Imperial College London

Investigations on numerical analysis of coupled thermo-hydraulic problems in geotechnical engineering

W. Cui, K.A. Gawecka, D.M. Potts, D.M.G. Taborda and L. Zdravković

Imperial College London

Presentation outline

1) Numerical facilities in Imperial College Finite Element Program (ICFEP)

2) Finite element analysis of highly convective heat transfer

3) Application to open-loop ground source energy systems

4) Conclusions

Imperial College London

Presentation outline

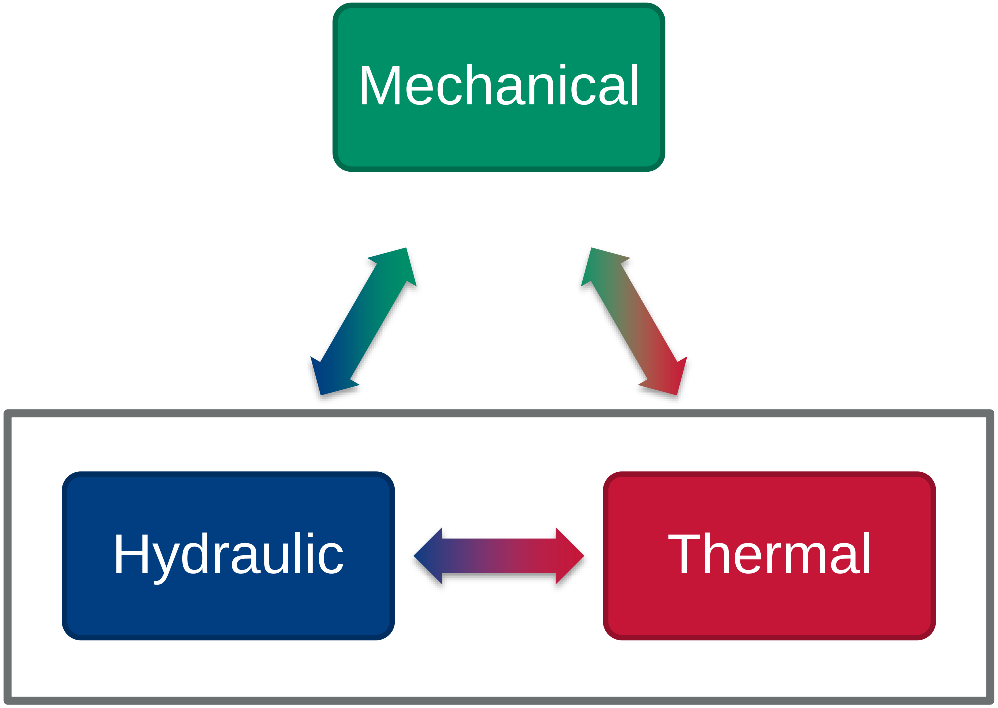
1) **Numerical facilities in Imperial College Finite Element Program (ICFEP)**

2) Finite element analysis of highly convective heat transfer

3) Application to open-loop ground source energy systems

4) Conclusions

1) Coupled TH FE analysis



Imperial College London

1) Coupled TH FE analysis

Governing formulation in ICFEP

1) Pore fluid flow

- Continuity equation $$\frac{\partial v_x}{\partial x}+\frac{\partial vy}{\partial y}+\frac{\partial vz}{\partial z}=Qw$$
- Darcy's law $$\{v_w\}=-[k_w]\{\nabla h\}$$

2) Heat transfer

- Conservation of energy law

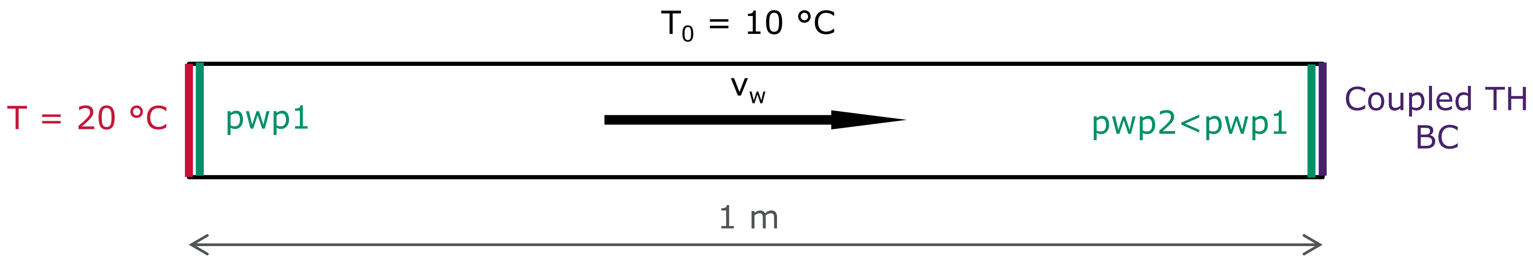
$$[n\rho_w C_{pw}+(1-n)\rho_s C_{ps}]\frac{\partial T}{\partial t}+\rho_w C_{pw}\{v_w\}^{\mathrm{T}}\{\nabla T\}-\nabla\cdot([k_\theta]\{\nabla T\})=Q^\theta$$

