forschen.
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09.05.2023
2. Sitzung des Projektbegleitenden Ausschusses

HELIOS Project: Modeling and simulation of nanomaterial-based liquids in solar thermal (Nano-Solarfluid) in OpenFOAM®

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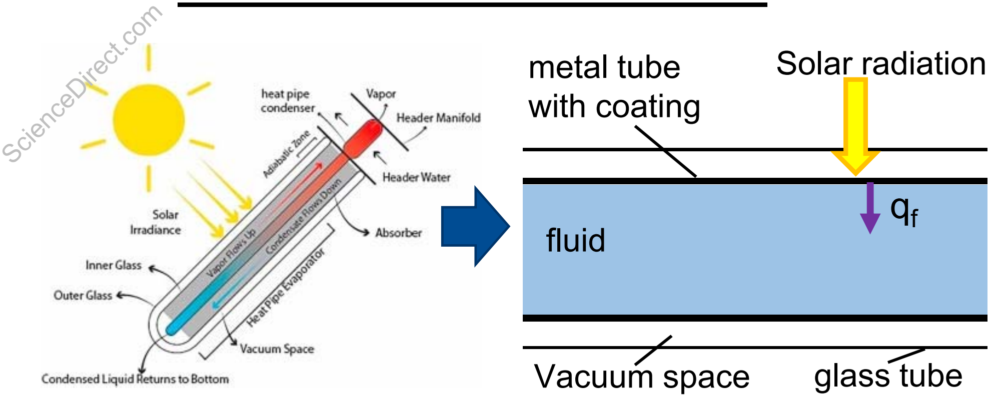
Mitglied der Johannes-Rau-Forschungsgemeinschaft JRF

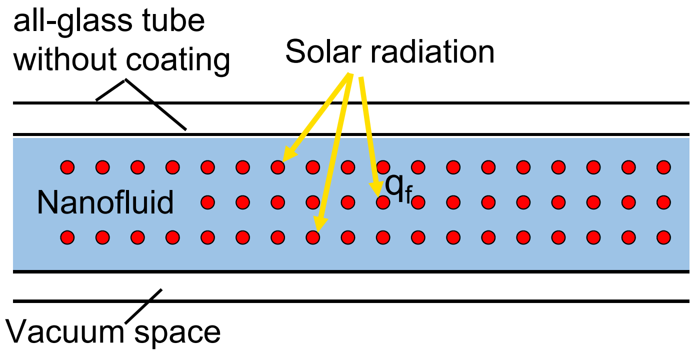
AiF Mitglied

Aim

Conventional solar collectors



Nanofluid solar collectors



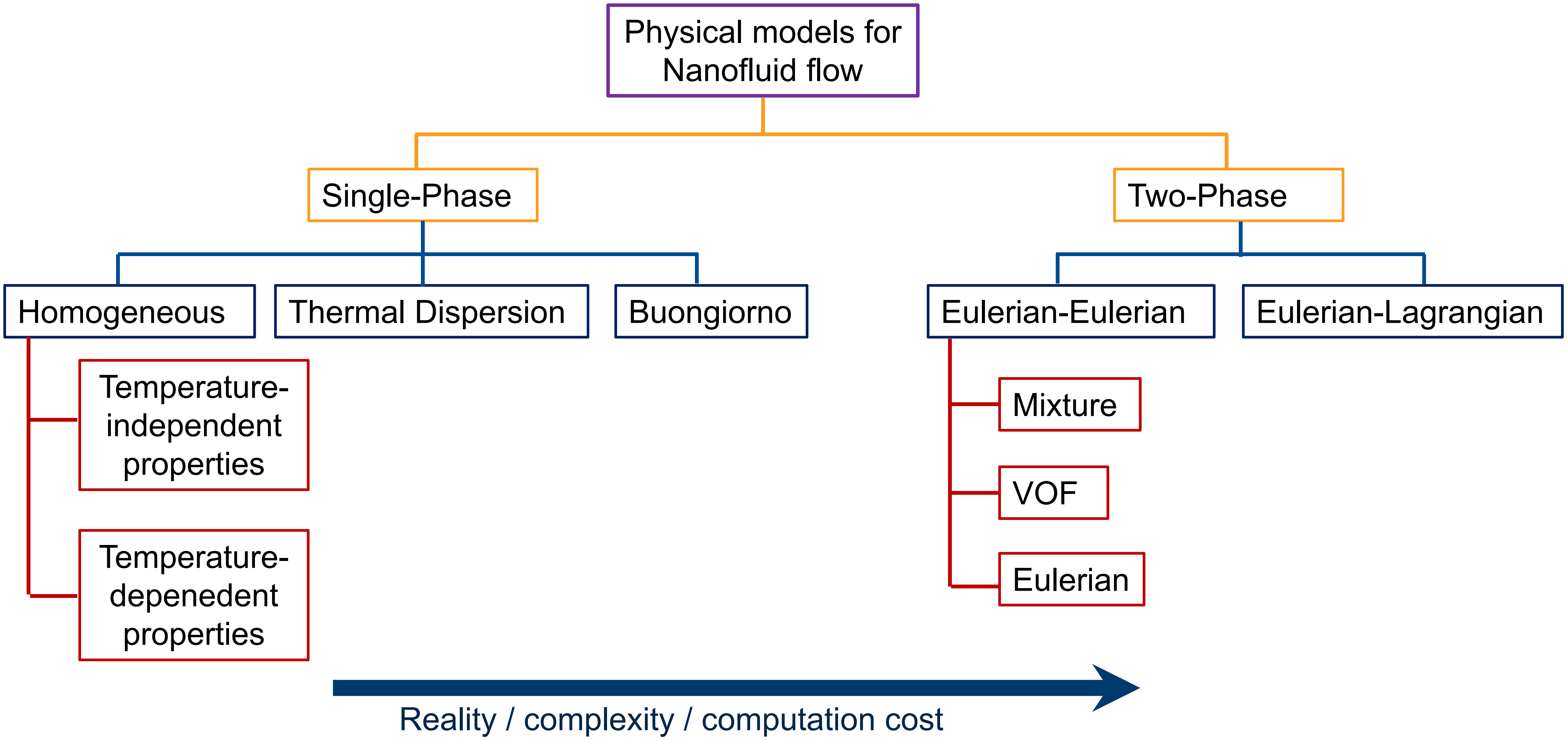
Background:

