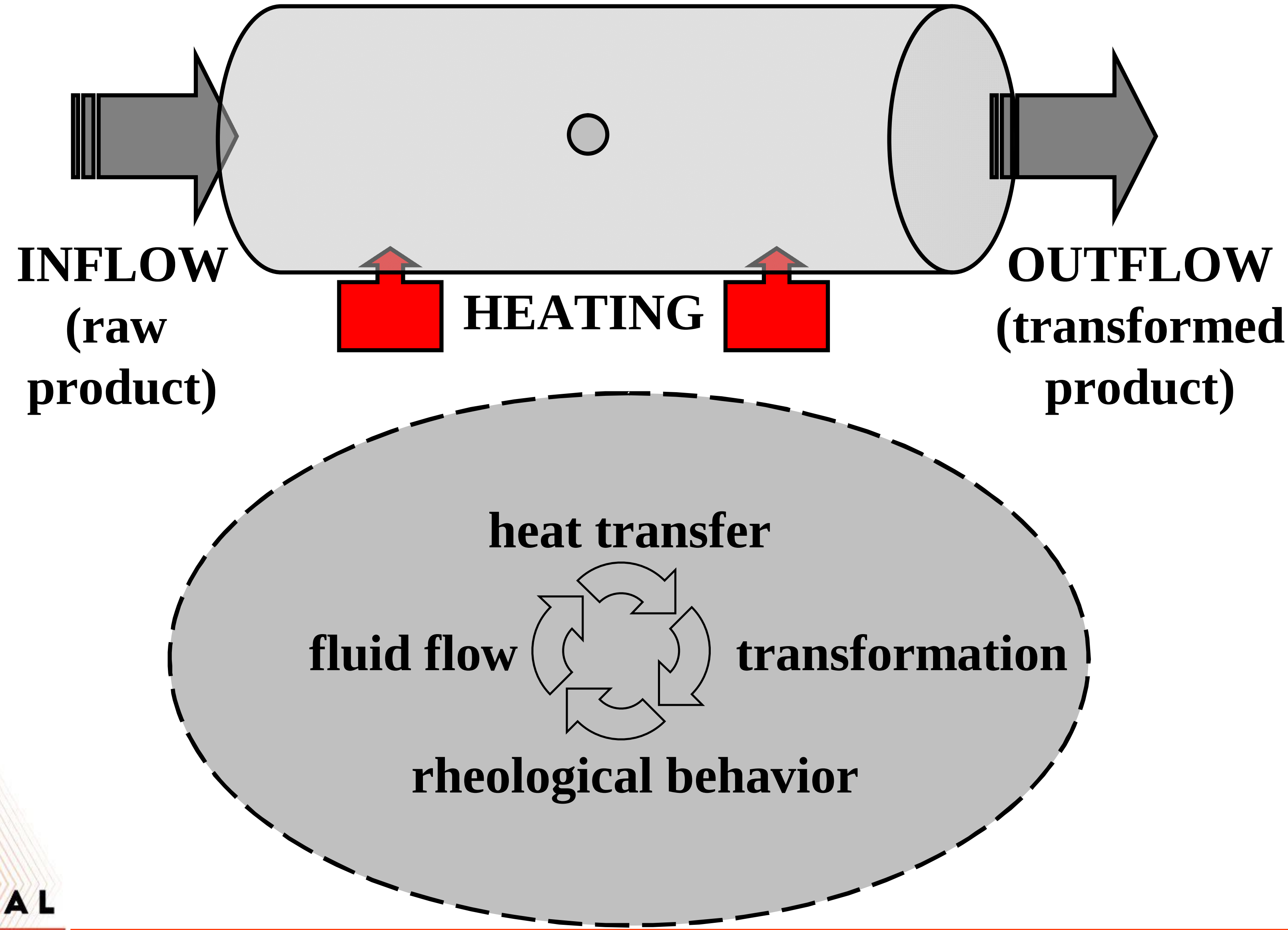
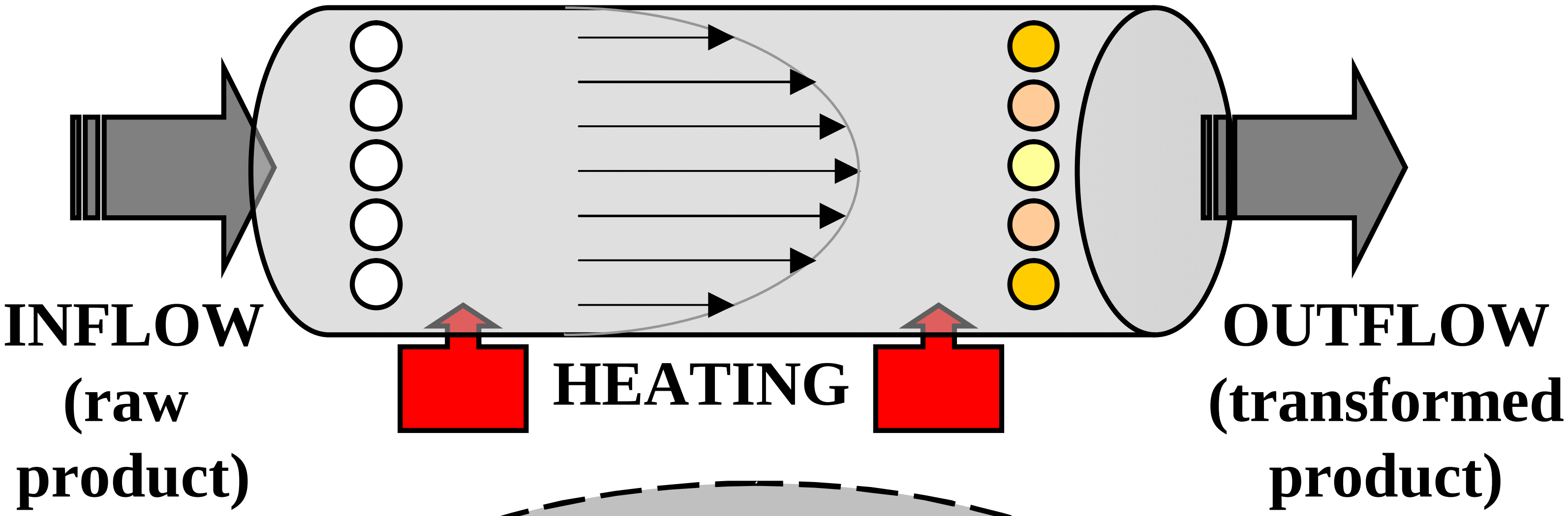
SCOPE


INFLOW
(raw
product)
HEATING
OUTFLOW
(transformed
product)
heat transfer
fluid flow
transformation
rheological behavior


INFLOW
(raw
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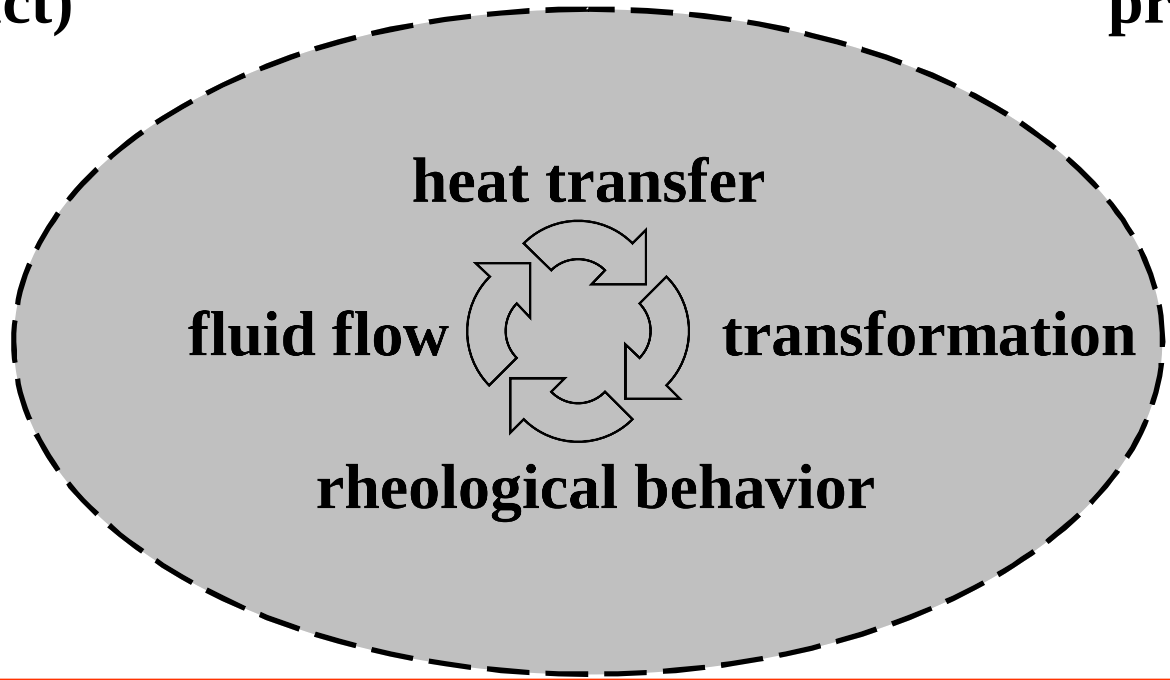
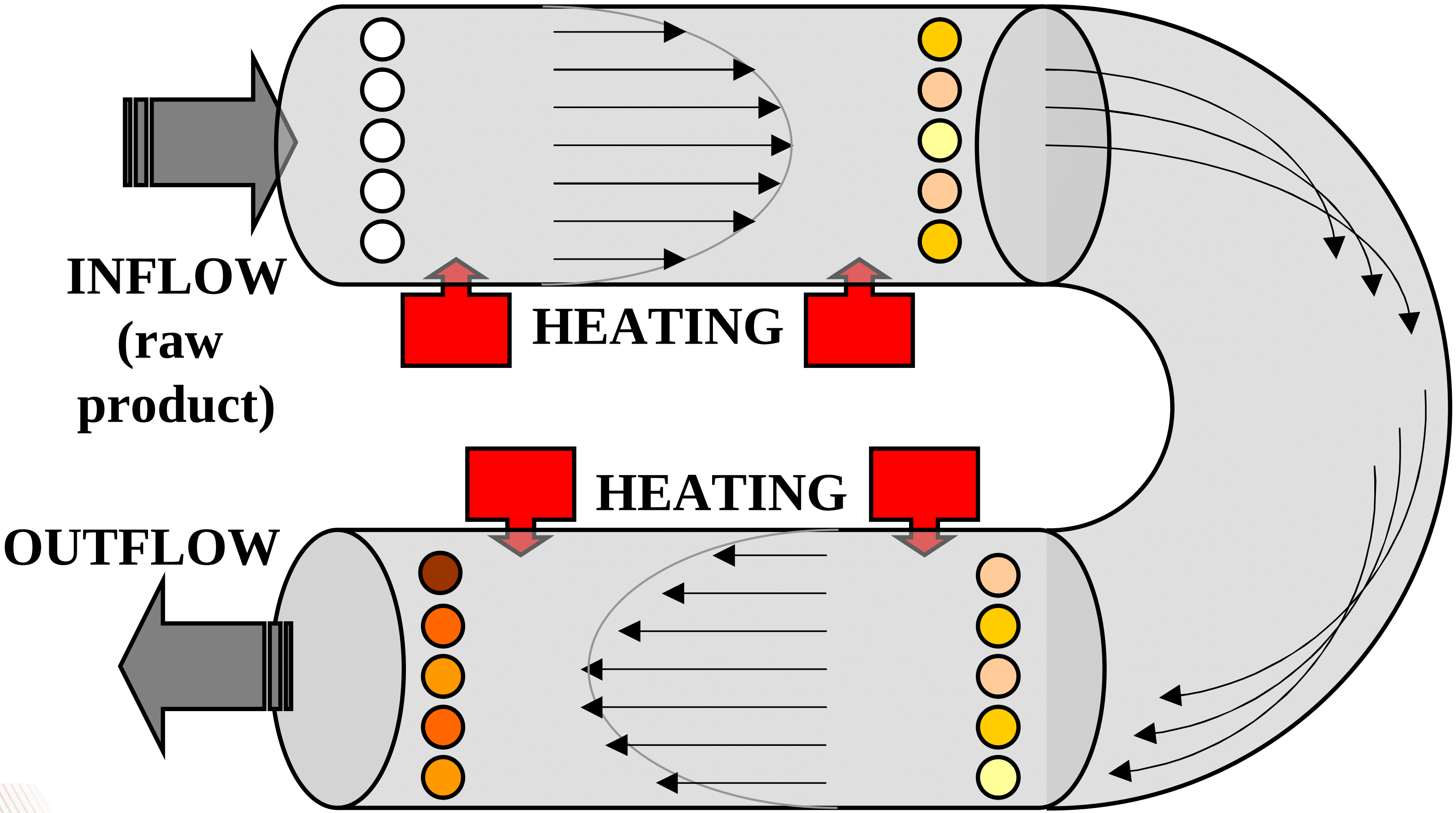
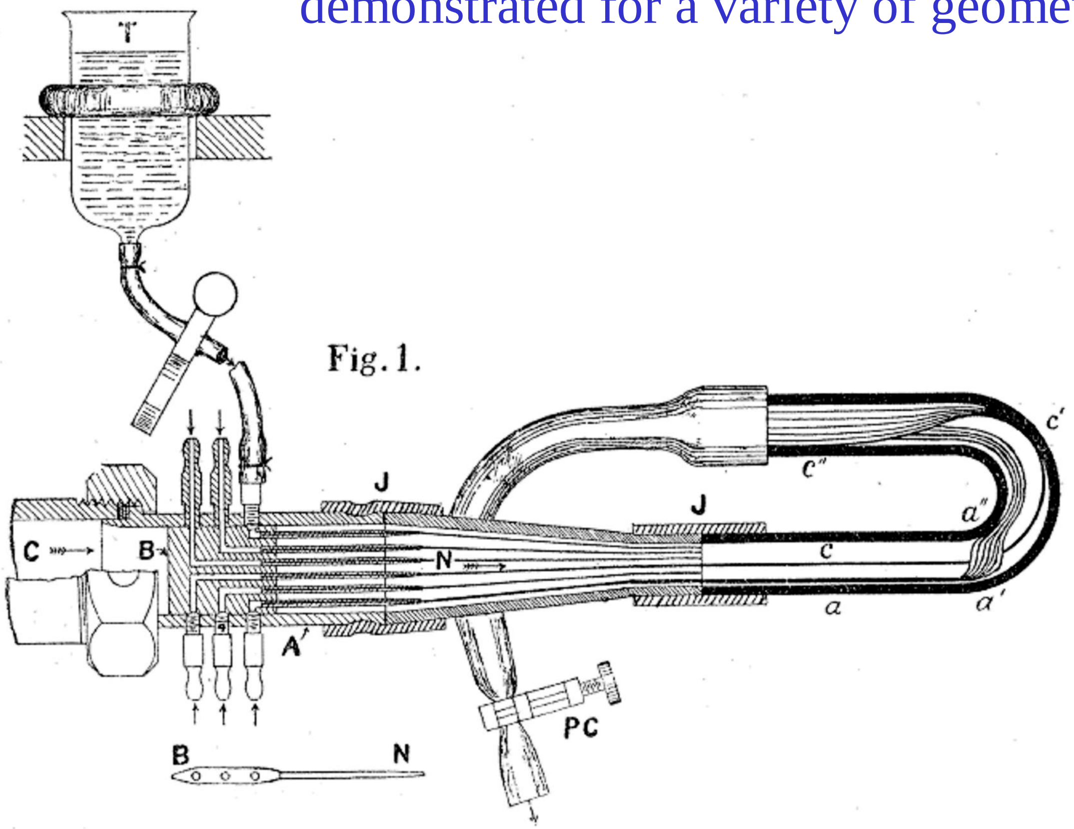