Heat content — Heat convection — Heat conduction (Fourier's Law)

1) Coupled TH FE analysis

Coupled thermo-hydraulic BC

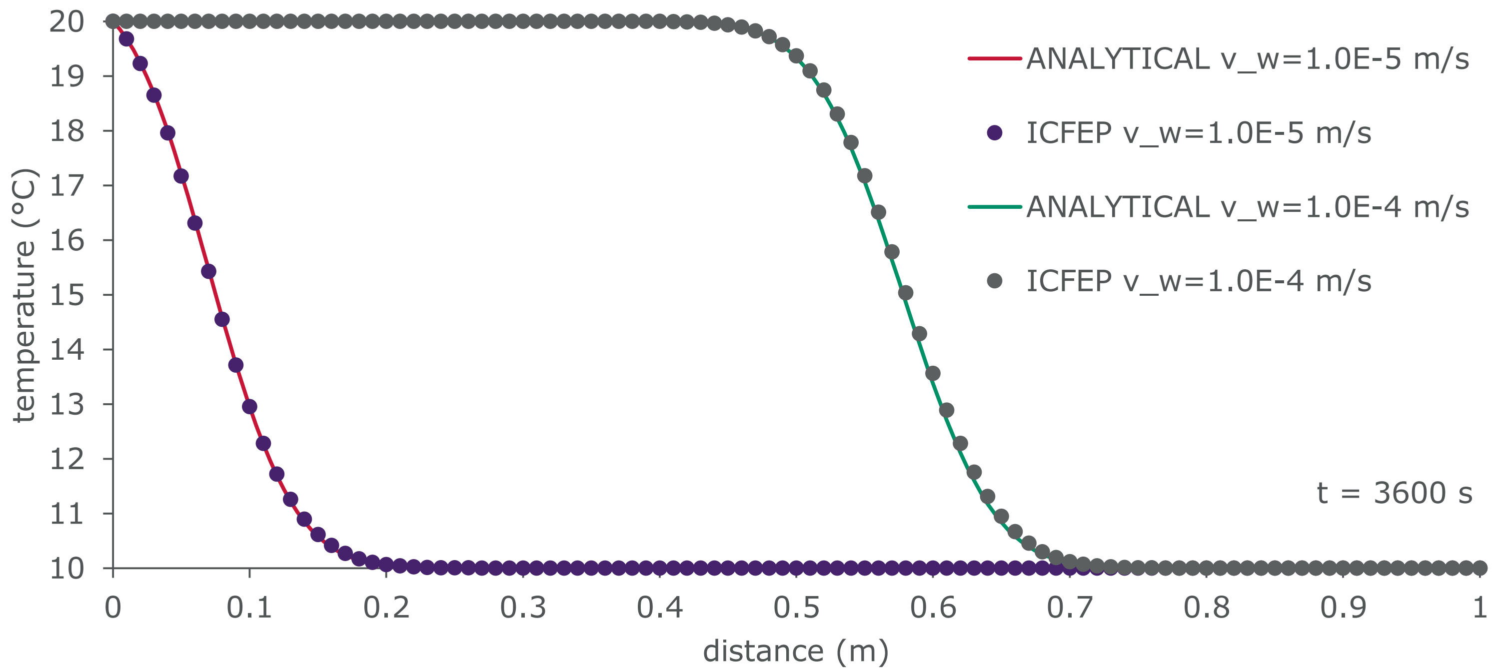
$$q = \int_{\Omega} \rho_w C_{pw} \{v_w\}_b T_b \, d\Omega$$



1) Coupled TH FE analysis

Coupled thermo-hydraulic BC

$$q = \int_{\Omega} \rho_w C_{pw} \{v_w\}_b T_b \, d\Omega$$



Imperial College London

Presentation outline

1) Numerical facilities in Imperial College Finite Element Program (ICFEP)