- ❑ Application of Nanofluid due to its mass and heat transfer enhancements:
  - ❖ Biomedical, Automobile, Aerospace, Microchannel, Optical, Detergency, Military, Solar energy (solar collectors)

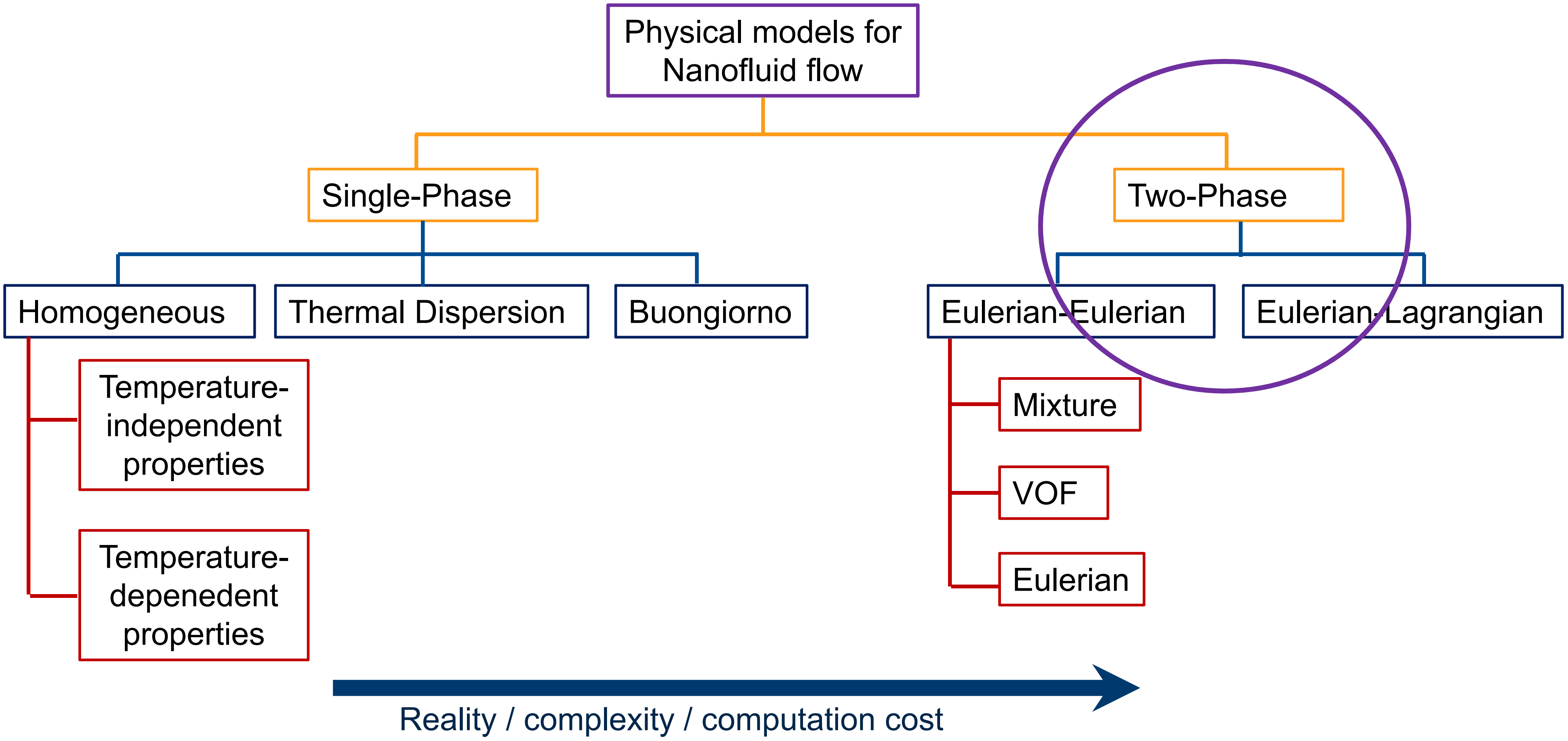
Aim:

- ❑ Modelling the **Nano-Solar fluid** in OpenFOAM
  - ❖ Investigate the effect of particle concentration on the viscosity of fluid → pumping power
  - ❖ Optimization of the dispersion properties of the solar absorber fluids

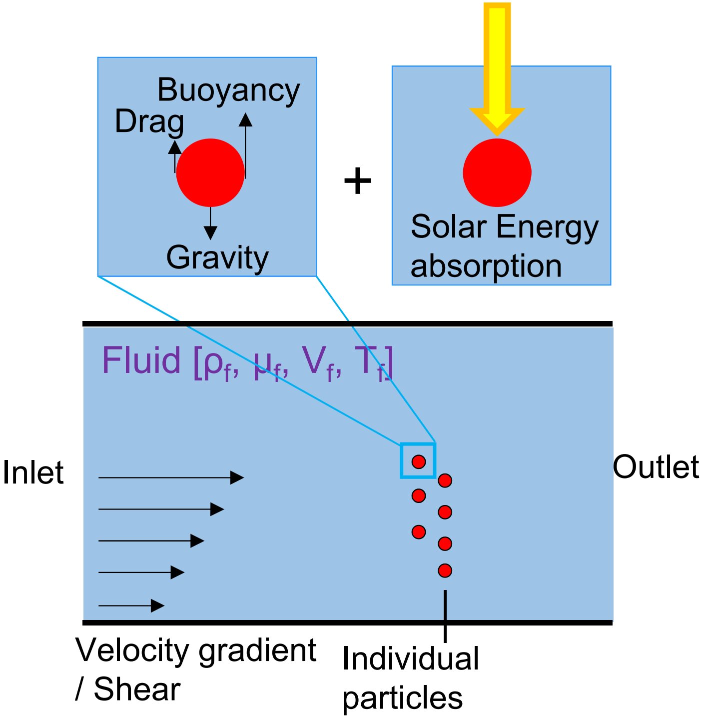
Nano-Solarfluid modelling: Simulation approaches