heat transfer
fluid flow
transformation
rheological behavior

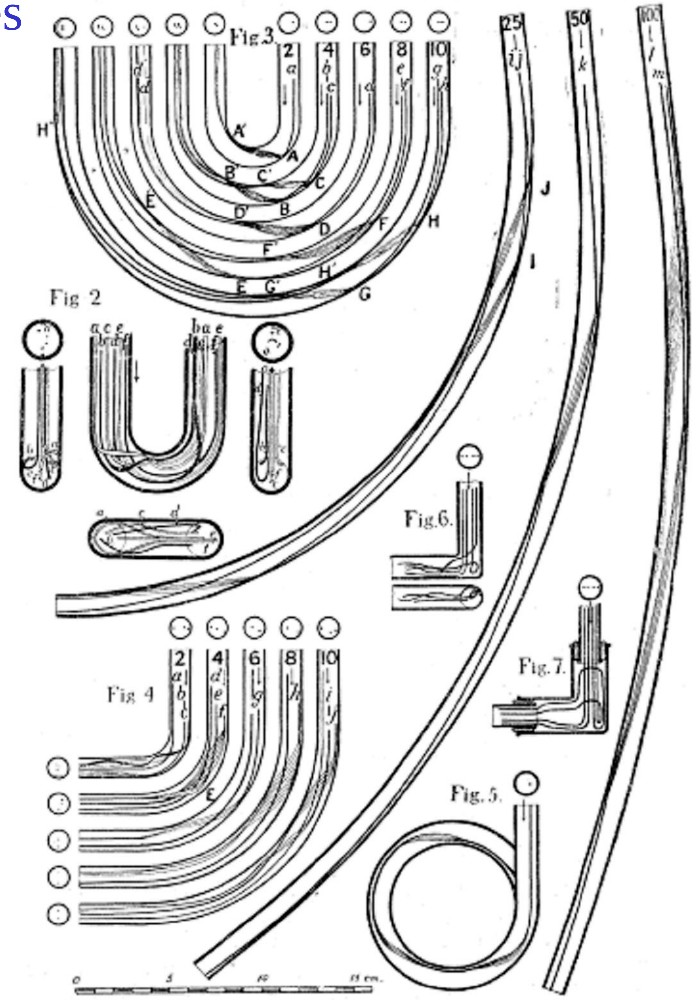


product ? velocity field ? product ?

- **experiment**

  # Eustice (1911): the existence of secondary flow in curved tubes is demonstrated for a variety of geometries





John Eustice
Proceedings of the Royal Society of London. Series A, Containing Papers of a Mathematical and Physical Character
Vol. 85, No. 576 (Apr. 11, 1911), pp. 119-131

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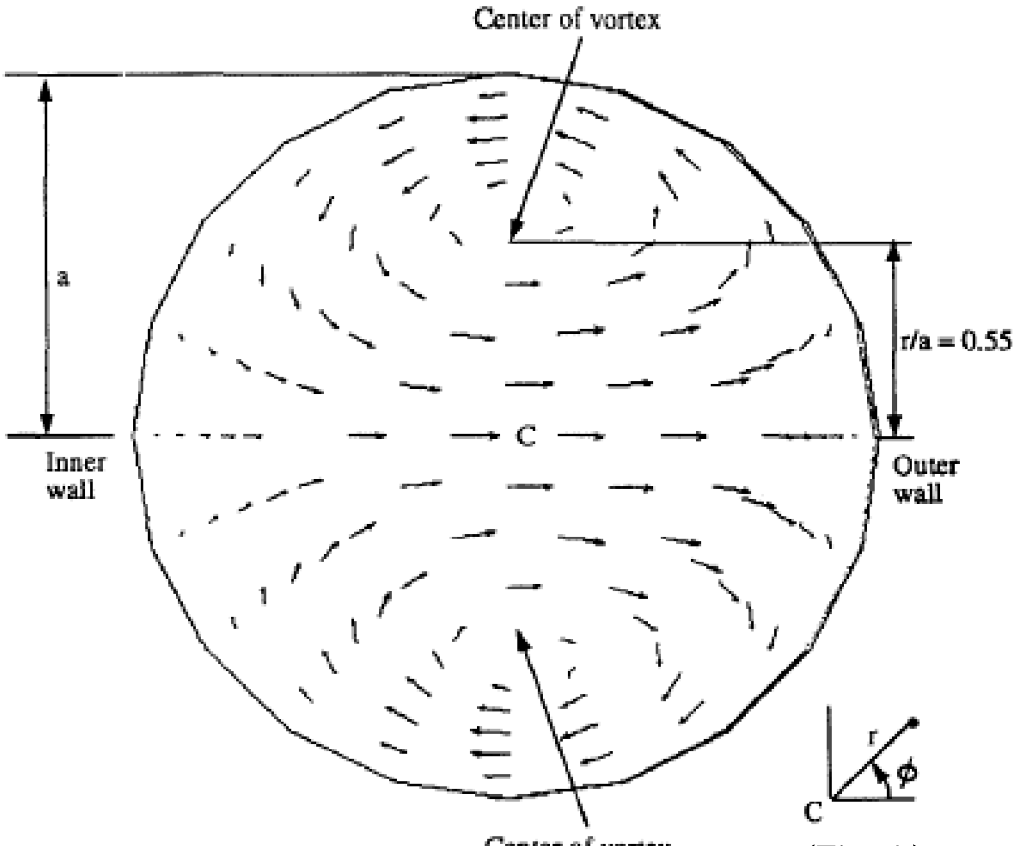
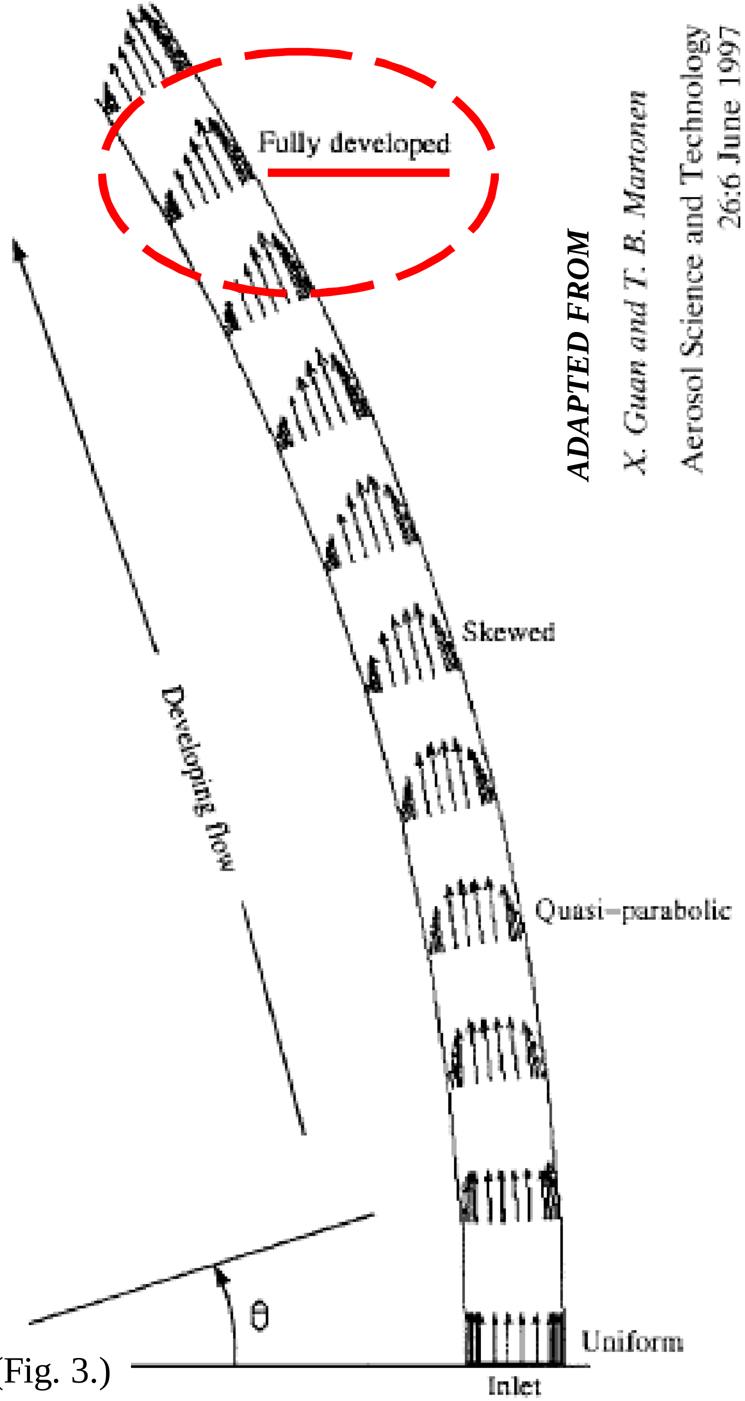
❑ theory

Dean (1928): fully-developed flow in helically coiled circular tubes



(Fig. 4.)



(Fig. 3.)

ADAPTED FROM
X. Guan and T. B. Martonen
Aerosol Science and Technology
26:6 June 1997

❑ numerical simulation

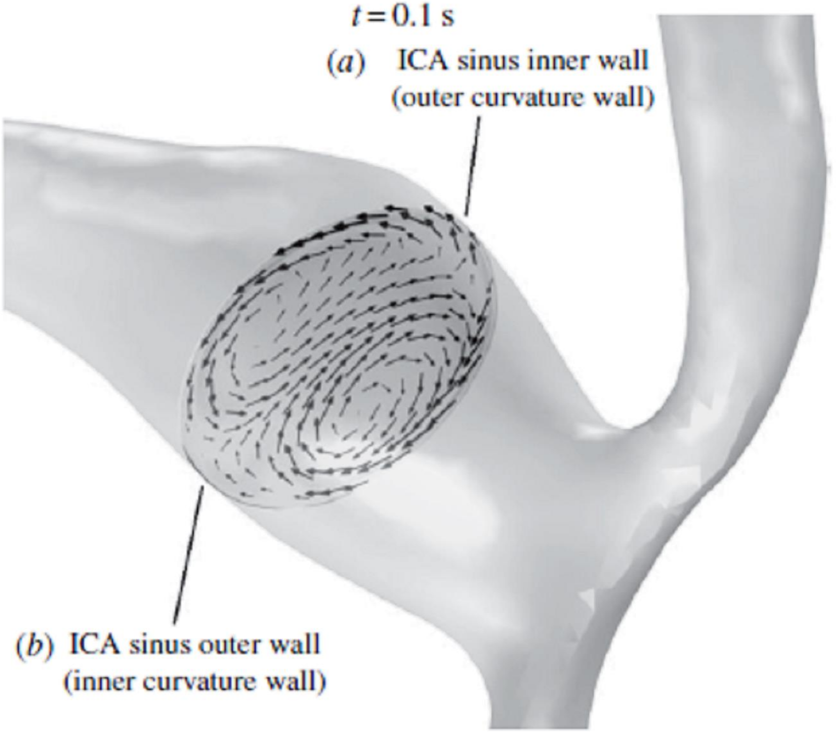


Figure 12. In-plane RBC velocity vectors on a plane normal to the centreline in the carotid sinus of the stenotic carotid bifurcation at $t = 0.10$ s. Secondary flows in the form of Dean vortices are observed and are present throughout the cardiac cycle (not shown). This secondary flow pattern plays a key role in lowering the haematocrit on the outer wall of the ICA sinus (see main text).