2) **Finite element analysis of highly convective heat transfer**

3) Application to open-loop ground source energy systems

4) Conclusions

2) FE analysis of highly convective heat transfer

Péclet number

$$Pe = \frac{convective\ heat\ transfer}{conductive\ heat\ transfer}$$

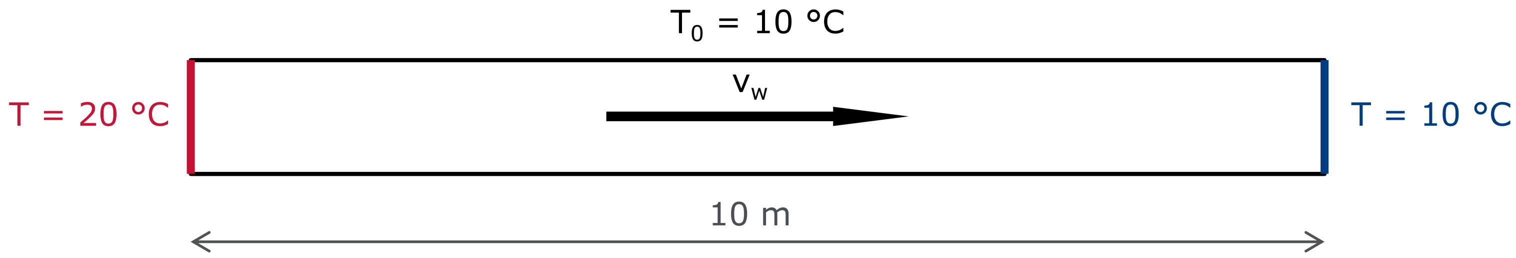
$$Pe = \frac{\rho_w C_{pw} v_w L}{k_\theta}$$

ρ_w – density of water
C_{pw} – specific heat capacity of water
v_w – pore water velocity
L – element length in direction of water flow
k_θ – thermal conductivity of material

2) FE analysis of highly convective heat transfer

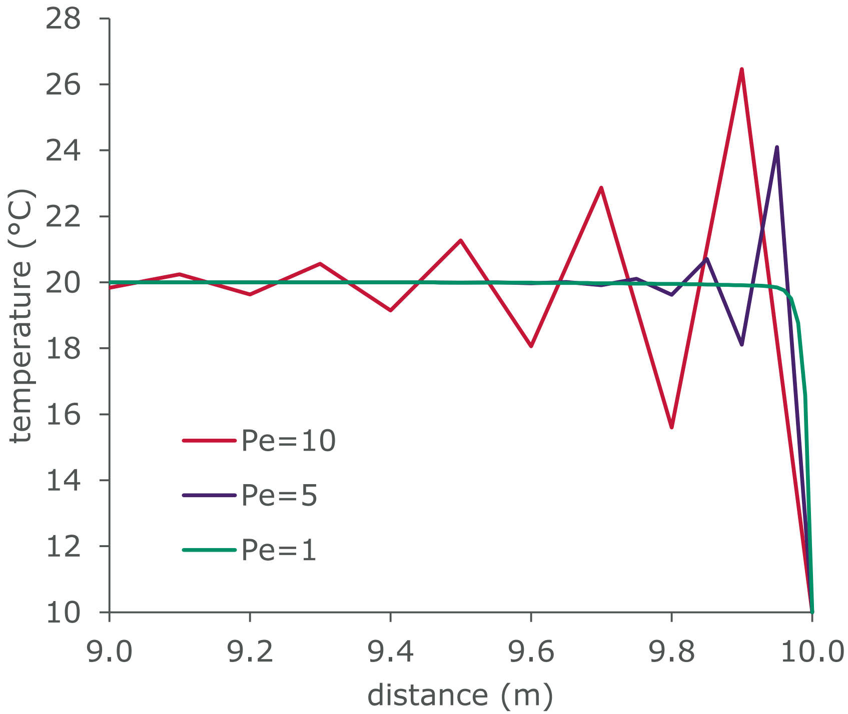
Effect of Péclet number

1) With prescribed temperature BC



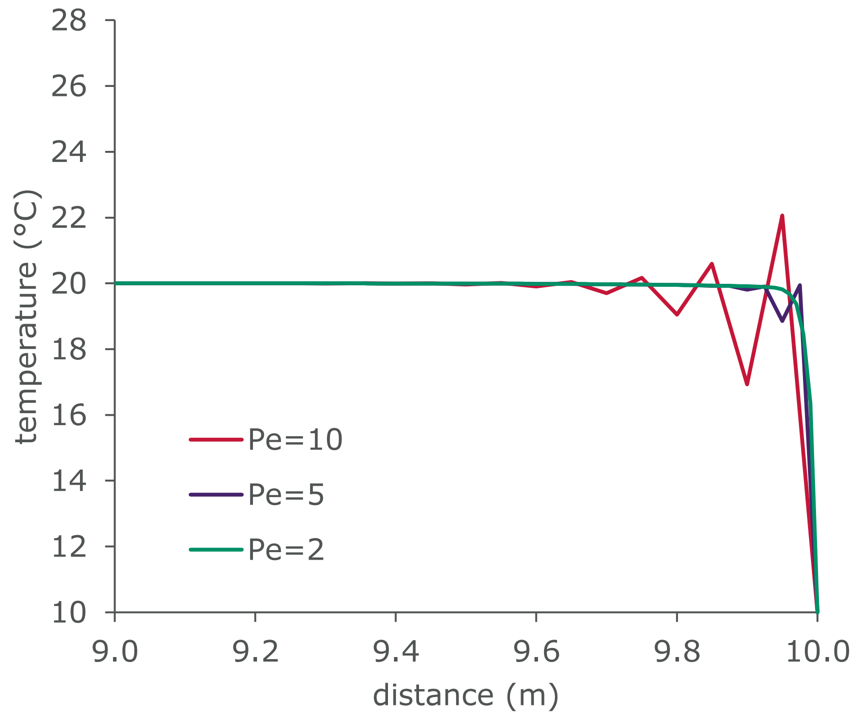
2) FE analysis of highly convective heat transfer