Nano-Solarfluid modelling: Simulation approaches



Nano-Solarfluid modelling: 2-Phases approach



Fluid phase (Euler approach)

- Conservation of mass and momentum: → **U** & p distributions of fluid

$$\underbrace{\nabla\cdot\mathbf{U}_f=0}_{Mass\ cons.}\qquad \underbrace{\frac{\partial(\rho_f\mathbf{U}_f)}{\partial t}}_{Temporal}+\underbrace{\nabla\cdot(\rho_f\mathbf{U}_f\mathbf{U}_f)}_{Advection}=\underbrace{-\nabla p}_{Pressure\ force}+\underbrace{\nabla\cdot(\mu_f\nabla\mathbf{U}_f)}_{Diffu./Turbulence}\boxed{+\frac{1}{\delta V}\sum_{np}\mathbf{F}}$$

- Conservation of energy: → Temperature distribution of fluid

$$\underbrace{\frac{\partial(\rho_f c_{p,f}T_f)}{\partial t}}_{Temporal}+\underbrace{\nabla\cdot(\rho_f c_{p,f}\mathbf{U}_f T_f)}_{\text{Advection by fluid velocity}}=\underbrace{\nabla\cdot(k_f\nabla T_f)}_{Diffusion}\boxed{+\frac{1}{\delta V}\sum_{np}Nu_p\pi d_p k_f(T_f-T_p)}$$

Particles (Lagrange approach)

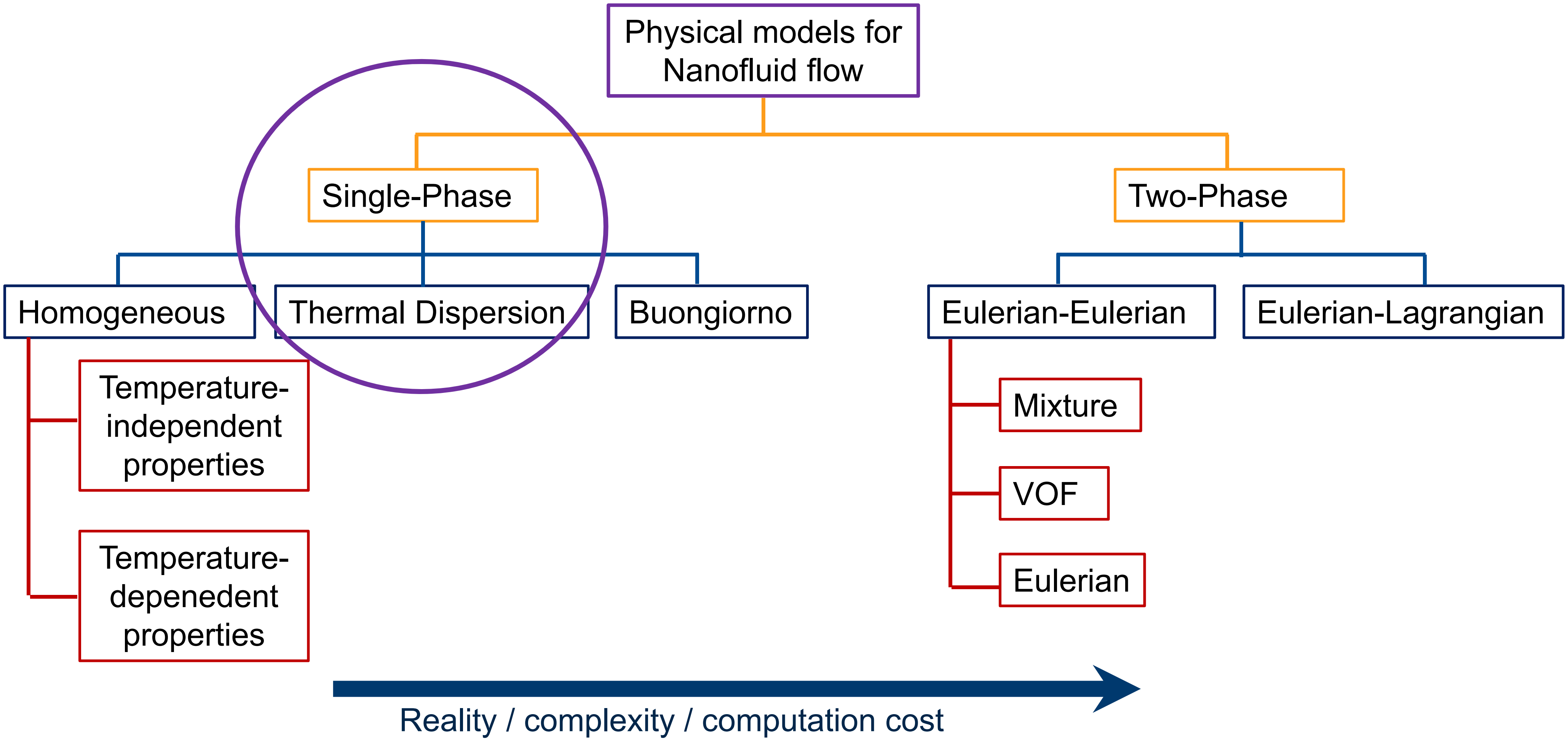
- The particle motion and energy equations: → **x**, **U**, T of particles

$$\boxed{m_P\frac{d\mathbf{u}_P}{dt}=\sum\mathbf{F}=\mathbf{F}_g+\mathbf{F}_D+\mathbf{F}_L+\mathbf{F}_{Br}+\mathbf{F}_b}\qquad\boxed{m_P c_{p,p}\frac{dT_P}{dt}=Nu_p\pi d_p k_f(T_f-T_p)+S_{E,p}}$$