J. Biasetti et al. / J. R. Soc. Interface 11 (2014) 20140403

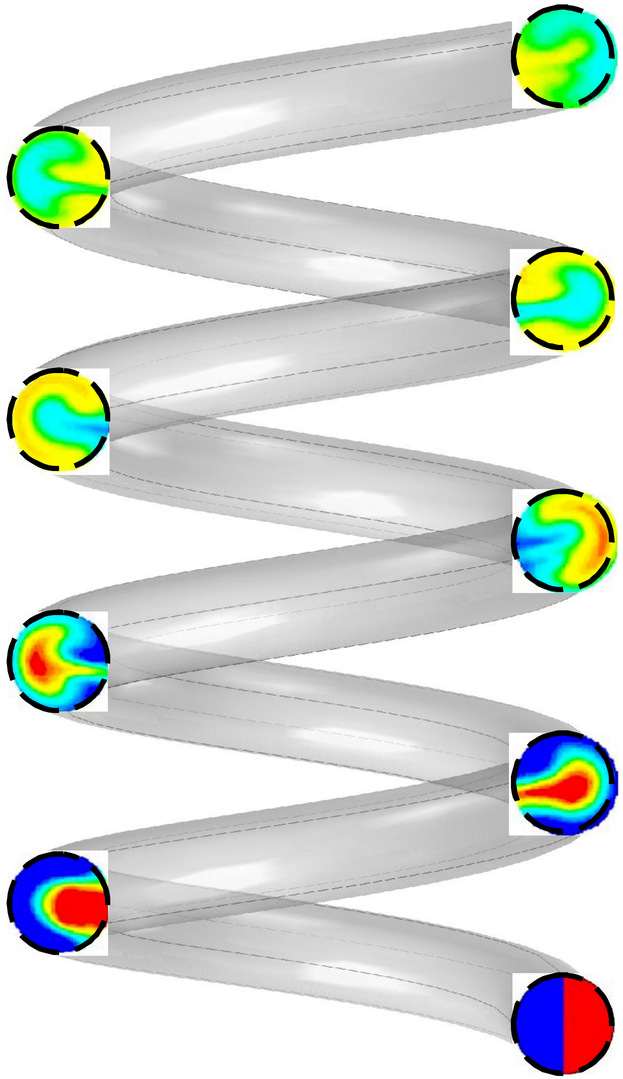


Fig. 10. Scalar concentration..., Re = 10.

ADAPTED FROM

V. Kumar et al. / Chemical Engineering Science 61 (2006) 5742–5753

SCOPE (AND SUMMARY)

- What about **continuous thermal processing of liquid food products**

  ...whose **rheological behavior** can change along the **product history**

  ...within **heat exchangers** characterized by **complex geometry** ...?

- In order to study these **coupled problems**, we need **numerical model**

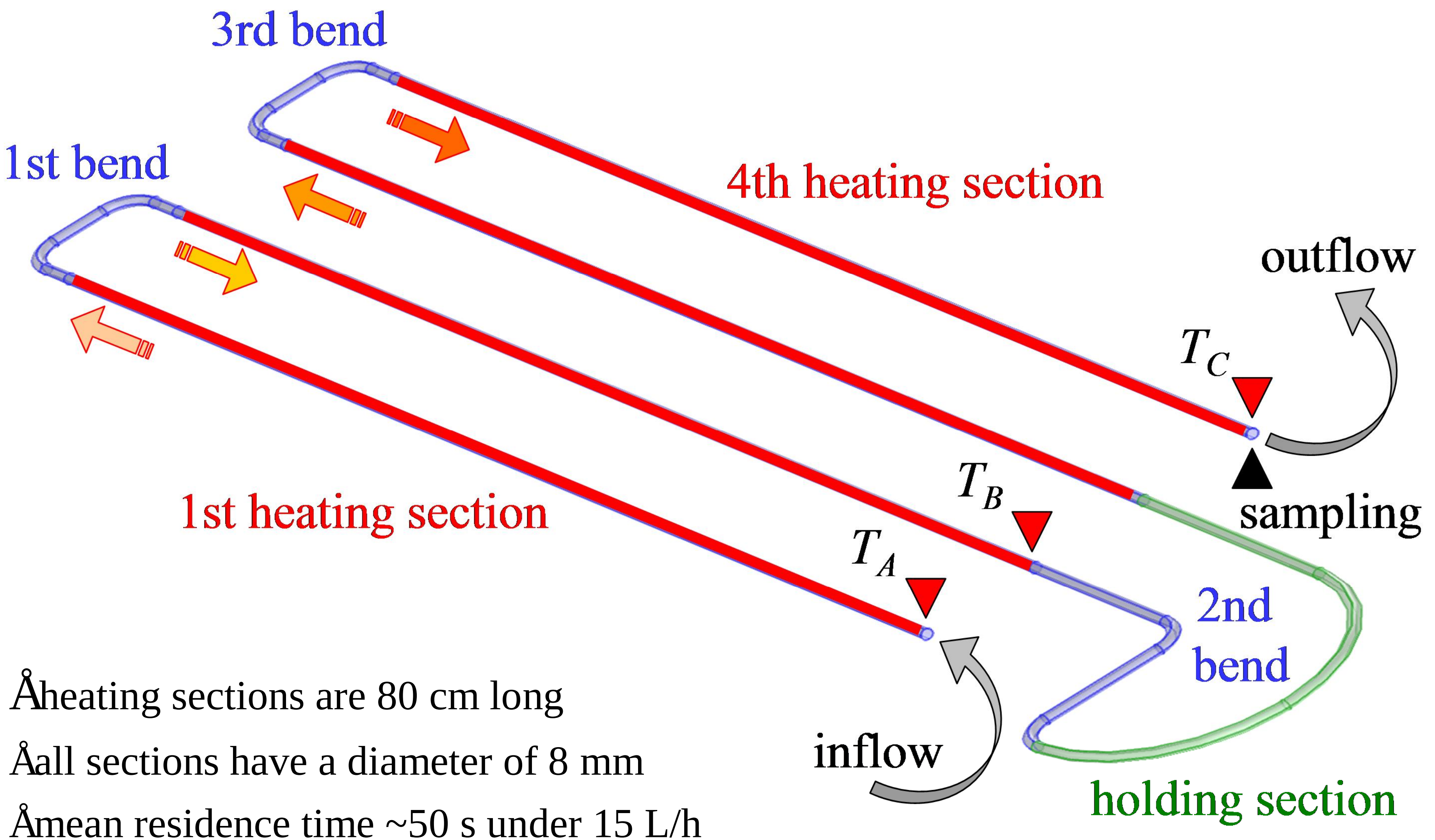
  ...which must include **realistic representation** for the product **transformation kinetics** and **rheological behavior**

  ...while considering the **3D characteristics of the processing unit** ...!

- In addition, we need assess the **model reliability** with the help of **independent observations**

  ...and evaluate the **influence of mesh resolution on model predictions** !

HEAT EXCHANGER



- heating sections are 80 cm long
- all sections have a diameter of 8 mm
- mean residence time ~50 s under 15 L/h

COUPLED PHYSICAL PROBLEM

- **aqueous suspension of modified waxy maize starch (3.42 % w/w)**
- **governing equations**

$$\vec{\nabla}.(\rho\vec{u}) = 0 \qquad \text{.....mass}$$

$$\rho\left(\vec{u}\cdot\vec{\nabla}\right)\vec{u} = \vec{\nabla}\cdot\left(-p\vec{I} + \eta\left(\vec{\nabla}\vec{u} + \left(\vec{\nabla}\vec{u}\right)^{T}\right) - \frac{2}{3}\eta\left(\vec{\nabla}\cdot\vec{u}\right)\vec{I}\right) \qquad \text{.....momentum}$$

$$\rho C_P\left(\vec{u}\cdot\vec{\nabla}\right)T = \vec{\nabla}\cdot\left(\lambda\vec{\nabla}T\right) \qquad \text{.....energy}$$

$$\vec{u}\cdot\vec{\nabla}S = V\{T\}(1-S)^2 + \vec{\nabla}\cdot\left(d_S\vec{\nabla}S\right) \qquad \text{.....transformation}$$

where $V\{T\} = Va\,(T - Ta)$

- **transformation state: the swelling degree**

$$S = (D - D_0)/(D_{MAX} - D_0)$$

where D = volume mean diameter of starch granules

❑ rheological model

$$\eta\{\dot{\gamma},\Phi,T\}=K\{\Phi,T\}\dot{\gamma}^{n\{\Phi\}-1}$$

$$K\{\Phi,T\} = k_1\, exp(k_2\,\Phi)\,\eta_{water}\{T\}$$

$$n\{\Phi\} = n*+(1-n*)\,exp(-k_3\,(\Phi-\Phi_0))$$

where

Φ = volume fraction occupied by starch granules

$$\Phi=\Phi_0\,(D/D_0)^3$$

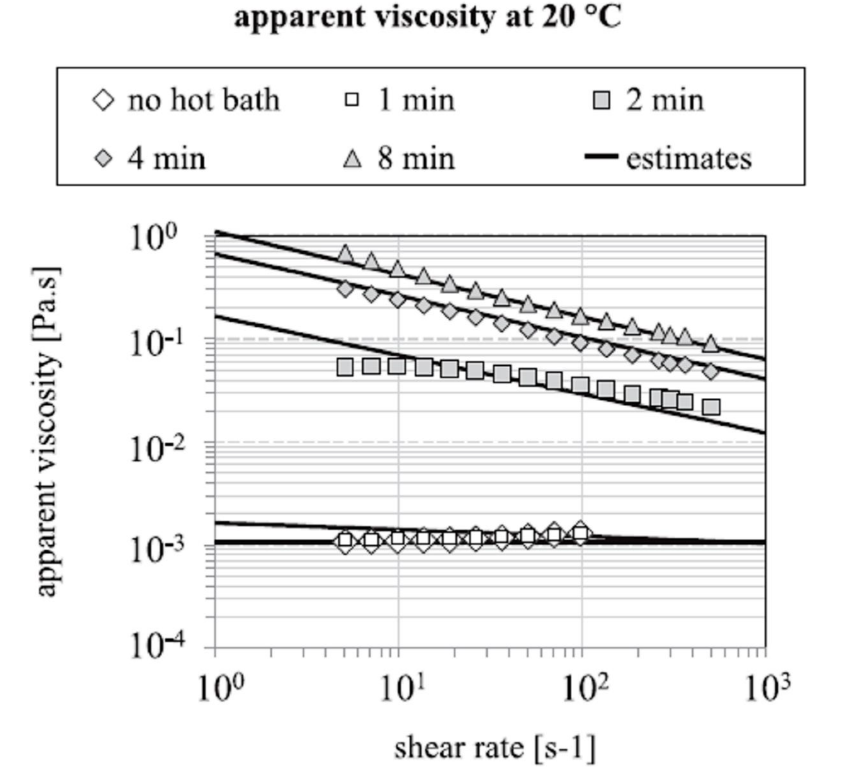


Fig. 2. Apparent viscosity values at 20 °C of the starch suspension, after selected thermal treatments. Lines indicate the corresponding predictions of apparent viscosity as a function of shear rate and solid volume fraction.

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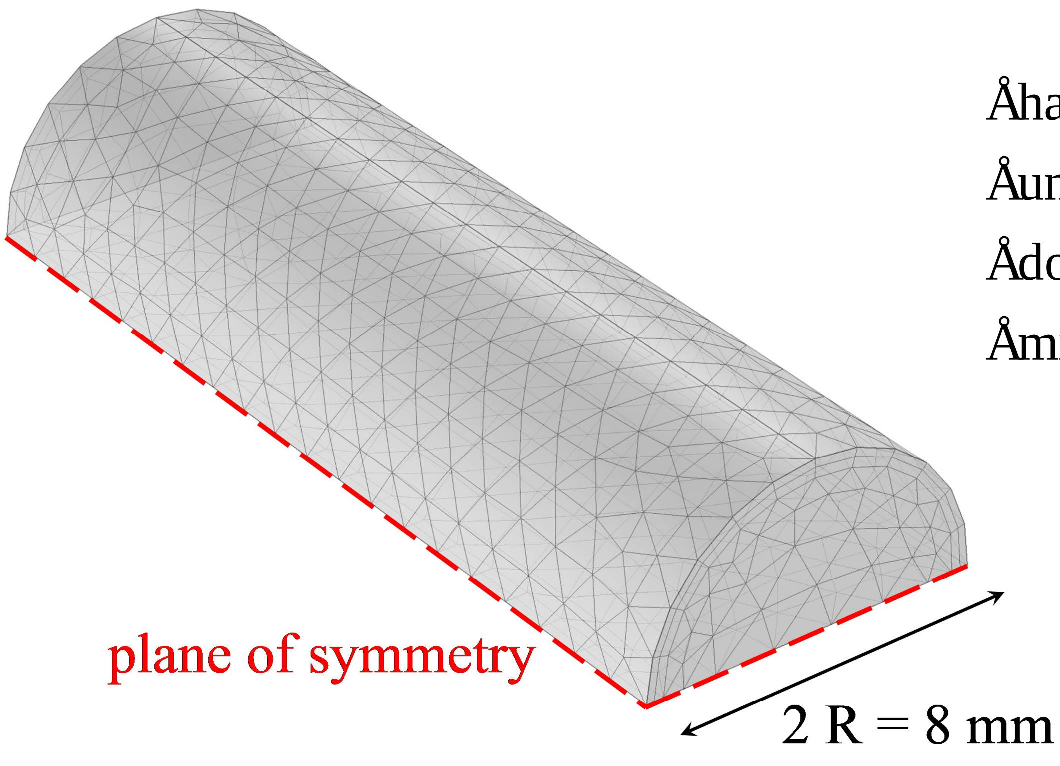
NUMERICAL MODEL