Effect of Péclet number



Linear elements

Pe ≤ 1



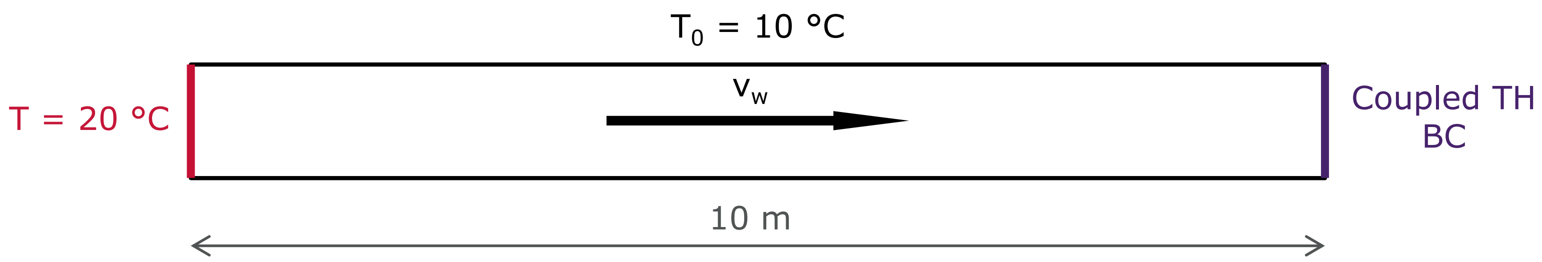
Quadratic elements

Pe ≤ 2

2) FE analysis of highly convective heat transfer

Effect of Péclet number

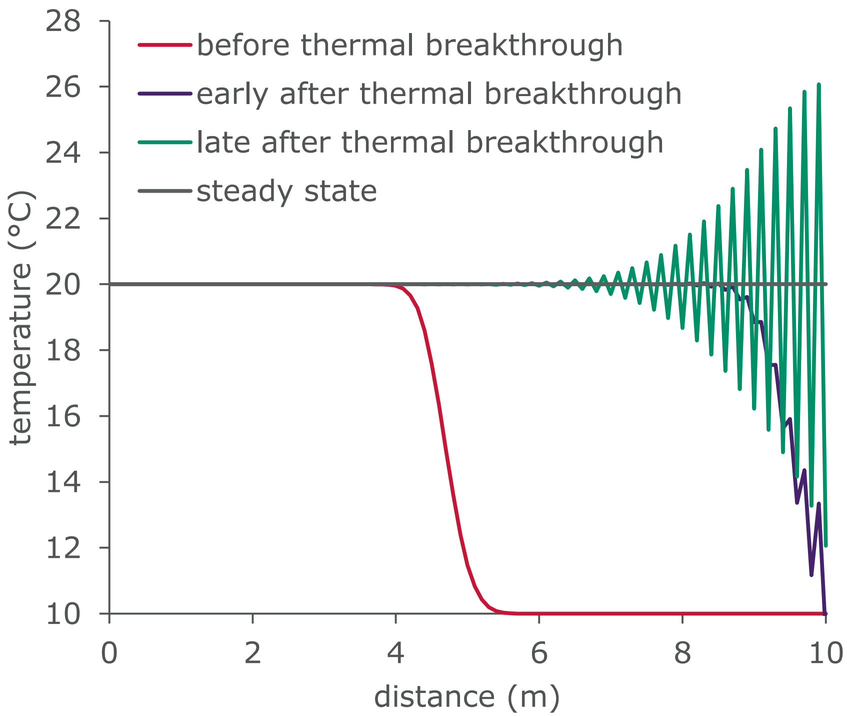
2) With coupled thermo-hydraulic BC