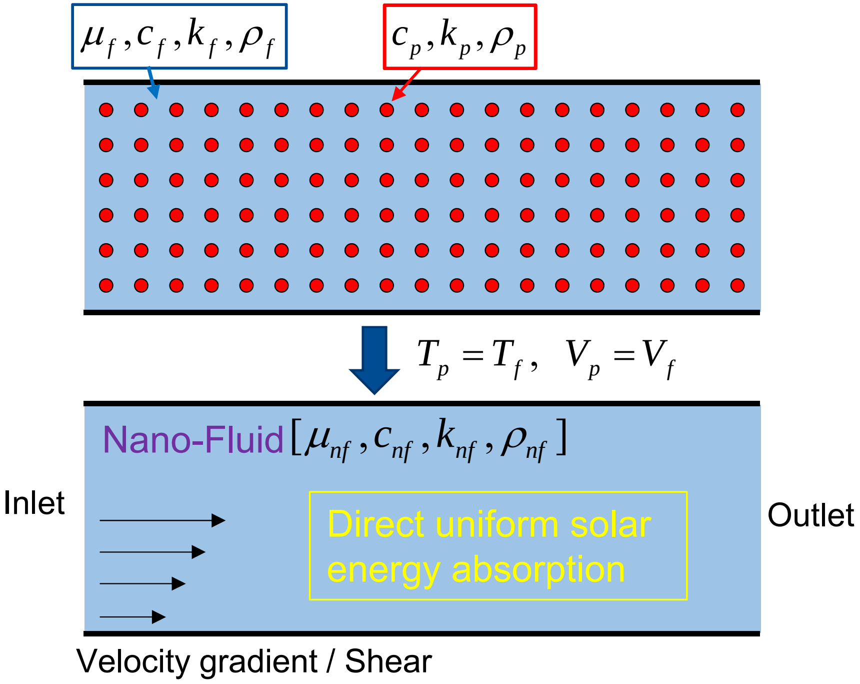
Pro and cons:

- Since it involves more physical phenomena, it provides more reliable results – closer to experiment data.
- Computationally costly – higher CPU and memory requirement - since it computes the trajectories of each particle

Nano-Solarfluid modelling – Simulation approaches



Nano-Solarfluid modelling: 1-Phase approach



Homogenous model:

- Assumptions:
  - Incompressible flow; No slip between particles and fluids
  - Ultrafine solid particles and dispersed uniformly
  - Both phases are locally in thermal equilibrium
  - No chemical reactions; Negligible viscous dissipation
- The pressure, velocity and temperature can calculated by:

$$\underbrace{\nabla \cdot \mathbf{U} = 0}_{\text{Mass balance}} \qquad \underbrace{\frac{\partial(\rho_{nf}\mathbf{U})}{\partial t}}_{\text{Temporal}} + \underbrace{\nabla \cdot (\rho_{nf}\mathbf{U}\mathbf{U})}_{\text{Advection}} = \underbrace{-\nabla p}_{\text{Pressure Force}} + \underbrace{\nabla \cdot (\mu_{nf}\nabla \mathbf{U})}_{\text{Diffusion}} + \mathbf{F}$$

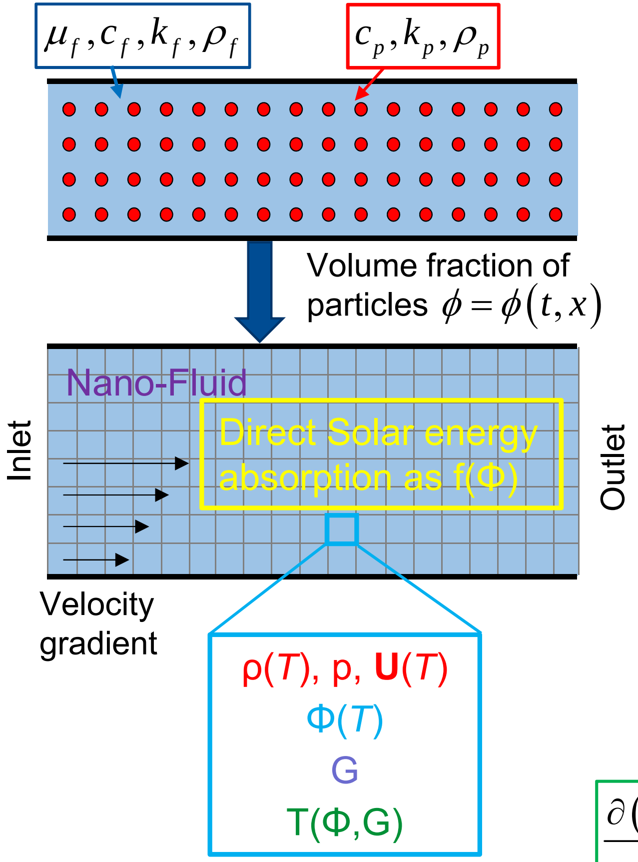
$$\underbrace{\frac{\partial(\rho_{nf}c_{nf}T)}{\partial t}}_{\text{Temporal}} + \underbrace{\nabla \cdot (\rho_{nf}c_{nf}\mathbf{U}T)}_{\text{Advection by fluid velocity}} = \underbrace{\nabla \cdot (k_{nf}\nabla T)}_{\text{Diffusion}} + S_{E,nf}$$

- Thermophysical properties: constant or temperature dependent

Note:

- These transport equations do not give any additional information for the natural convection in enclosures problem where the walls have either constant temperature or adiabatic condition.
  - Heat transfer enhancement: the ratio of nanofluid thermophysical properties to base fluid properties
- Require non-homogenous model for nanosolar fluid

Nano-Solarfluid modelling: intermediate approach



Nano-solarfluid model:

- ❑ Non-uniform dispersion → Particle phase as vol. fraction (concentration)
  - o Buoyancy effects by Boussinesq approximation for fluid phase
  - o Thermophoresis and Brownian diffusion for particle concentration