Ågoverning equations are solved through the finite-element method

Åsimulation package COMSOL Multiphysics 4.4



Åhalf- heat exchanger

Åun-structured mesh

Ådouble boundary-layer along the walls

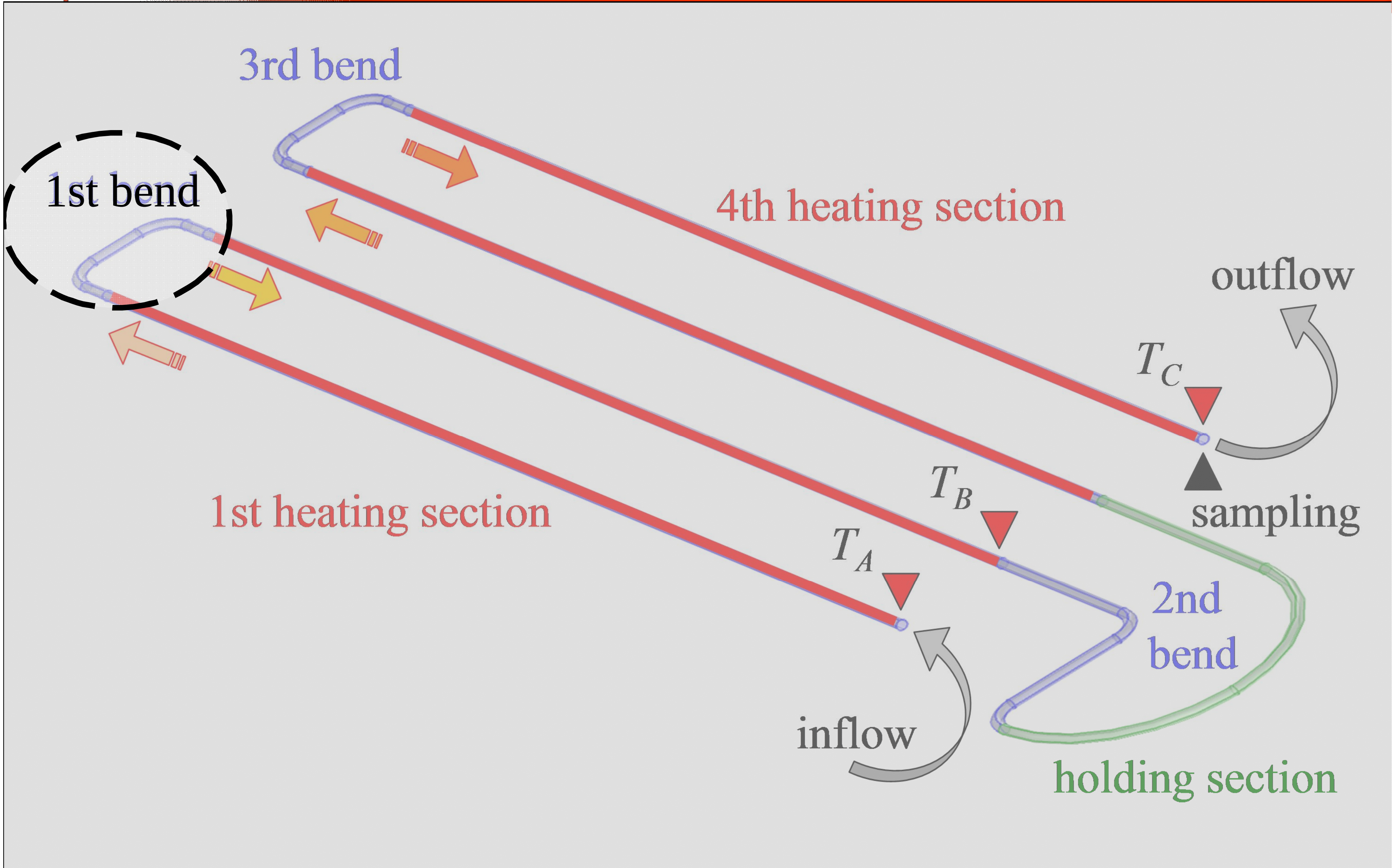
Åminimum element size = R / 6

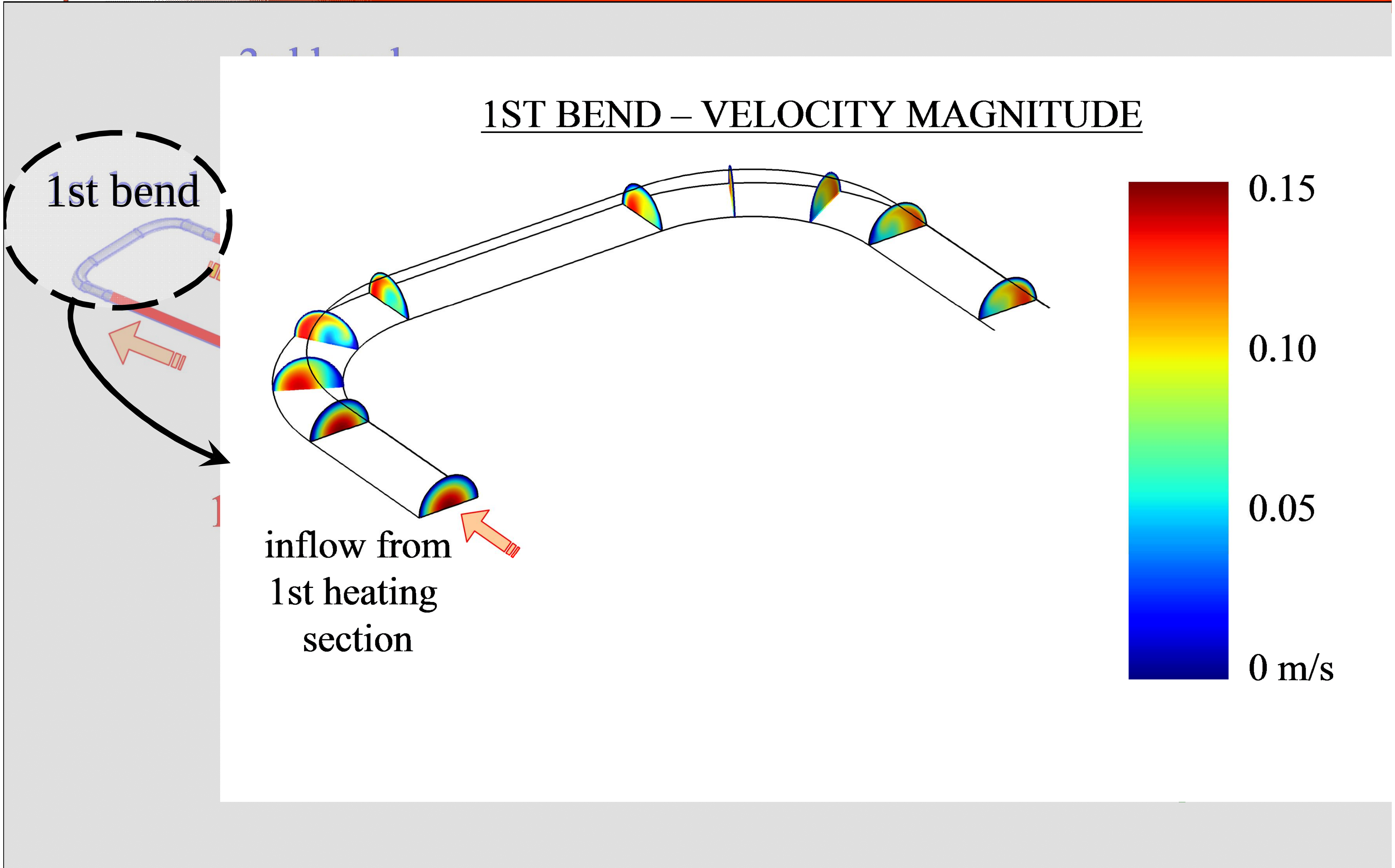
1.3 10^7 degrees of freedom (!)

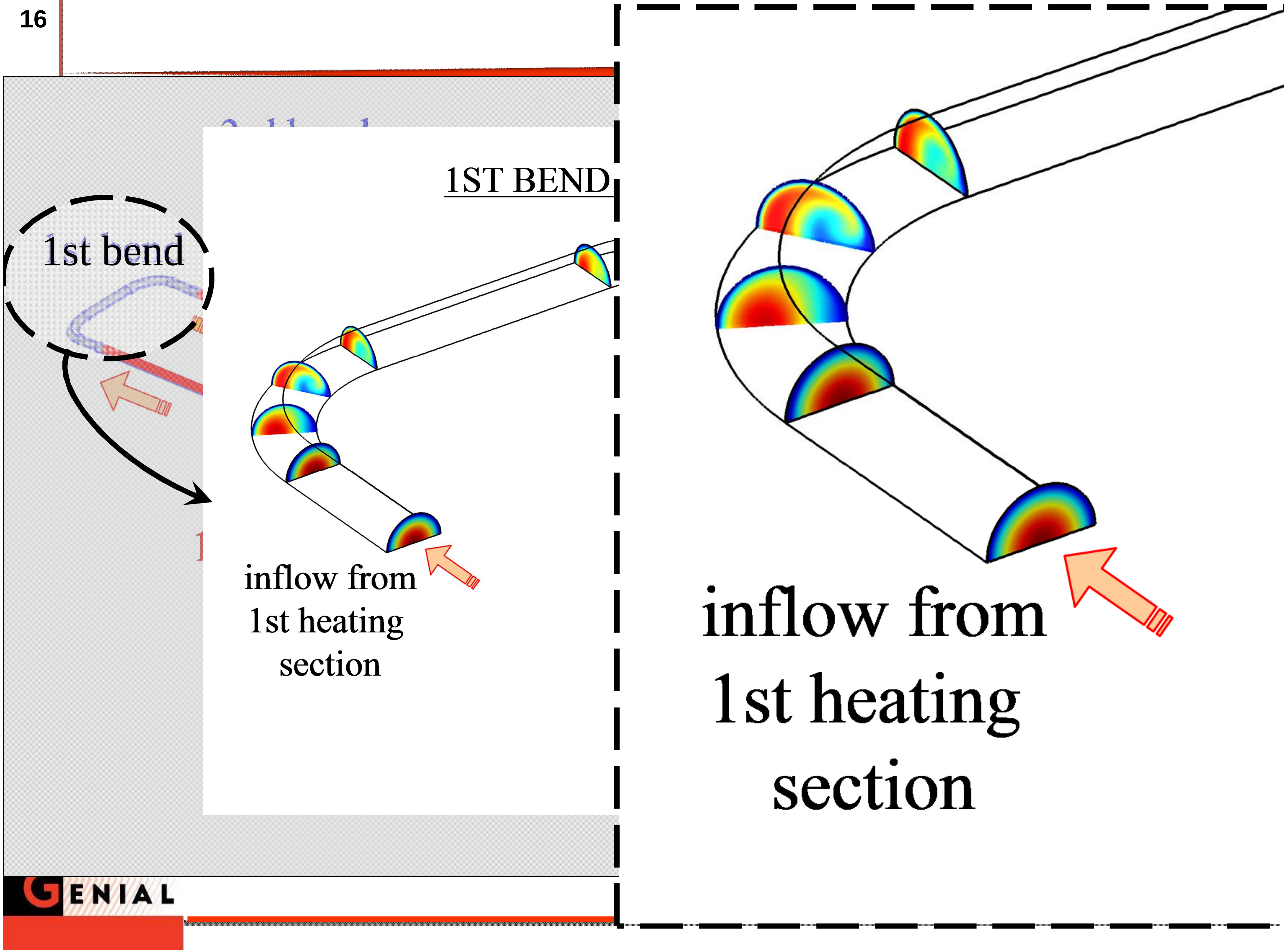
NUMERICAL MODEL: Boundary Conditions

	FLUID FLOW	HEAT TRANSFER	TRANSFORMATION
INLET	VELOCITY: $\vec{u} = -u_0\,\vec{n}$, fully-developed flow (parabolic profile), $\dot{V}$ = 15 L/h (assignment); Reynolds number ~ 1040	TEMPERATURE: T_A = 43.9 °C (experiment)	SWELLING DEGREE: $D = D_0$ = 16.3 µm (experiment), hence $S = 0$
OUTLET	NO VISCOUS STRESS, NULL PRESSURE: $\left(-p\vec{I} + \eta\left(\vec{\nabla}\vec{u} + (\vec{\nabla}\vec{u})^T\right) - \frac{2}{3}\eta\left(\vec{\nabla}\bullet\vec{u}\right)\vec{I}\right) = -p_0\,\vec{n}$ $\vec{u}\bullet\vec{t} = 0$, $p_0 = 0$	CONVECTIVE FLUX ONLY: $-\vec{n}\bullet\left(-\lambda\,\vec{\nabla}T\right) = 0$	CONVECTIVE FLUX ONLY: $-\vec{n}\bullet\left(-d_S\,\vec{\nabla}S\right) = 0$
PLANE OF SYMMETRY	SYMMETRY: $\vec{u}\bullet\vec{n} = 0$	SYMMETRY: $-\vec{n}\bullet\left(-\lambda\,\vec{\nabla}T\right) = 0$	SYMMETRY: $-\vec{n}\bullet\left(-d_S\,\vec{\nabla}S + \vec{u}\,S\right) = 0$
WALLS	NO SLIPPING: $\vec{u} = 0$	FLUX DENSITY (HEATING): $-\vec{n}\bullet\left(-\lambda\,\vec{\nabla}T\right) = \dot{q}$ INSULATION (BENDS & HOLDING): $-\vec{n}\bullet\left(-\lambda\,\vec{\nabla}T\right) = 0$	INSULATION: $-\vec{n}\bullet\left(-d_S\,\vec{\nabla}S + \vec{u}\,S\right) = 0$