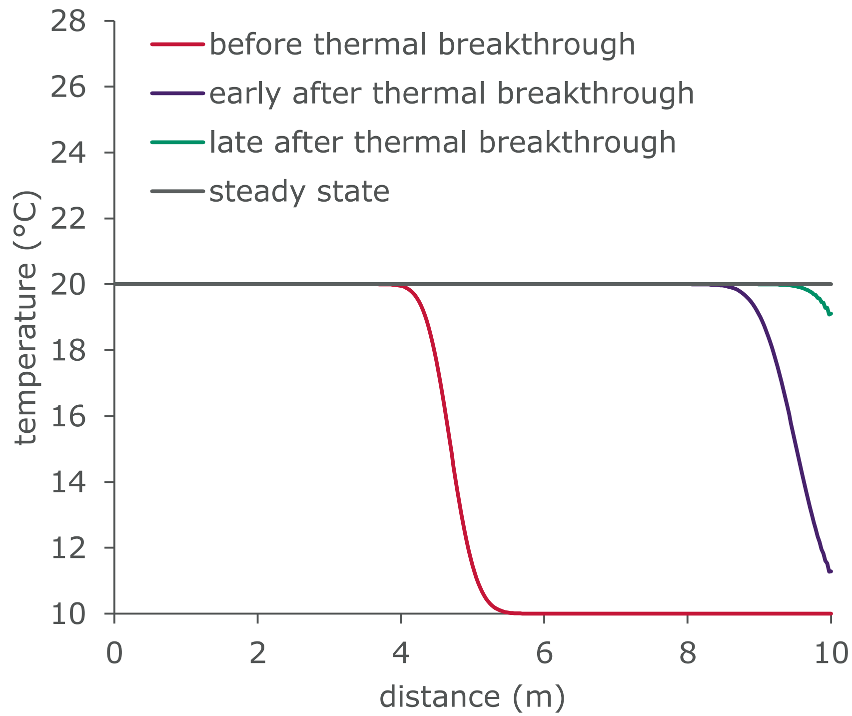
2) FE analysis of highly convective heat transfer

Effect of Péclet number

Linear elements



Pe = 60

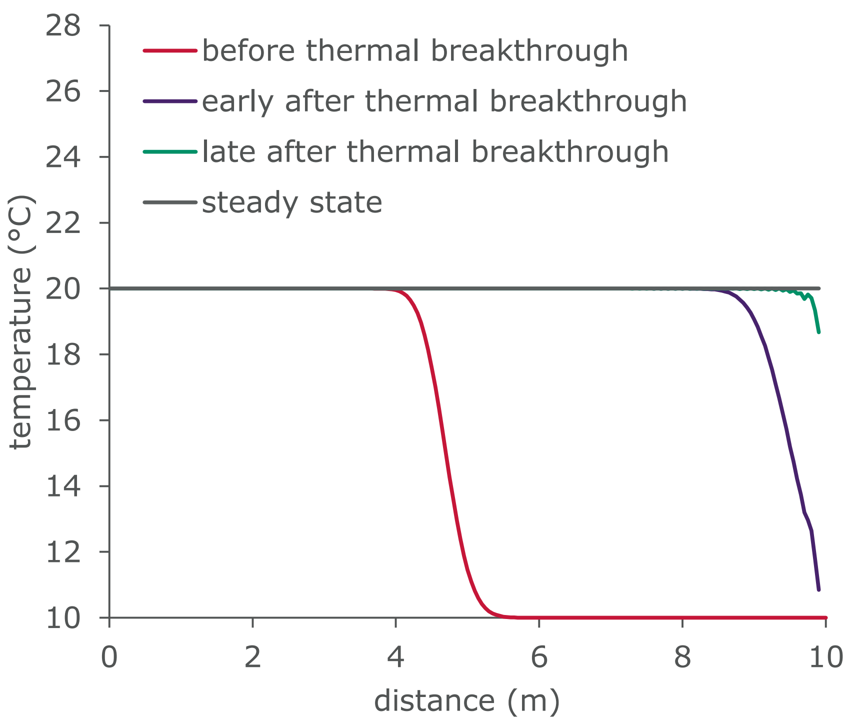


Pe = 16

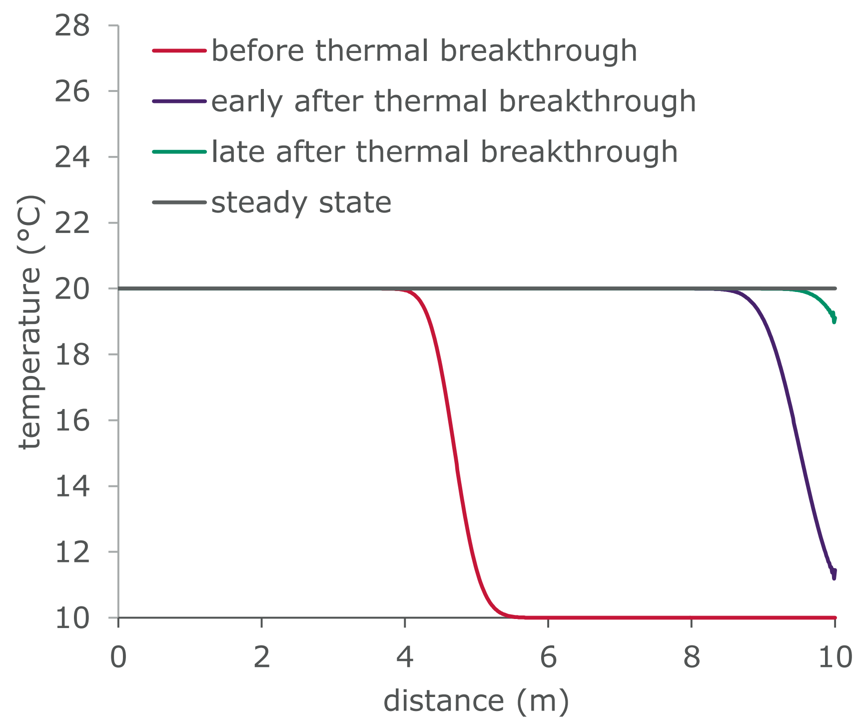
2) FE analysis of highly convective heat transfer