- ❑ The pressure and velocity can be calculated by:

$$\underbrace{\nabla \cdot \mathbf{U} = 0}_{\text{Mass balance}}$$

$$\underbrace{\frac{\partial(\rho\mathbf{U})}{\partial t}}_{\text{Temporal}} + \underbrace{\rho(\mathbf{U}\cdot\nabla)\mathbf{U}}_{\text{Advection of fluid}} = \underbrace{-\nabla p}_{\text{Pressure Force}} + \underbrace{\nabla\cdot\left(\mu(\phi)D(\mathbf{U})\right)}_{\text{Diffusion/Turbulence}} - \underbrace{\rho\beta\mathbf{g}(T - T_0)}_{\text{Buoyancy-Boussinesq}}$$

- ❑ The particle phase fraction and radiation intensity distributions are given by:

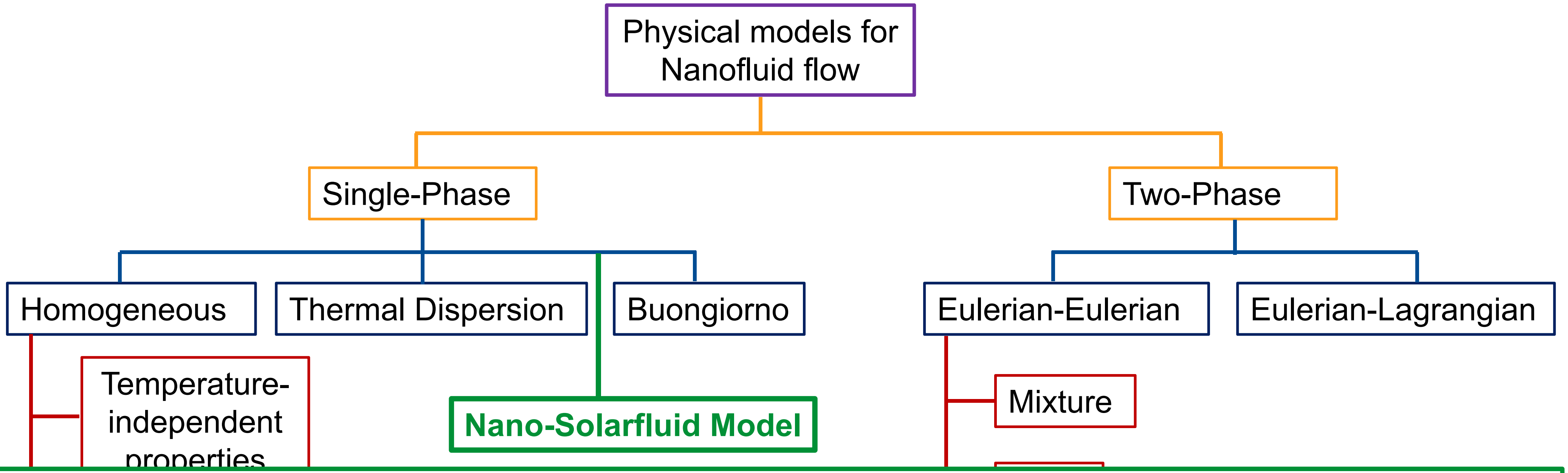
$$\underbrace{\frac{\partial\phi}{\partial t}}_{\text{Temporal}} + \underbrace{\mathbf{U}\cdot\nabla\phi}_{\text{Advection}} = \underbrace{\nabla\cdot\left[D_B\nabla\phi + D_T\frac{\nabla T}{T_0}\right]}_{\text{Thermophoresis \& Brownian diffu.}}$$

$$\nabla\cdot\left(\frac{1}{3\kappa\phi + \sigma_s(3 - C)}\nabla G\right) - \kappa\phi G = -4\left(e\sigma_{SB}T^4 + E\right)$$

- ❑ The temperature distribution is given by:

$$\underbrace{\frac{\partial(\rho c T)}{\partial t}}_{\text{Temporal}} + \underbrace{\nabla\cdot(\rho c\mathbf{U}T)}_{\text{Advection by fluid}} = \underbrace{\nabla\cdot(k_{nf}\nabla T)}_{\text{Thermal diffusion}} + \rho c_p \underbrace{\left[D_B\nabla\phi\cdot\nabla T + D_T\frac{\nabla T\cdot\nabla T}{T_0}\right]}_{\text{Brownian diffusion and thermophoresis}} + \underbrace{\kappa\phi G - 4\left(e\sigma_{SB}T^4 + E\right)}_{\text{Absorbed and emitted irradiation}}$$

Nano-Solarfluid modelling – Simulation approaches

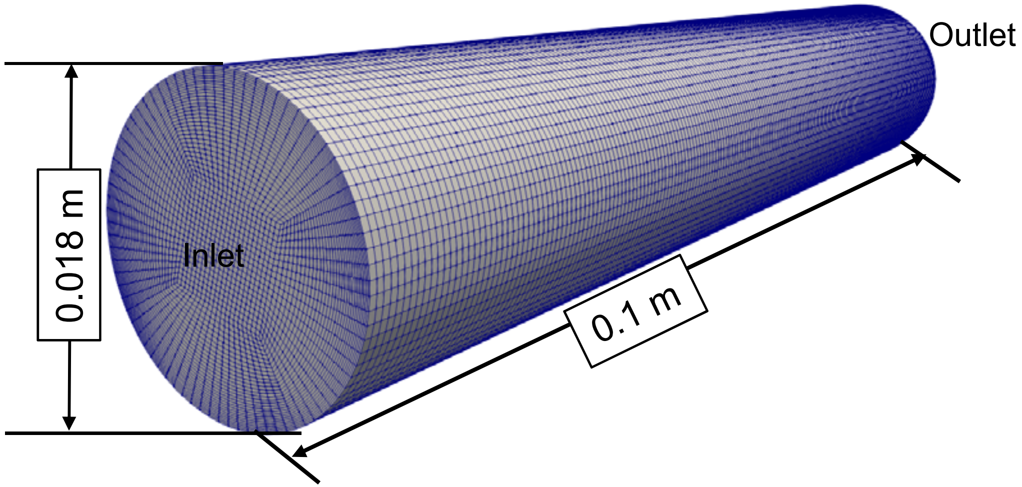


Advantages:
- ❑ Still computationally cheaper due to single phase approach (particle concentration in Eulerian frame)
- ❑ Simulation for any number of nano-particles with considering both most important slip mechanisms: Brownian diffusion and thermophoresis