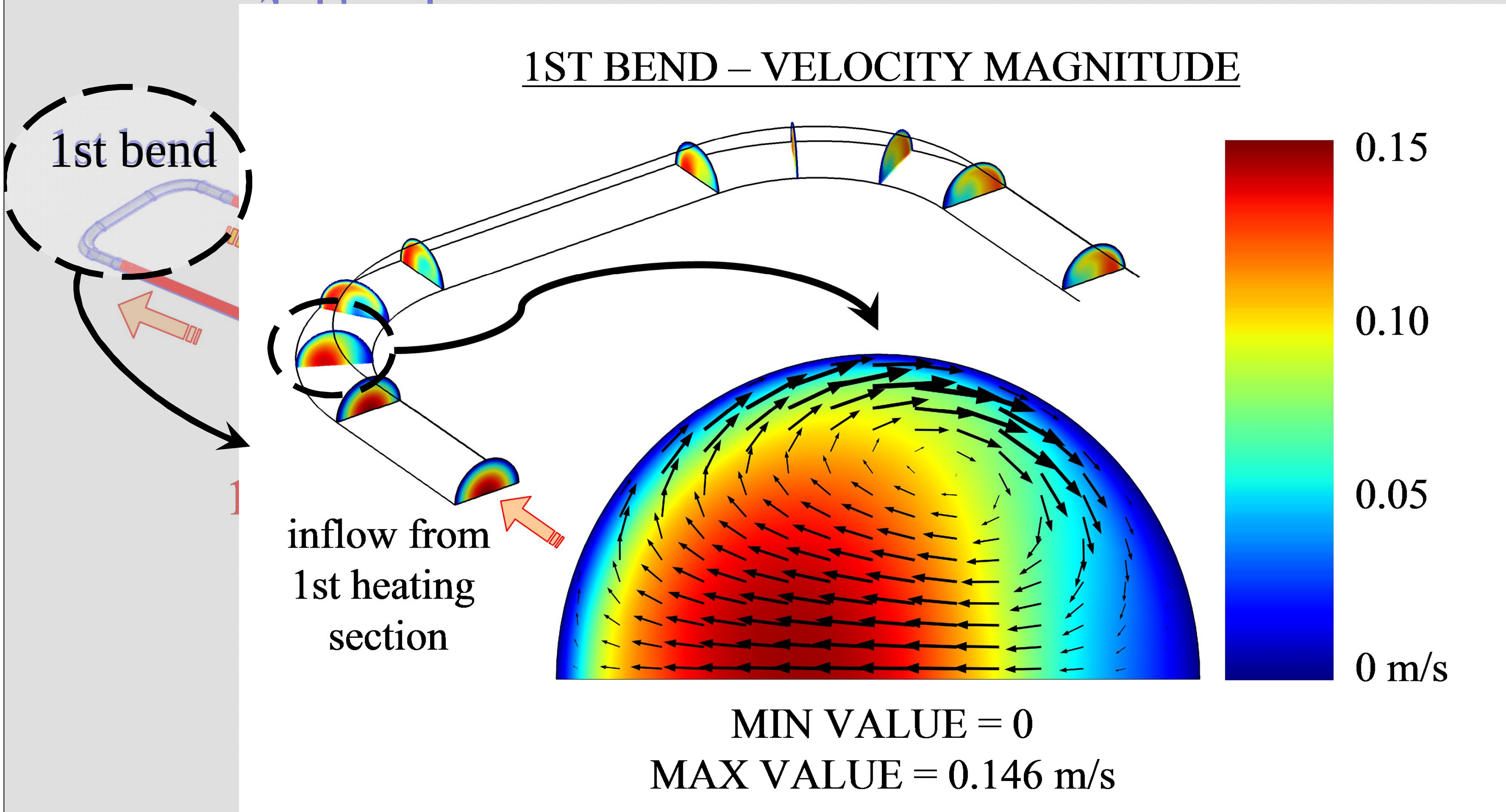
RESULTS: Secondary Flow



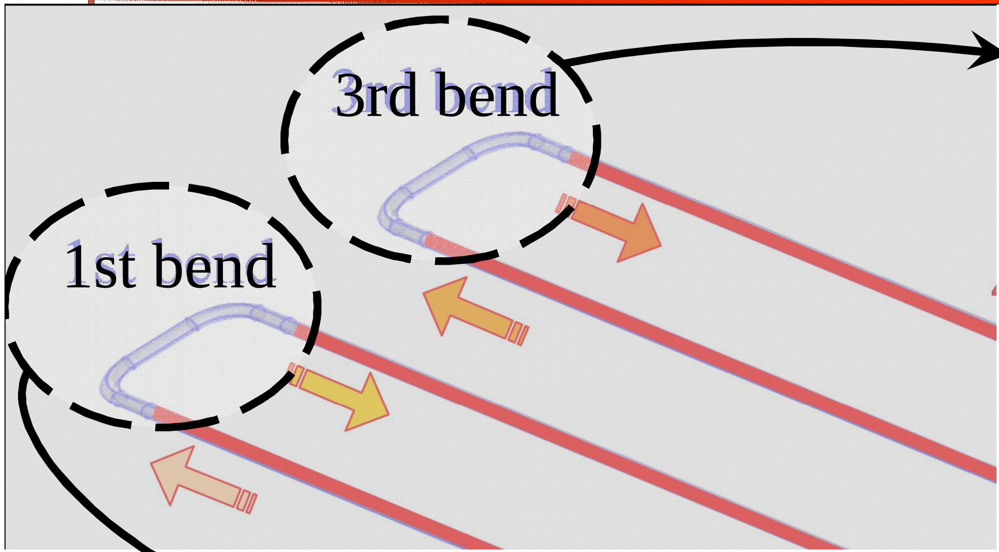

1ST BEND – VELOCITY MAGNITUDE
1st bend
inflow from
1st heating
section
0.15
0.10
0.05
0 m/s


1ST BEND
1st bend
inflow from
1st heating
section
inflow from
1st heating
section