Effect of Péclet number

Quadratic elements



Pe = 60



Pe = 16

Presentation outline

1) Numerical facilities in Imperial College Finite Element Program (ICFEP)

2) Finite element analysis of highly convective heat transfer

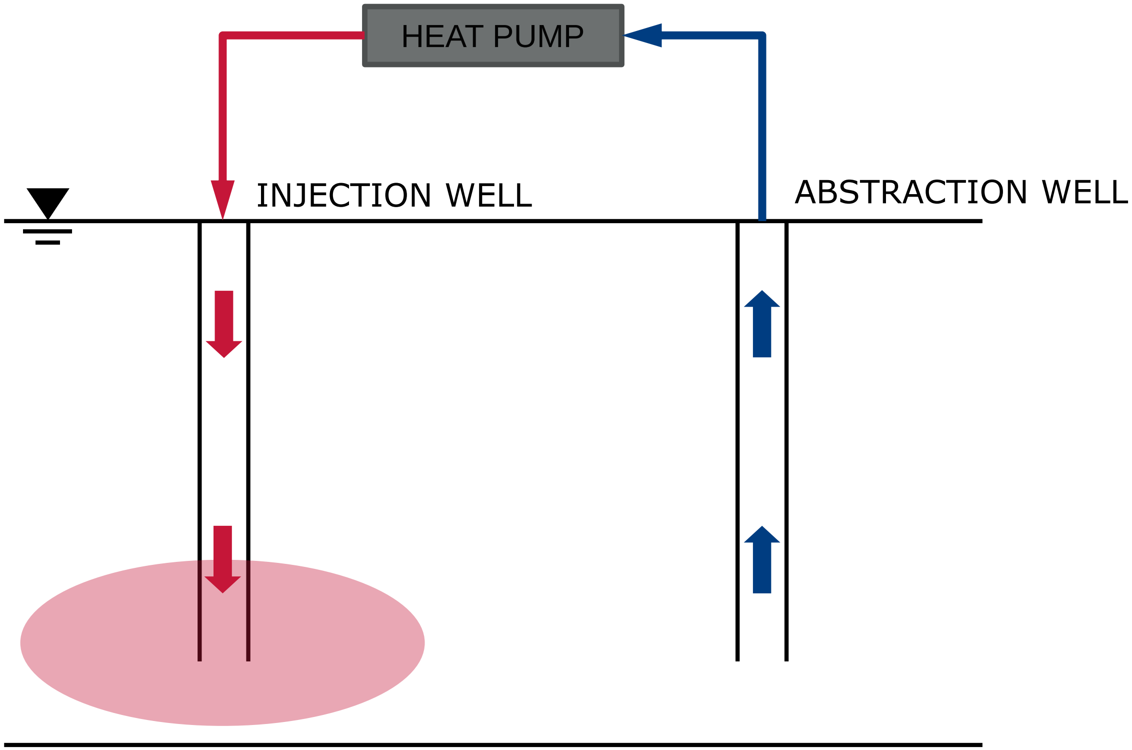
3) Application to open-loop ground source energy systems