Reality / complexity / computation cost

Simulation results: model test

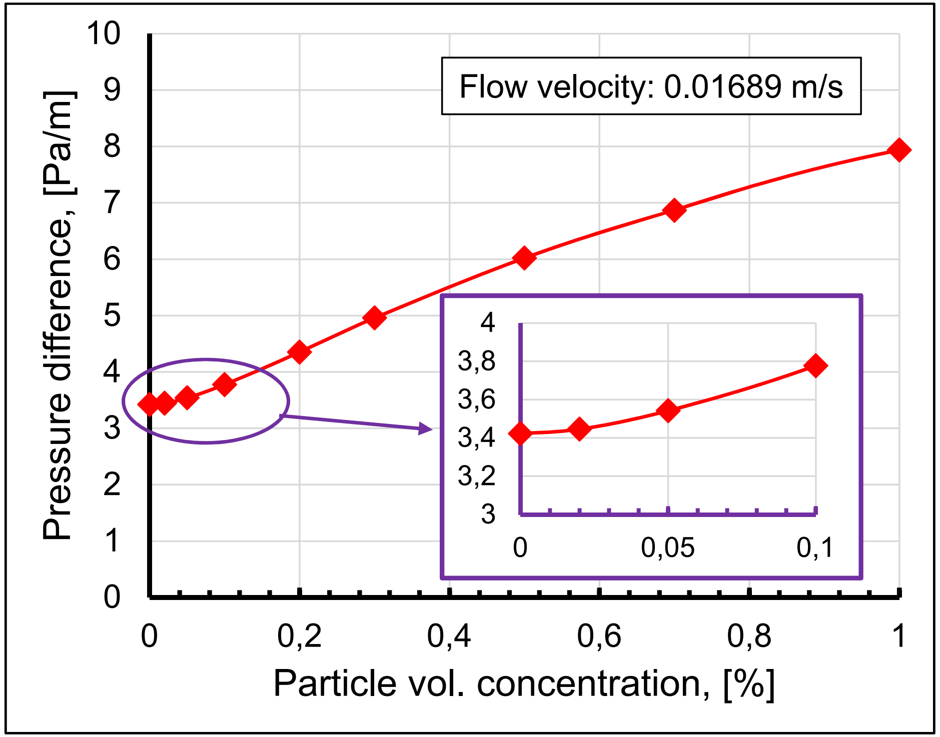
Computational domain



Conditions and parameters:

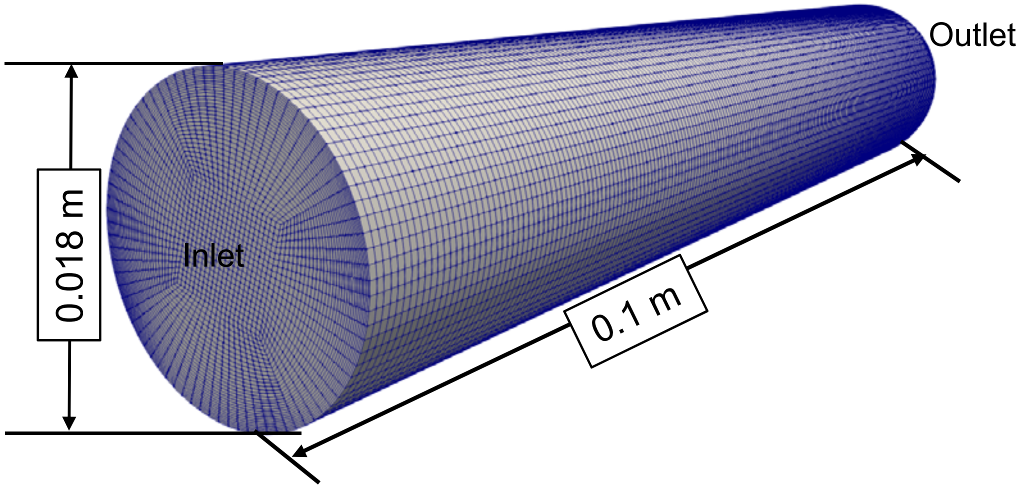
- Laminar flow simulation
- Nanofluid
  - Base fluid: Water (1000 kg/m³)
  - 100 nm particles (2200 kg/m³)
- No solar radiation → constant temperature

Effect of particle concentration on the pressure drop due to the change in viscosity