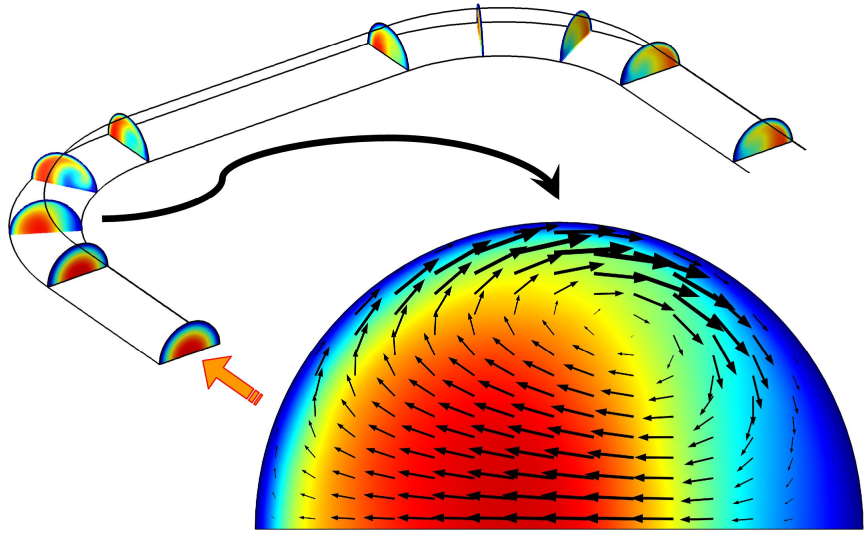
RESULTS: Secondary Flow



RESULTS: Secondary Flow and Product History

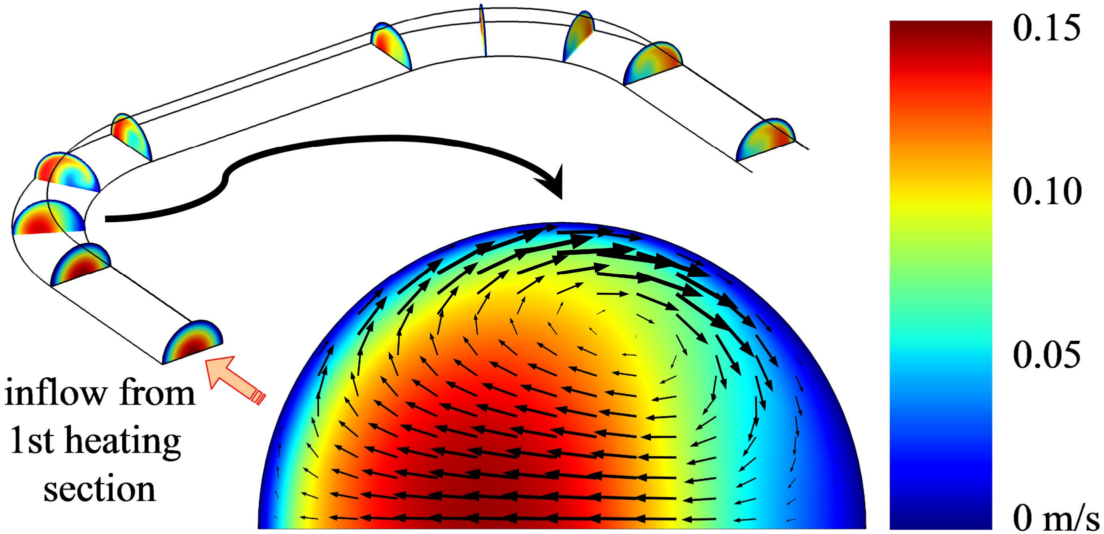


3RD BEND – VELOCITY MAGNITUDE

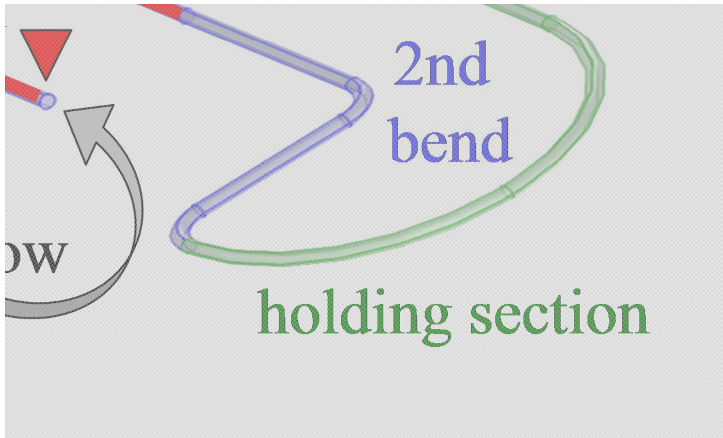


MIN VALUE = 0
MAX VALUE = 0.138 m/s

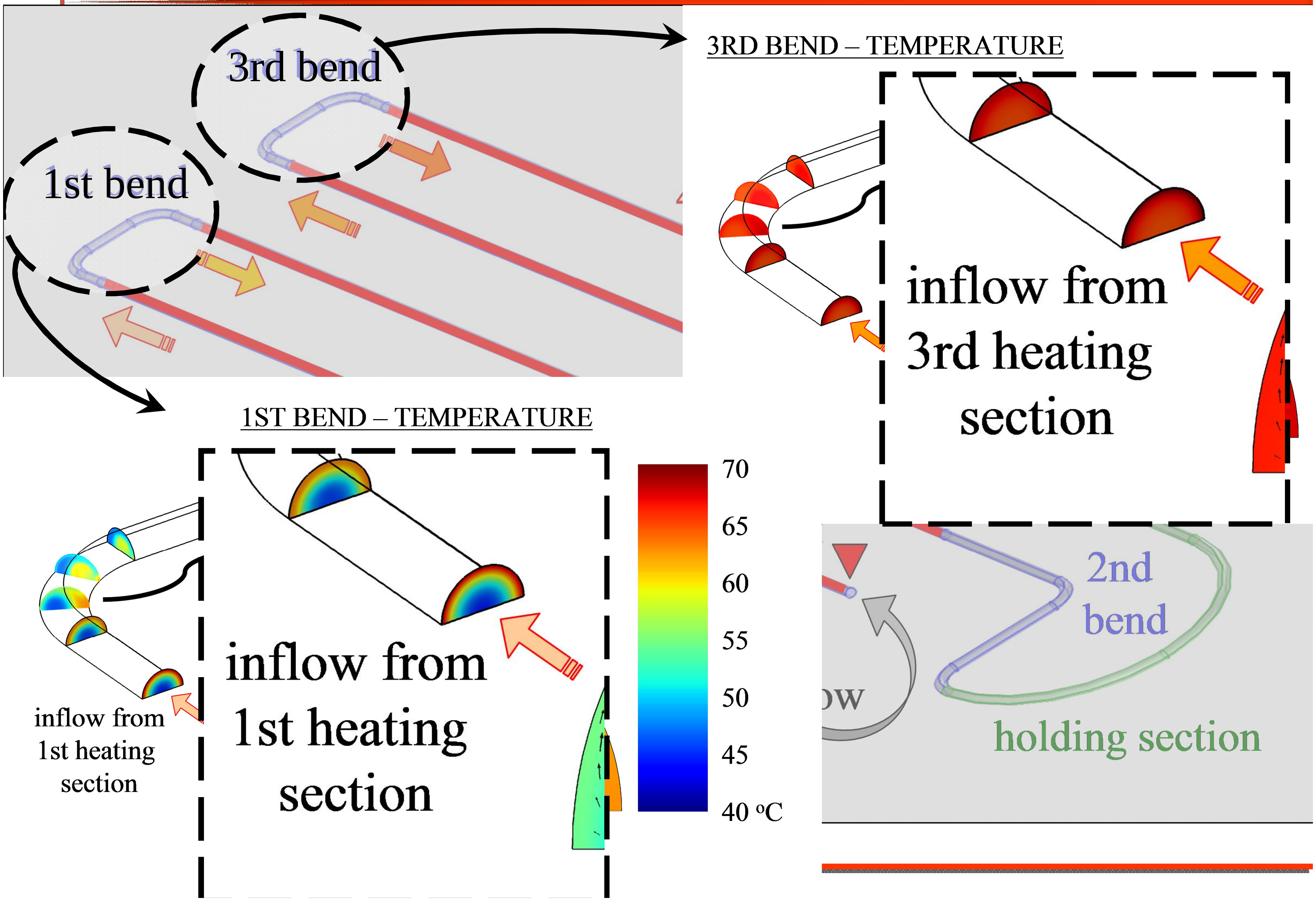
1ST BEND – VELOCITY MAGNITUDE



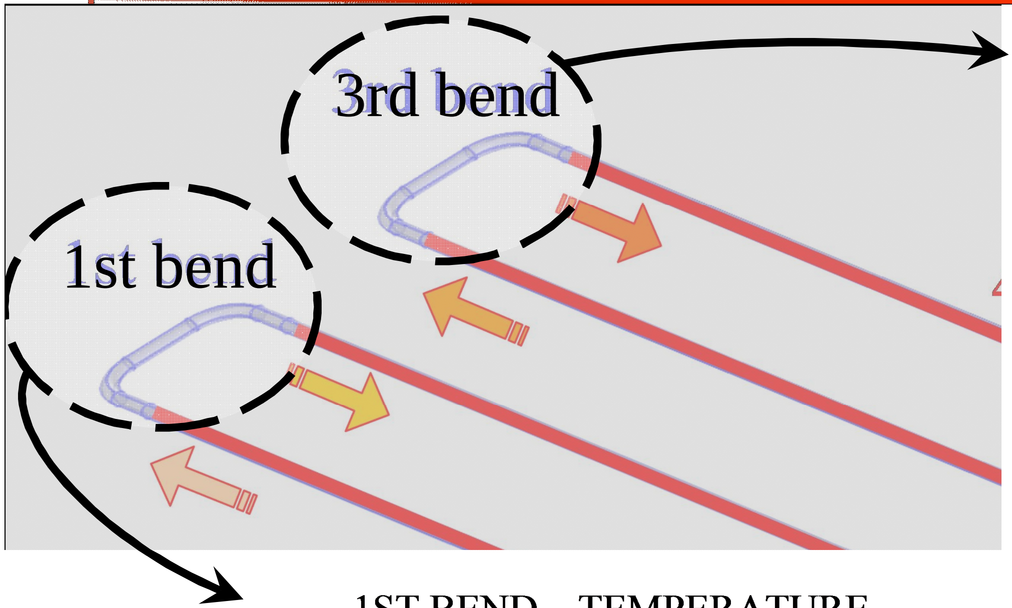
MIN VALUE = 0
MAX VALUE = 0.146 m/s



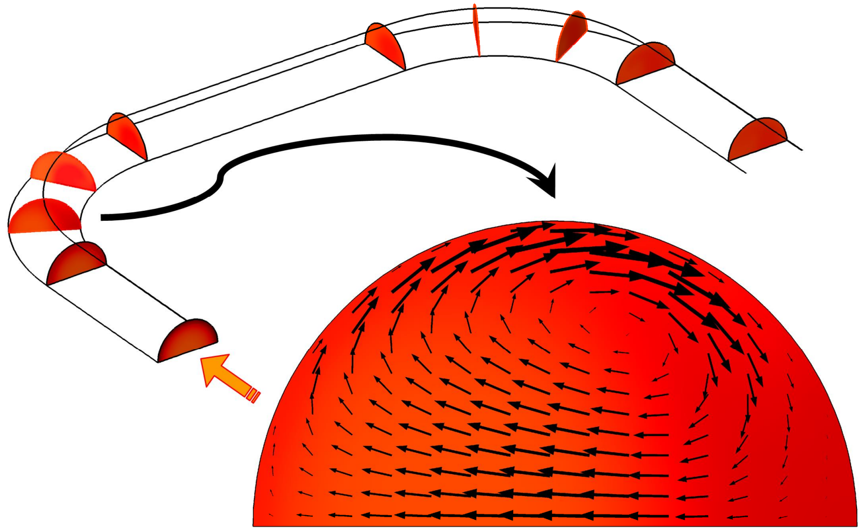
RESULTS: Temperature and Product History