4) Conclusions

3) Application to open-loop GSES

Open-loop Ground Source Energy Systems

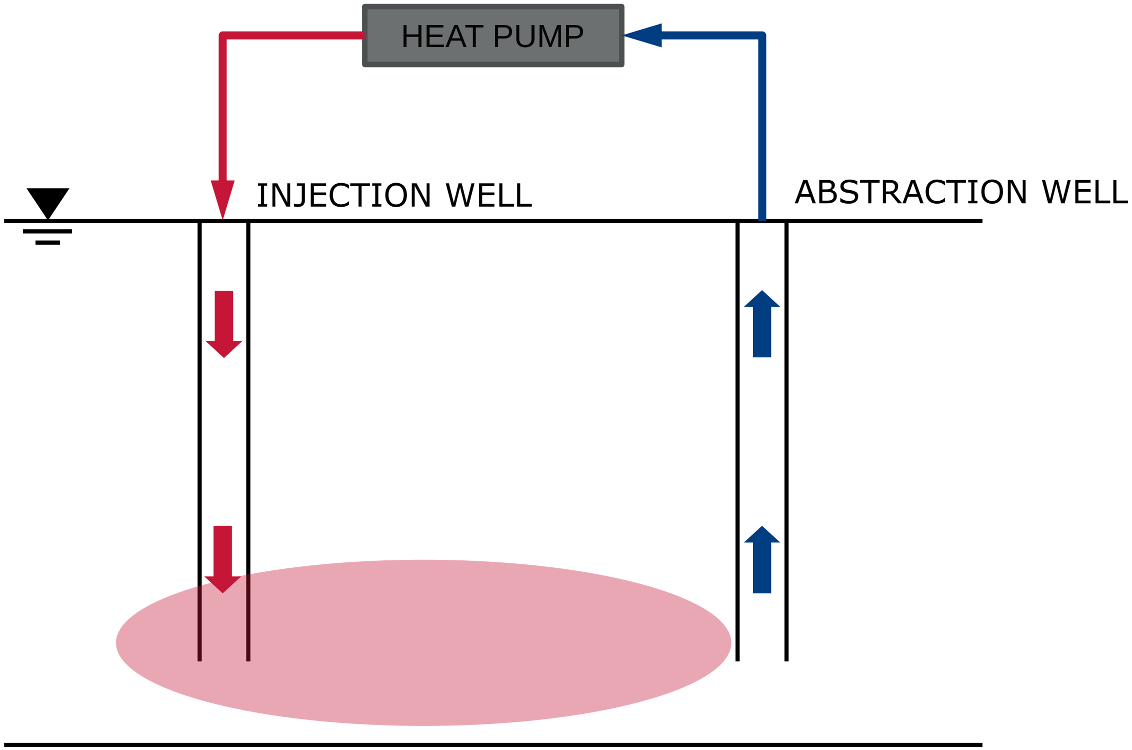
Cooling scenario



3) Application to open-loop GSES

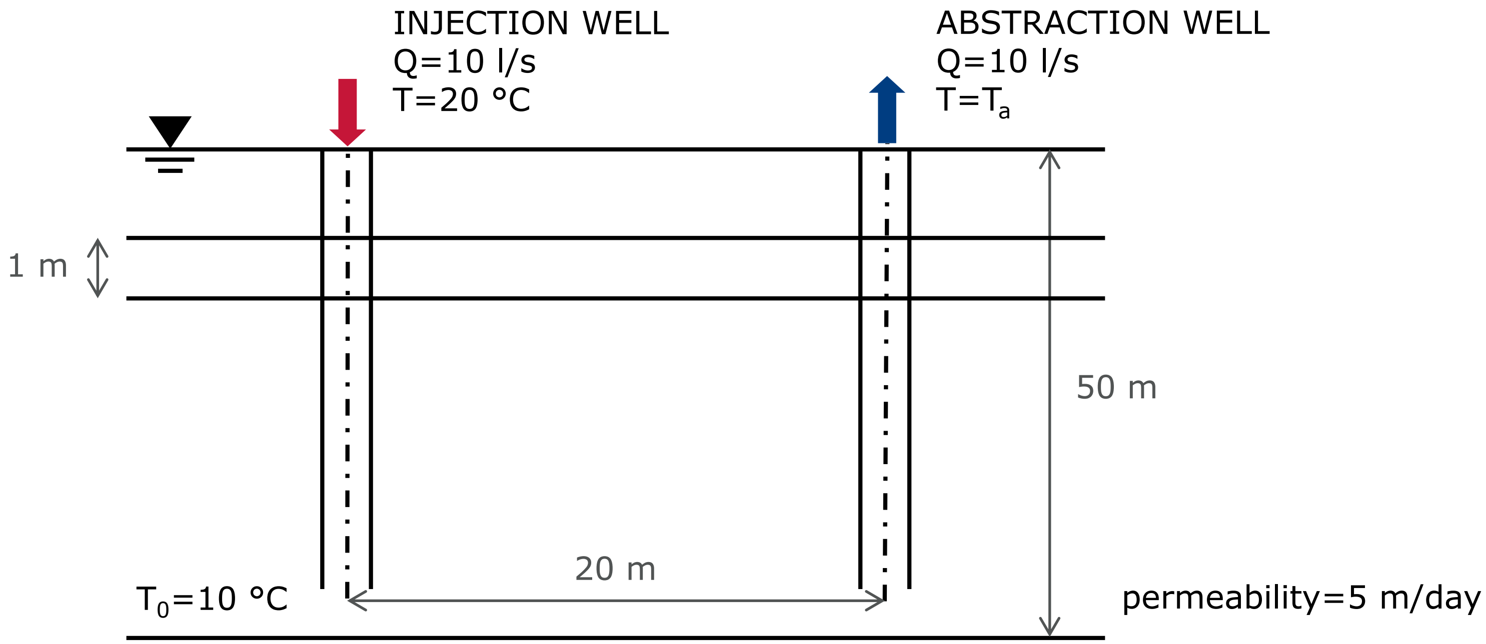
Open-loop Ground Source Energy Systems

Cooling scenario



3) Application to open-loop GSES

Problem description