Simulation results: model test

Computational domain



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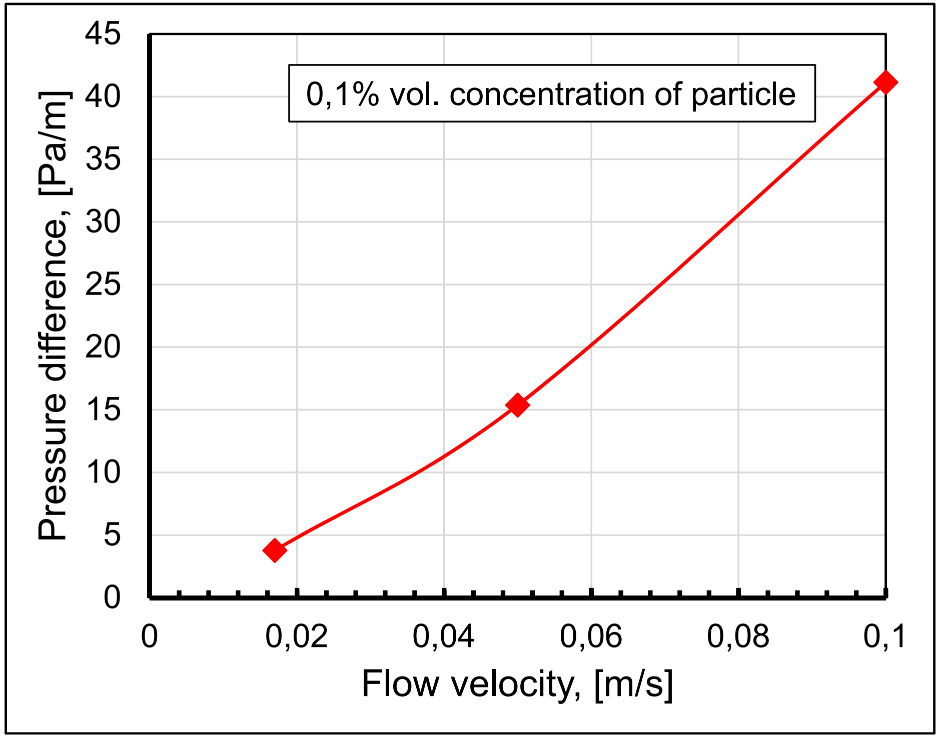
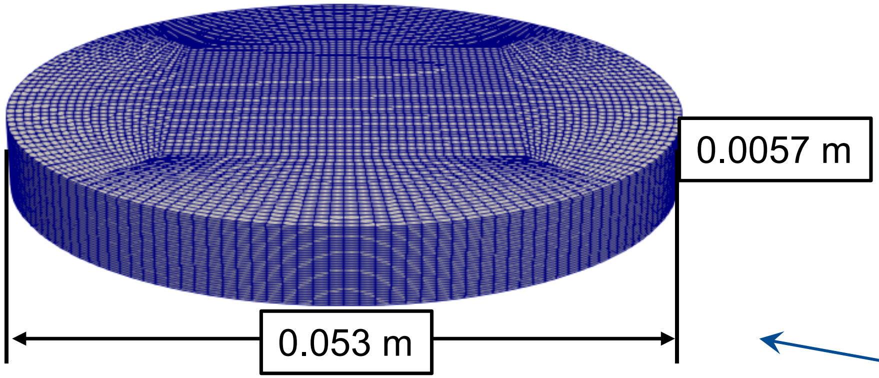
- ❑ No solar radiation → constant temperature

Effect of flow velocity on the pressure drop

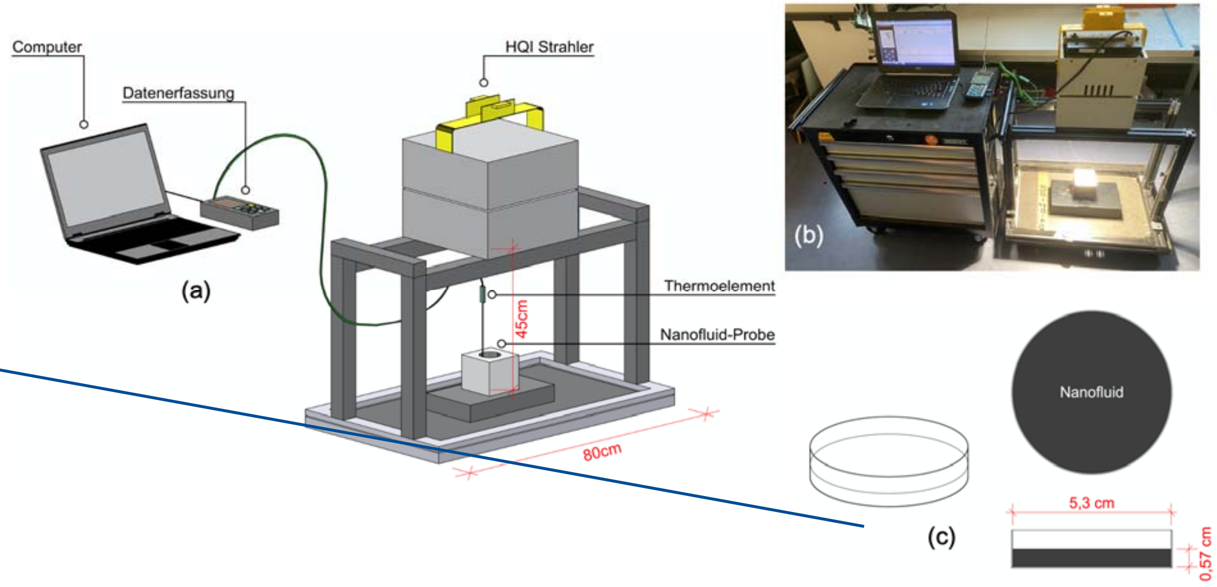


Simulation results: model test

Computational domain



Laboratory experiment set up

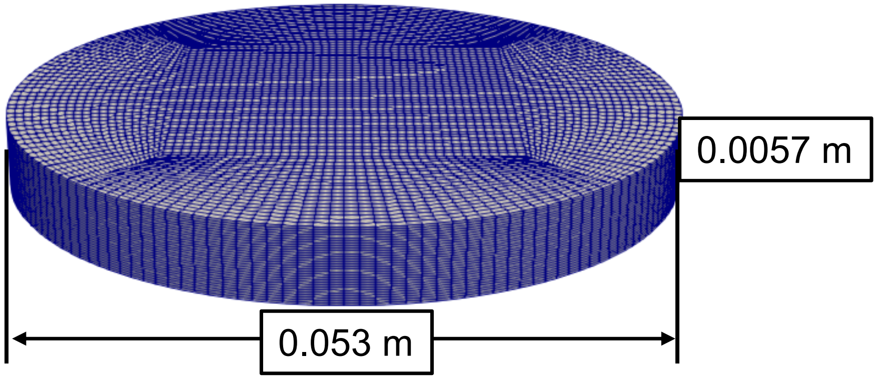


Conditions and parameters:

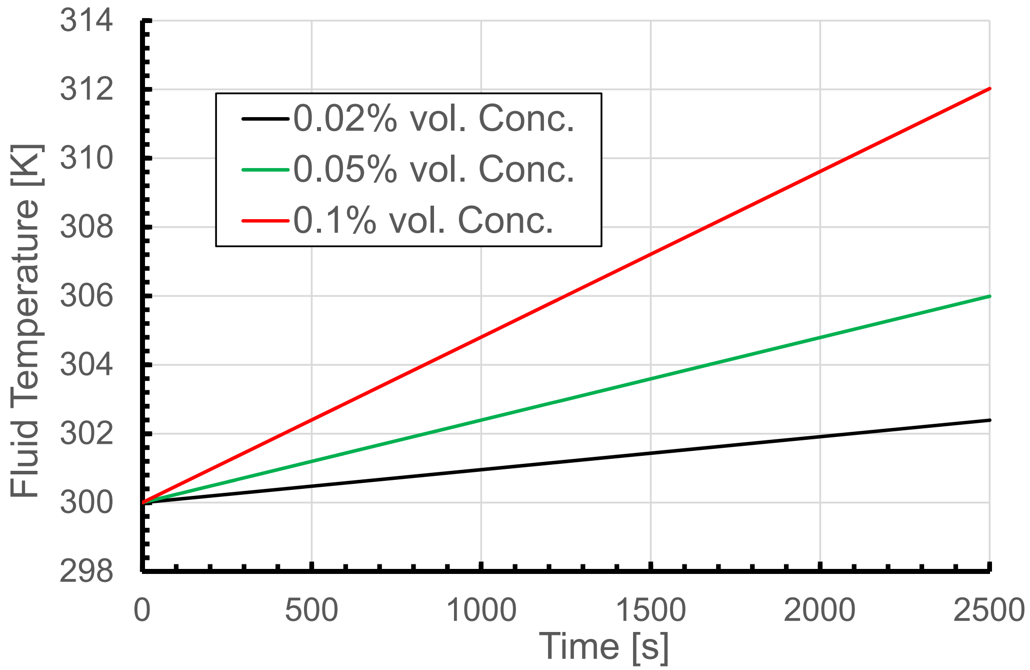
- ❑ Laminar flow simulation
- ❑ Nanofluid
  - ❖ Base fluid: Water (1000 kg/m³)
  - ❖ 100 nm particles (2200 kg/m³)
- ❑ Solar radiation → From top patch

Simulation results: model test

Computational domain



Energy conversion by nano-solar fluid



Conditions and parameters:

- ❑ Laminar flow simulation
- ❑ Nanofluid
  - ❖ Base fluid: Water (1000 kg/m³)
  - ❖ 100 nm particles (2200 kg/m³)
- ❑ Solar radiation → From top patch

- ❑ Model is capable to simulate the absorption of solar radiation and its energy conversion to fluid.

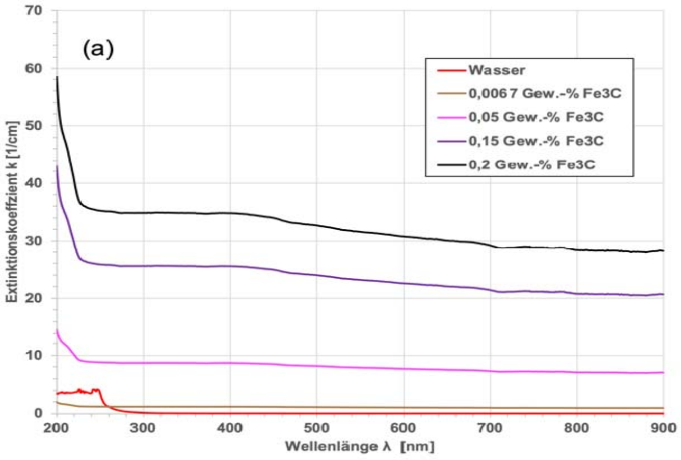
Simulation: Current status and next steps

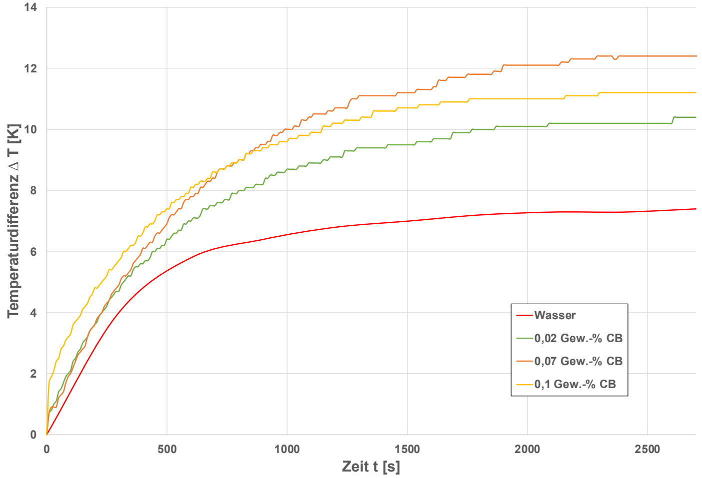
☑ Modelling and implementation of fluid flow
  - o Mass, momentum and temperature
  - o Volume of fraction (particle phase)
    - o Brownian diffusion & thermophoresis

☑ Modelling and implementation of direct solar energy absorption as function of concentration of particles

❑ Validate the model with experimental results (in progress)
  - ❖ Extract the coefficients from the experimental results
  - ❖ Simplify the solar absorption model if needed

❑ Parametric studies
  - ❖ Volume concentration of particles; Intensity of solar incidences
  - ❖ Optimization of the dispersion properties of solar absorber fluids for solar thermal collectors





Experimentally measured results

Thank you very much for your kind attention

Current status and next steps

One phase model (Euler approach)

- ❑ Modelling and implementation of fluid flow
  - ✓ o Mass, momentum and temperature
  - ✓ o Volume of fraction (particle phase)
    - o Brownian diffusion & thermophoresis
- ❑ Direct solar energy absorption as function of concentration of particles

Two phase model (Euler-Lagrange approach)

- ❑ Modelling, implementation and coupling
  - ✓ o Fluid: mass, momentum and temperature
  - ✓ o Particles: various forces calculations and 2-ways coupling
- ❑ Implementation of direct energy absorption for individual particles

- ❑ Simulation with both approaches:
  - o Validate the results with experiments
  - o Parametric studies: volume concentration of particles; Intensity of solar incidences
  - o Optimization of the dispersion properties of solar absorber fluids for solar thermal collectors
  - o Investigation of effects of the increase in viscosity of nanofluid on the pumping power