RESULTS: Temperature and Product History

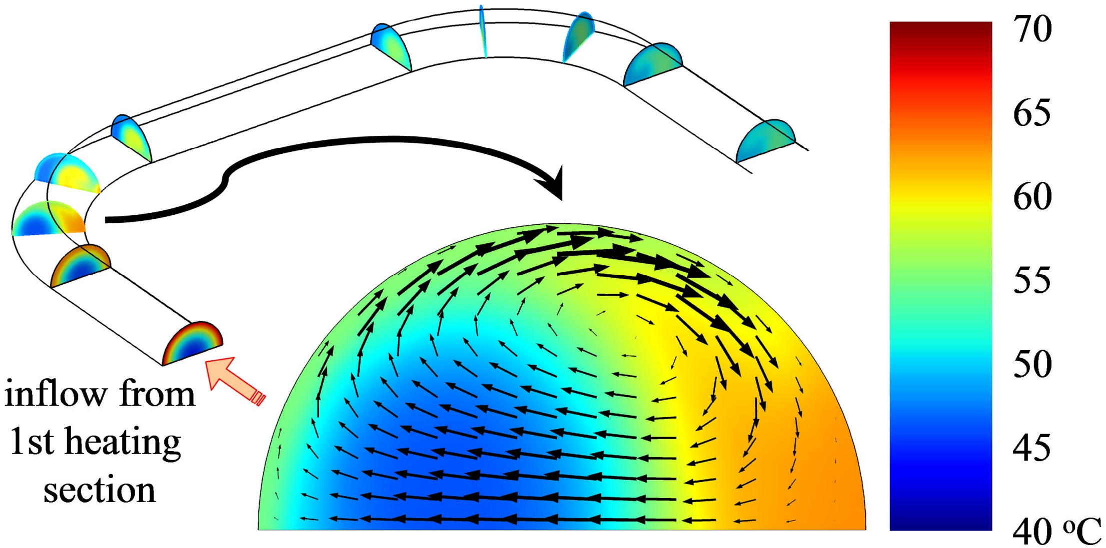


3RD BEND – TEMPERATURE

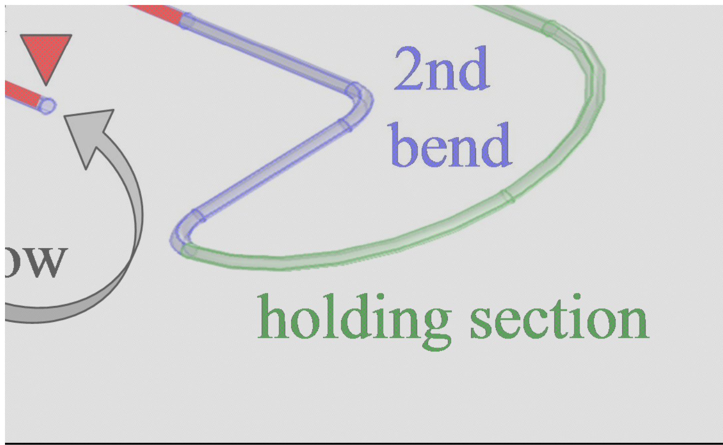


MIN VALUE = 64.1 °C
MAX VALUE = 67.6 °C

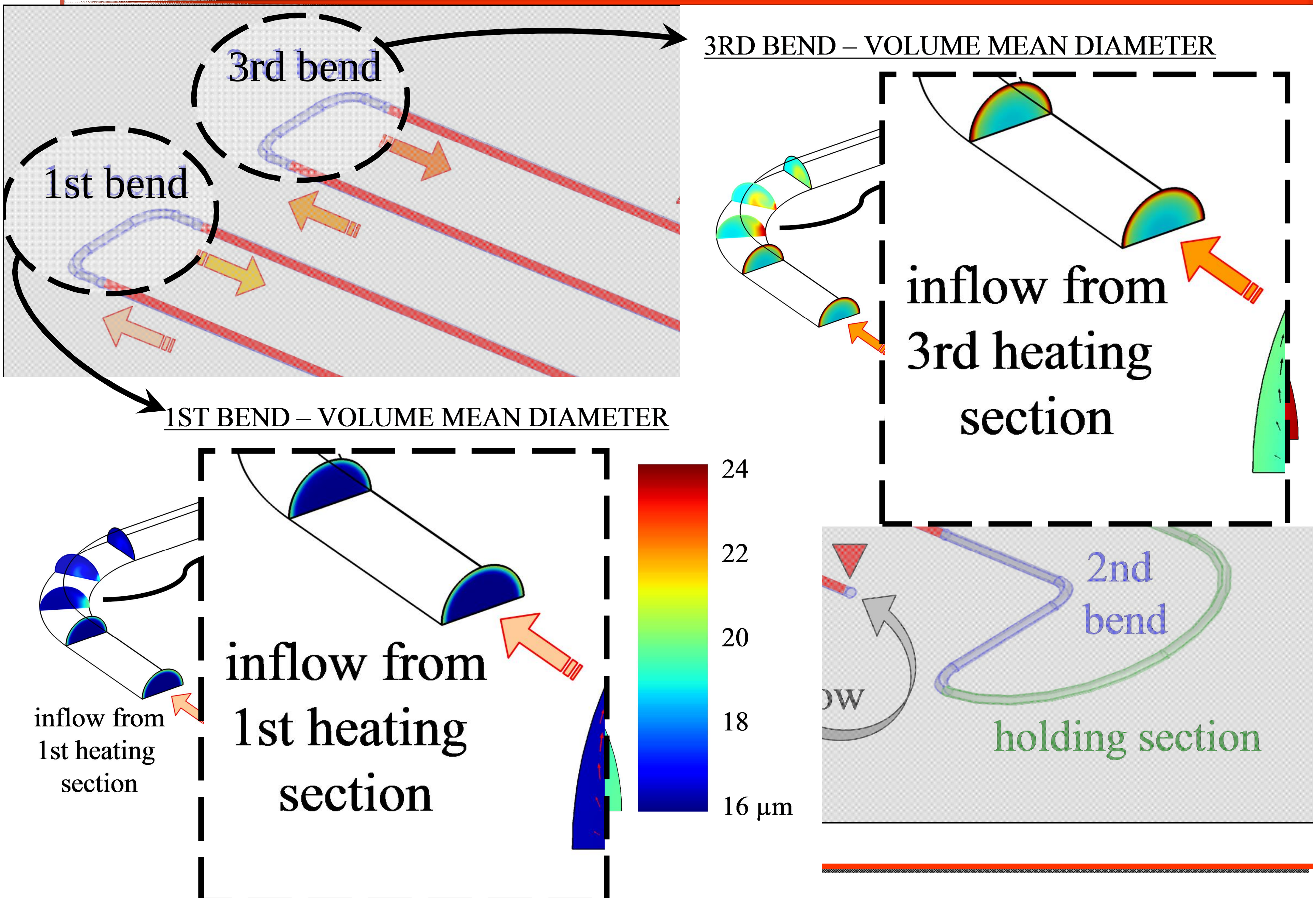
1ST BEND – TEMPERATURE



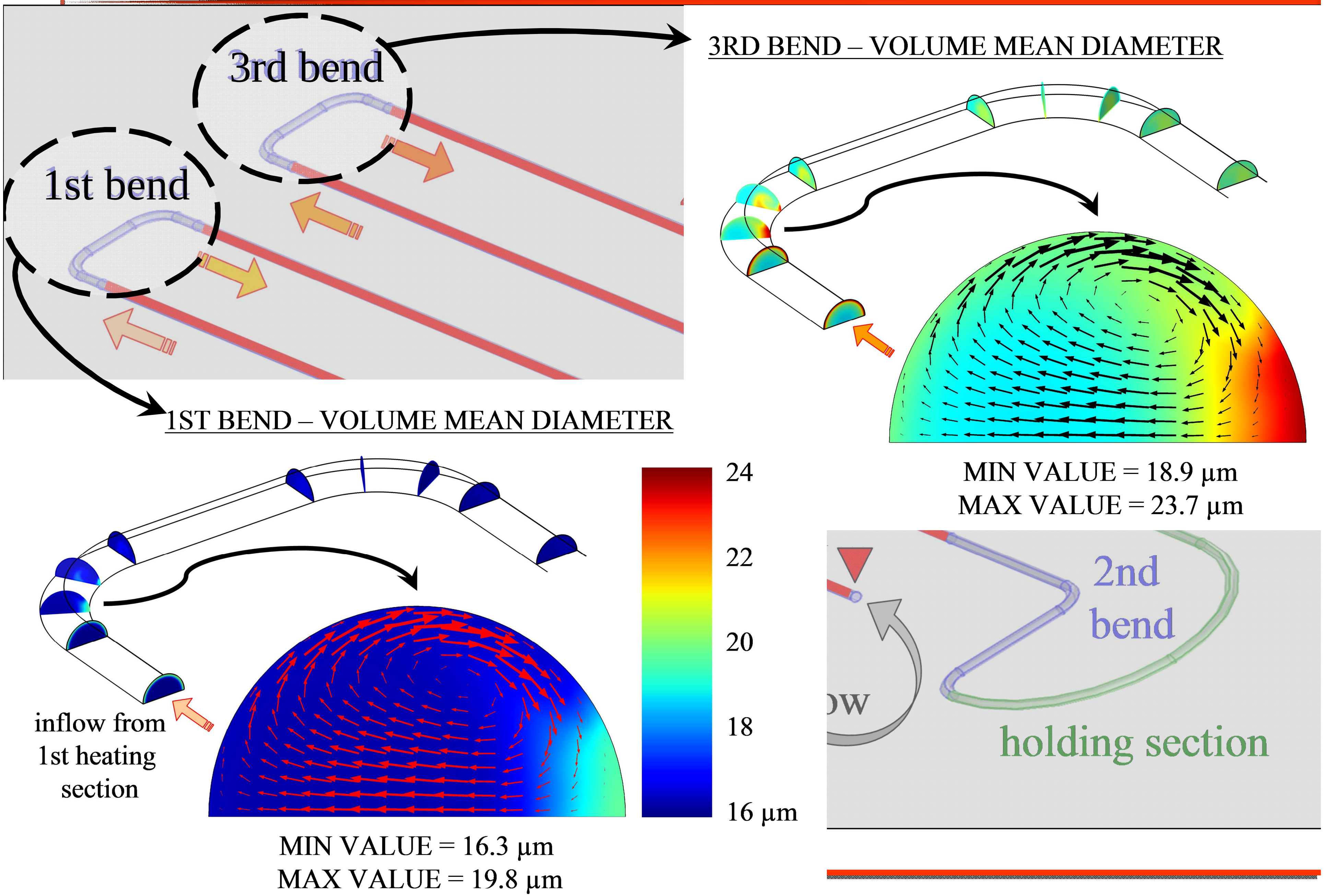
MIN VALUE = 46.2 °C
MAX VALUE = 62.1 °C



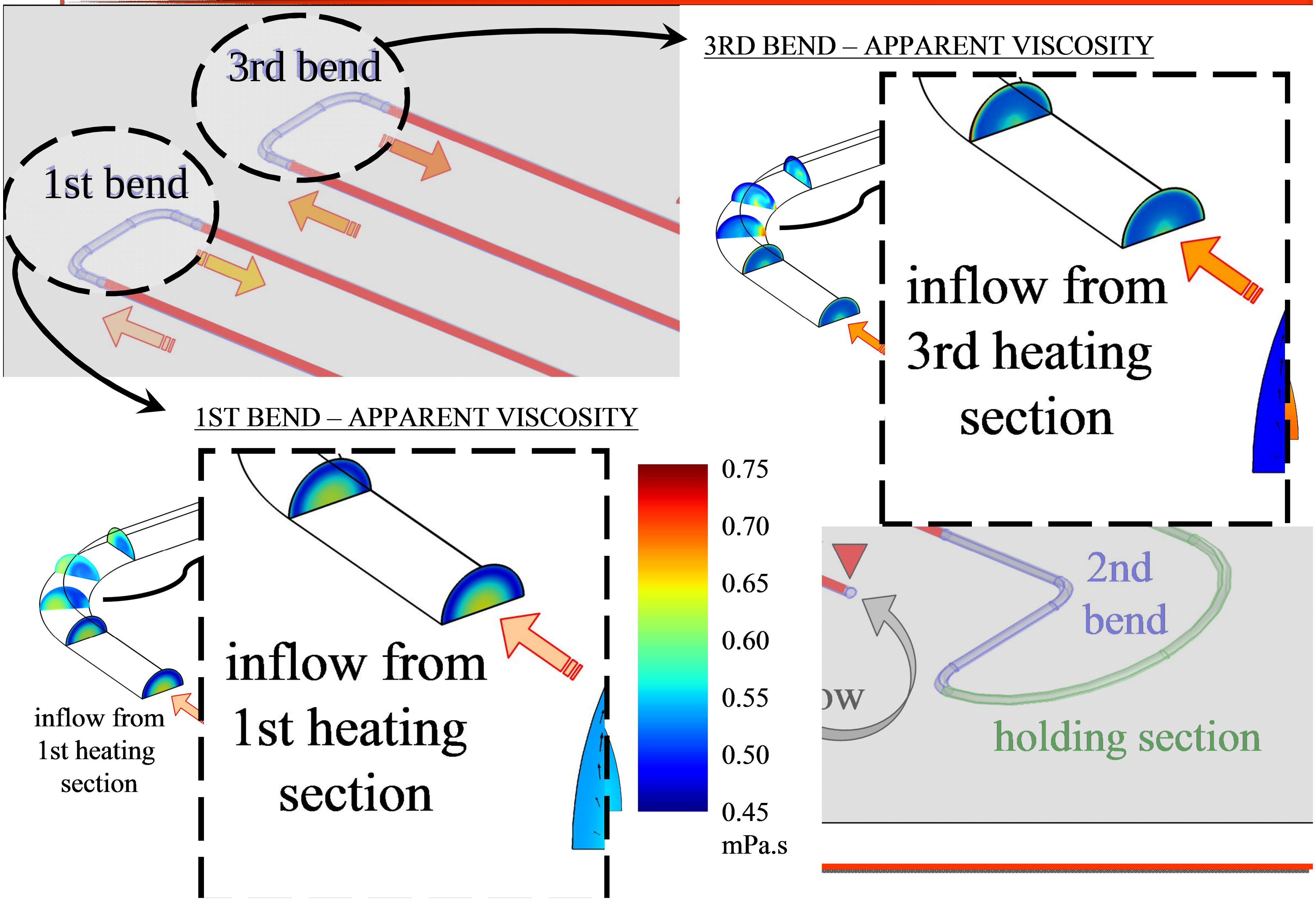
RESULTS: Transformation and Product History



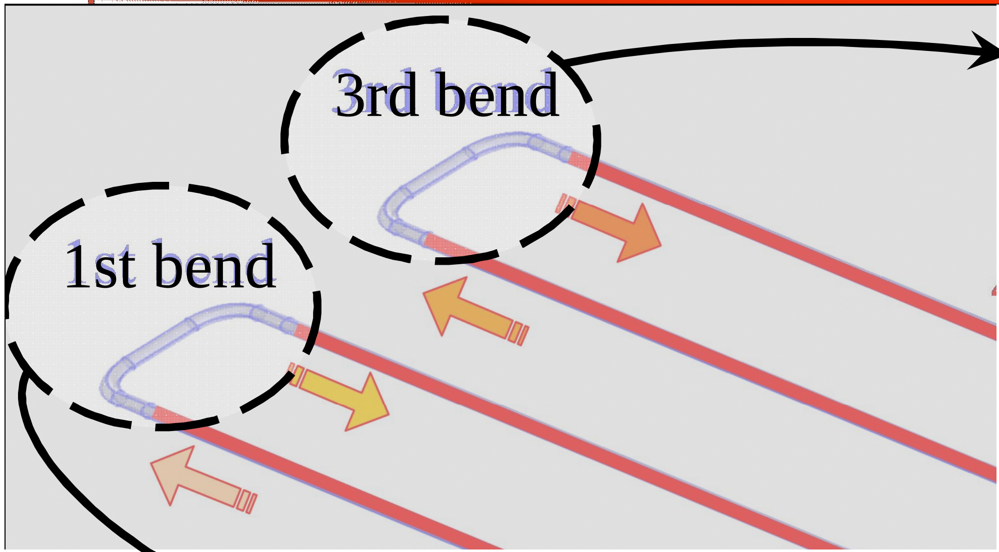
RESULTS: Transformation and Product History



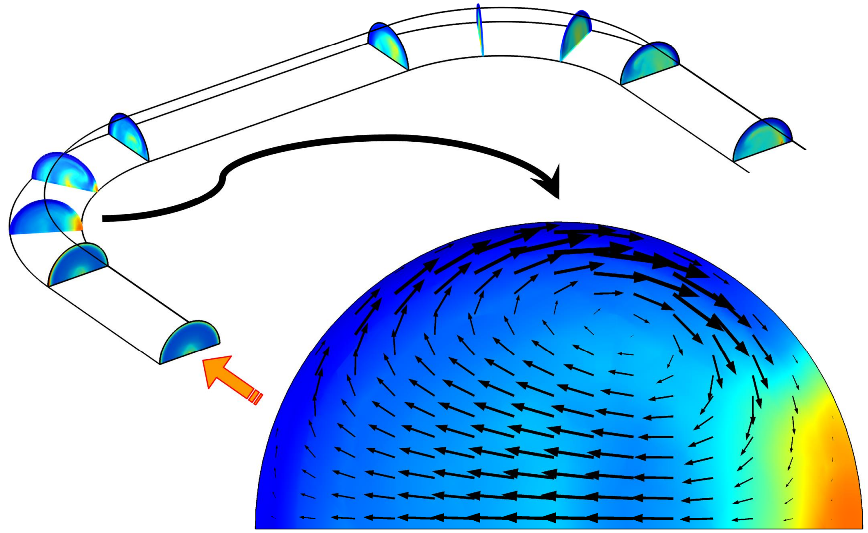
RESULTS: Apparent Viscosity and Product History



RESULTS: Apparent Viscosity and Product History

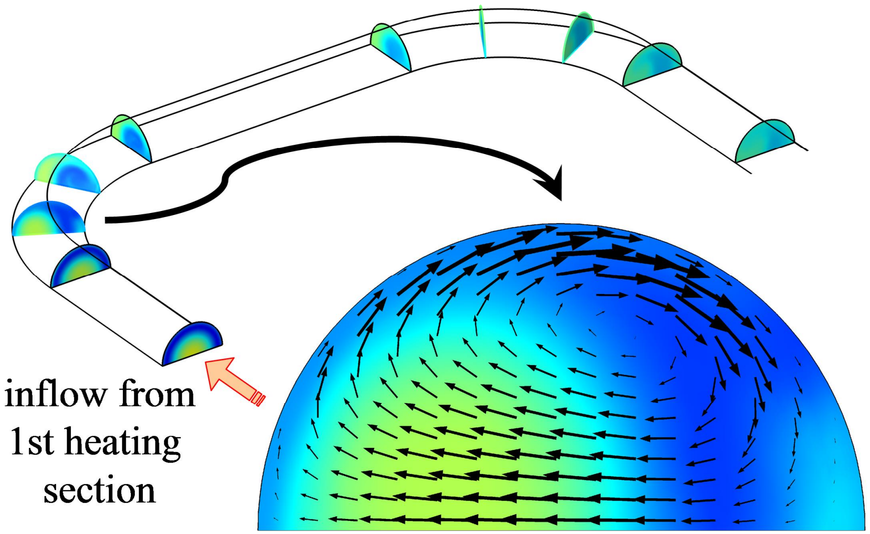


3RD BEND – APPARENT VISCOSITY

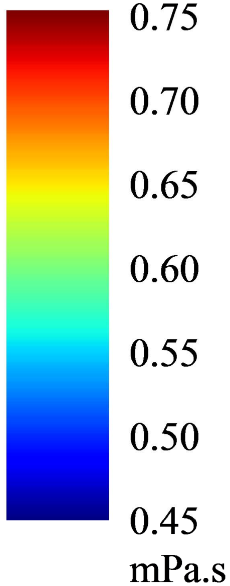


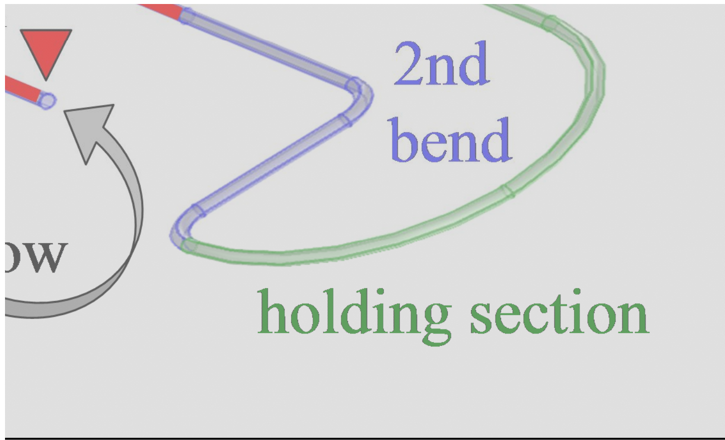
MIN VALUE = 0.465 mPa.s
MAX VALUE = 0.709 mPa.s

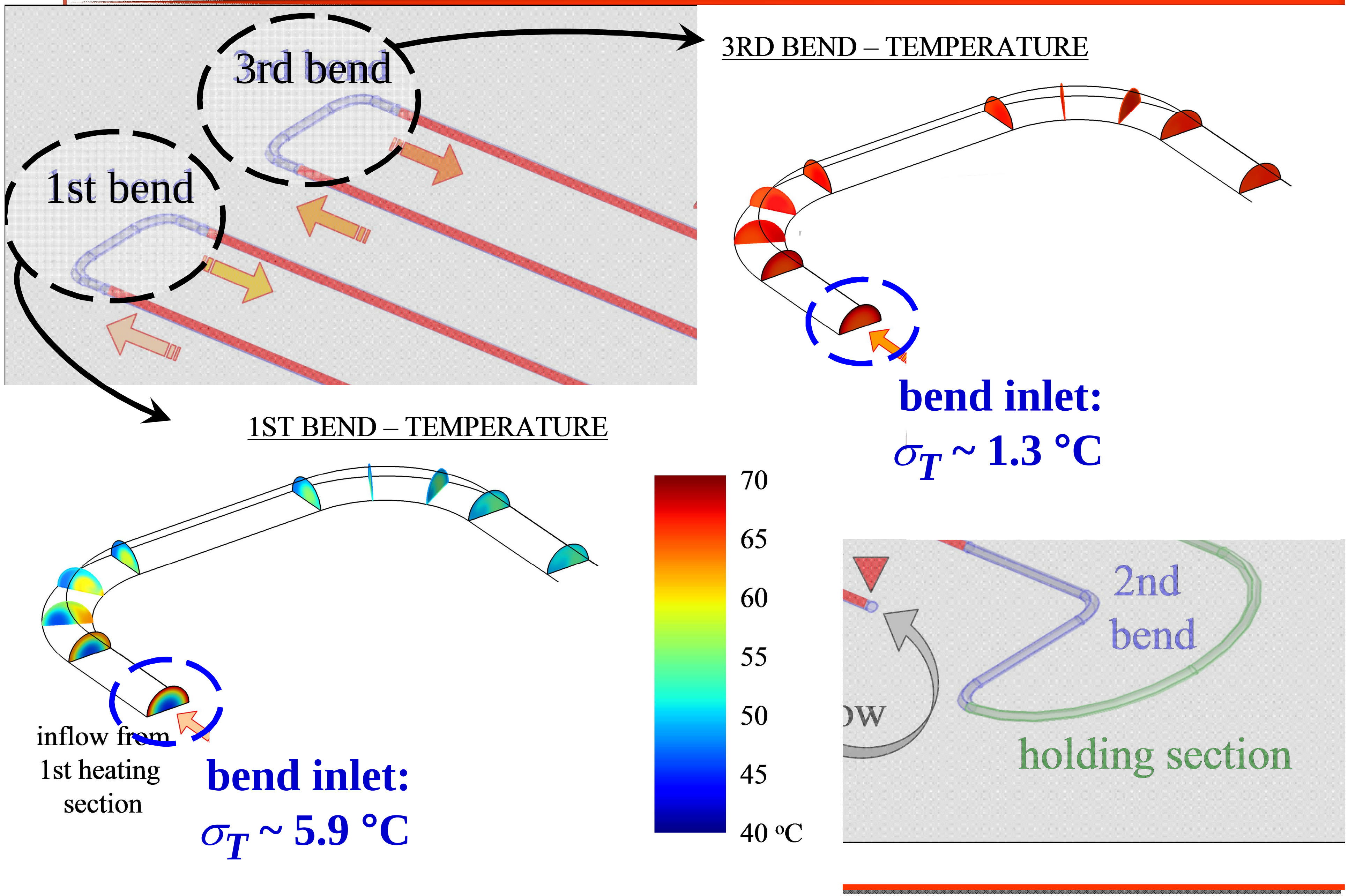
1ST BEND – APPARENT VISCOSITY

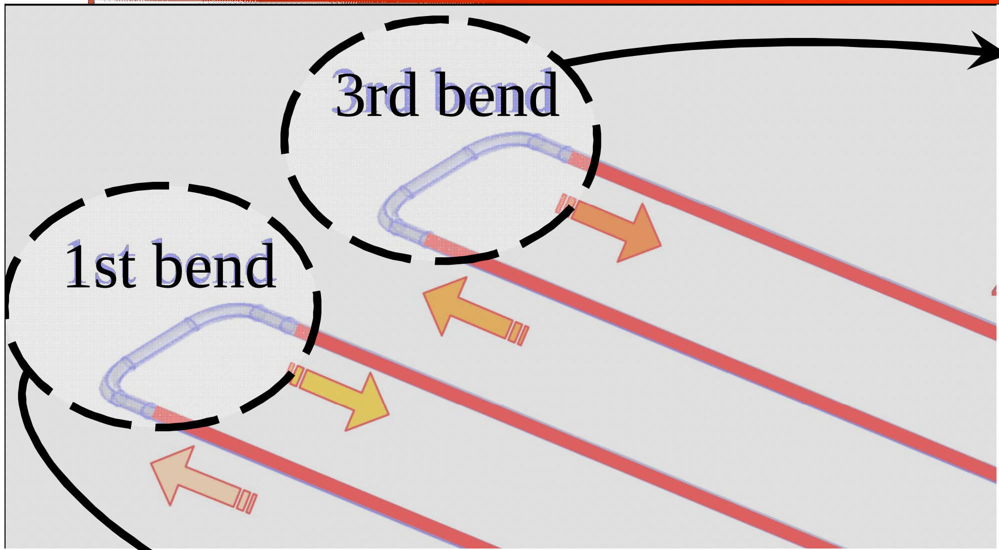


MIN VALUE = 0.504 mPa.s
MAX VALUE = 0.615 mPa.s

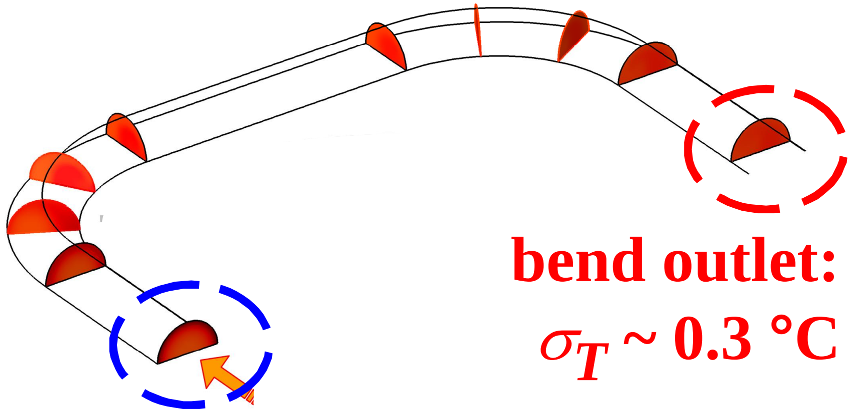





3rd bend
1st bend
3RD BEND – TEMPERATURE
bend inlet:
σ_T ~ 1.3 °C
1ST BEND – TEMPERATURE
inflow from
1st heating
section
bend inlet:
σ_T ~ 5.9 °C
70
65
60
55
50
45
40 ºC
2nd
bend
holding section



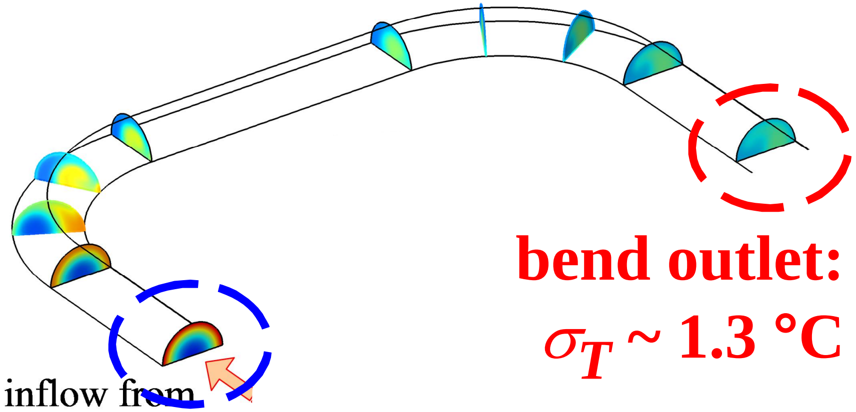
3RD BEND – TEMPERATURE



bend outlet:
σ_T **~ 0.3 °C**

bend inlet:
σ_T **~ 1.3 °C**

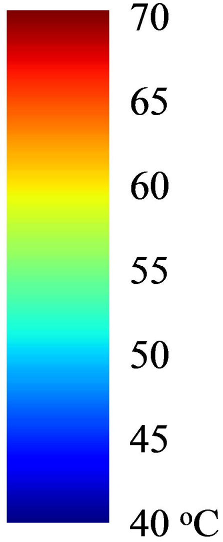
1ST BEND – TEMPERATURE

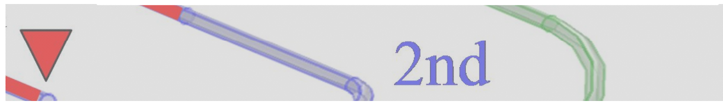


inflow from 1st heating section

bend outlet:
σ_T **~ 1.3 °C**

bend inlet:
σ_T **~ 5.9 °C**

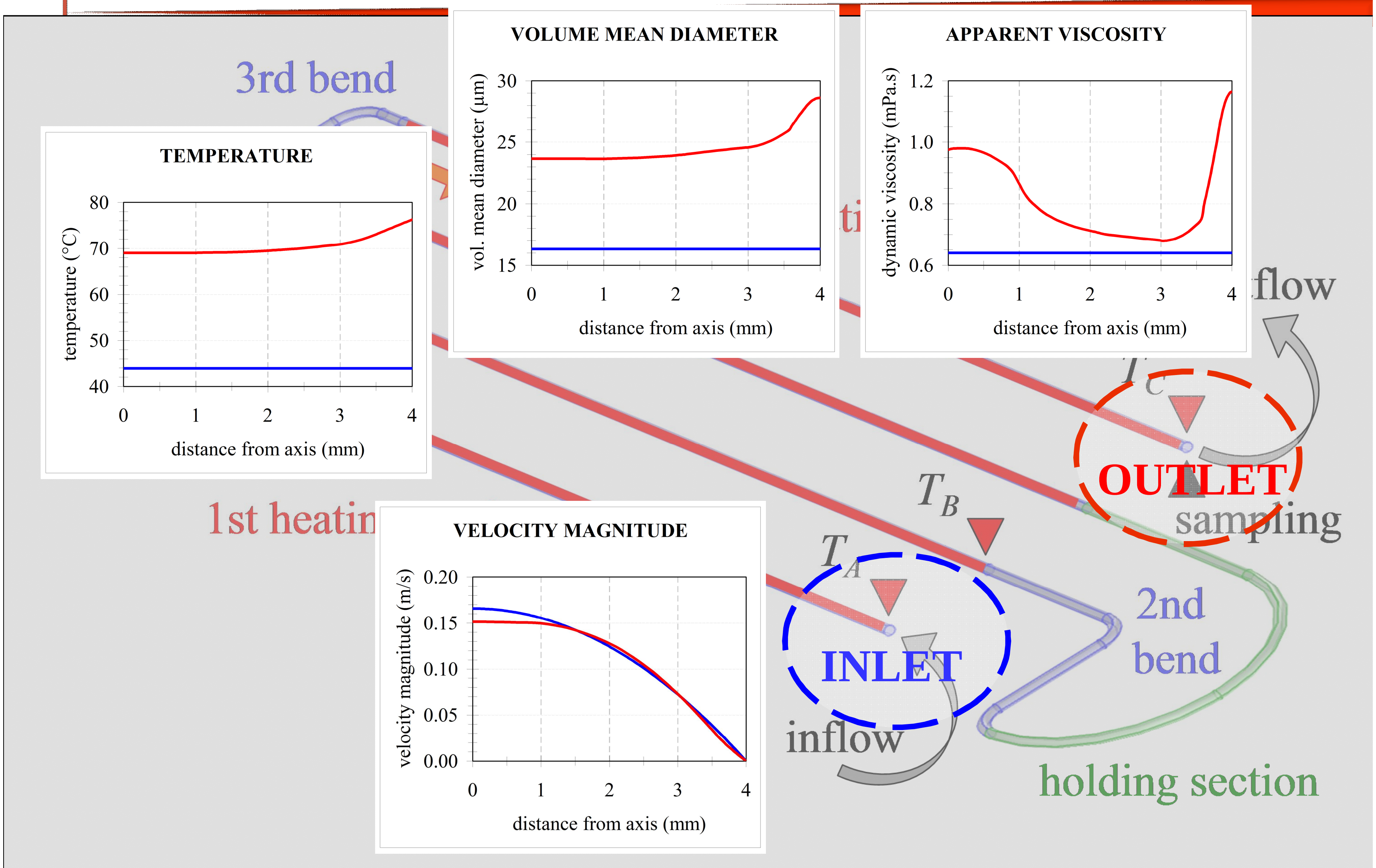




$\sigma_{T,outlet} / \sigma_{T,inlet}$ **~ 0.2**

mixing effectiveness ~ 80 %

RESULTS: Selected Variables at the Exchanger Inlet and Outlet



RESULTS: Comparison with Observations

- experimental value of the volume mean diameter of starch granules at the exchanger outlet (after sampling the product while running the heat exchanger):

  # 23.6 +/– 0.4 µm (three samples separated by five minutes)

- model prediction of the volume mean diameter of starch granules at the exchanger outlet:

  # 24.22 µm (minimum element size = R/6)

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  ... or δ_D = (23.6 ï 16.3) = 7.3 µm in diameter increase

- model prediction of the volume mean diameter of starch granules at the exchanger outlet:

  # 24.22 µm (minimum element size = R/6)

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RESULTS: Comparison with Observations

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- model prediction of the volume mean diameter of starch granules at the exchanger outlet:

  # 24.22 µm (minimum element size = R/6)

  ... or δ_D = (24.22 ï 16.3) = 7.9 µm (+8 %) in diameter increase

- influence of mesh resolution on these model predictions:

  # 24.18 µm (minimum element size = R/5)

  # 24.25 µm (minimum element size = R/7)

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- 3D numerical modeling of fluid flow, heat transfer and starch swelling under thermal continuous processing, **with no assumption regarding the mixing role played by curved sections**

  # **assessment of mixing:** σ_T **decreases to 20 % of its previous value (mixing effectiveness ~ 80 %)**

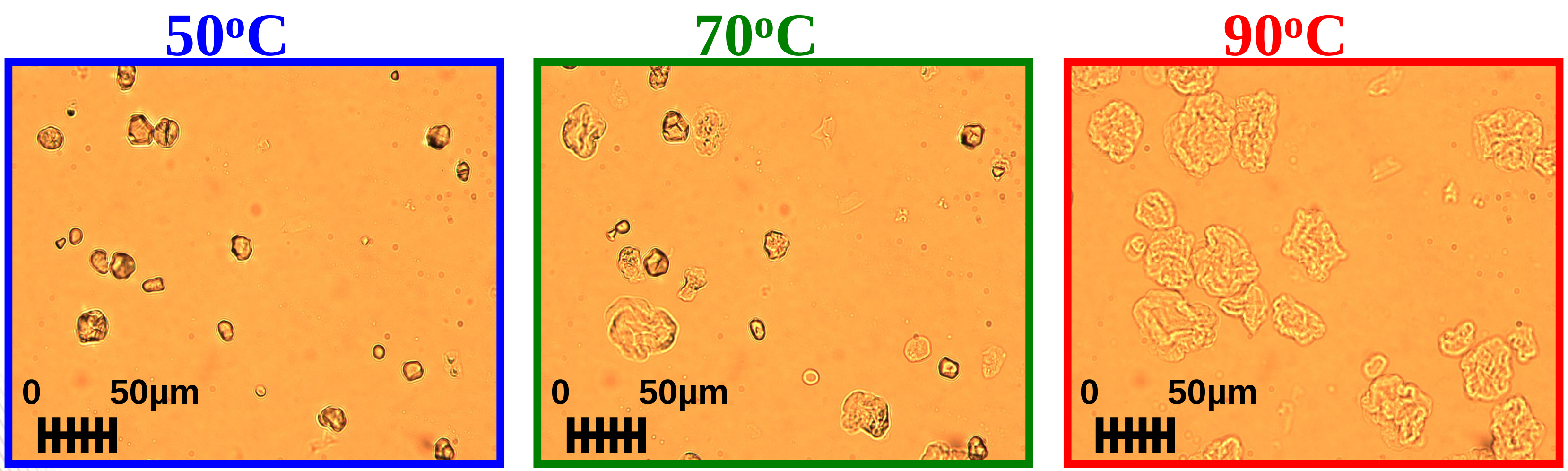
  # **reliability of model predictions: the increase** $\delta_D = (D - D_0)$ **in volume mean diameter is overestimated by about 8 % at the heat exchanger outlet**

  # **computational resources: hundreds of Gb RAM, some days**

- looking for more realistic representation of starch swelling kinetics

  # observations with an optical microscope coupled to a warming plate, in order to follow the behavior of starch granules during thermal treatments

  # in the case of modified waxy maize starch, the swelling mechanism exhibits some stochastic nature, associated with diffusion of surrounding water into the starch granule.



Plana-Fattori et. (2015), 12th International Congress on Engineering and Food, Quebec City