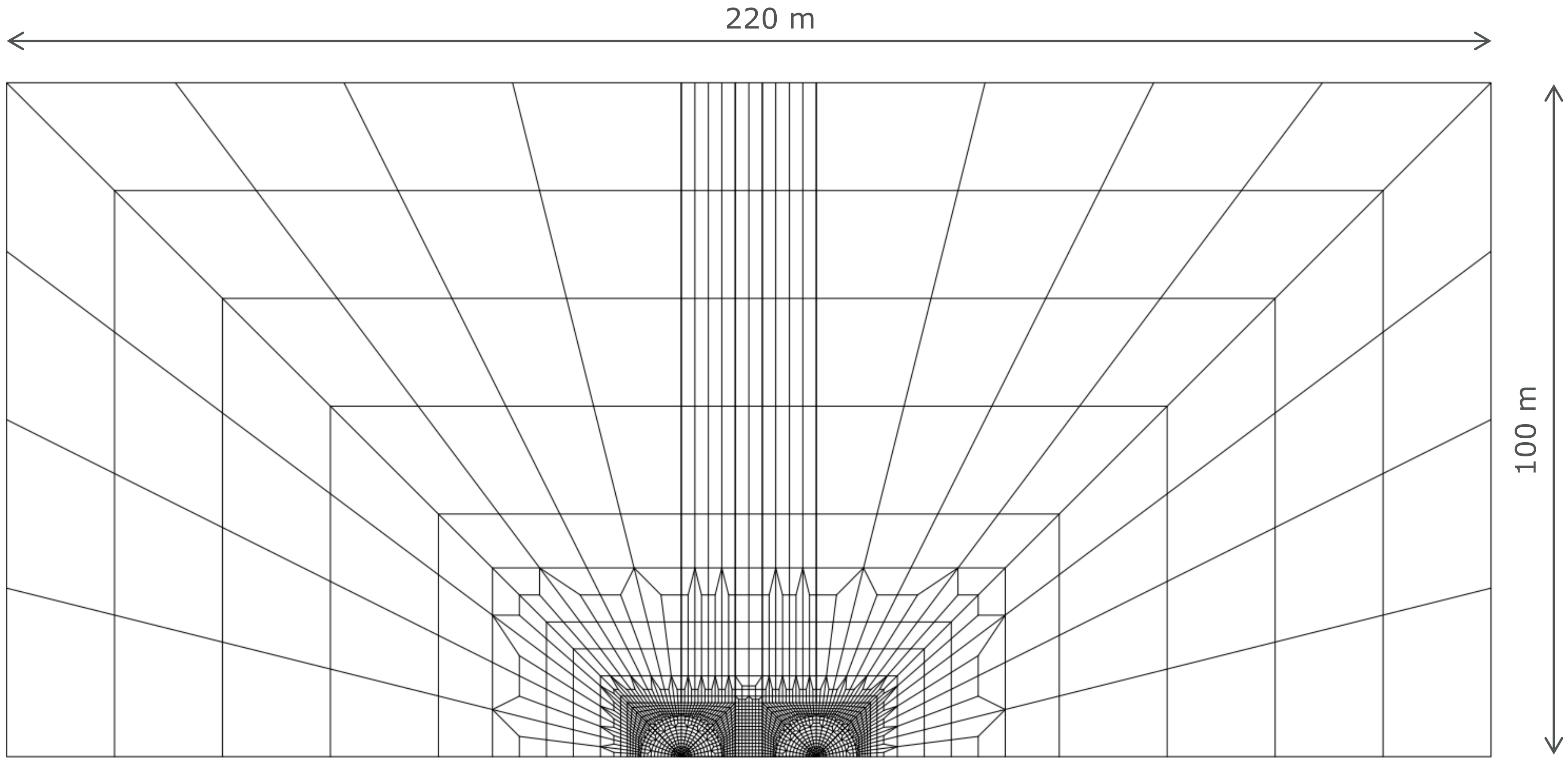
3) Application to open-loop GSES

Numerical modelling

- 2D plane strain
- Rigid elastic material
- Element type and size varied
- Δt = 180 s

Analysis	Element type	Number of elements	Minimum element size (m)	Maximum Péclet number
A	Linear	1908	0.12	60
B	Quadratic	1908	0.12	60
C	Linear	5336	0.03	16
D	Quadratic	5336	0.03	16

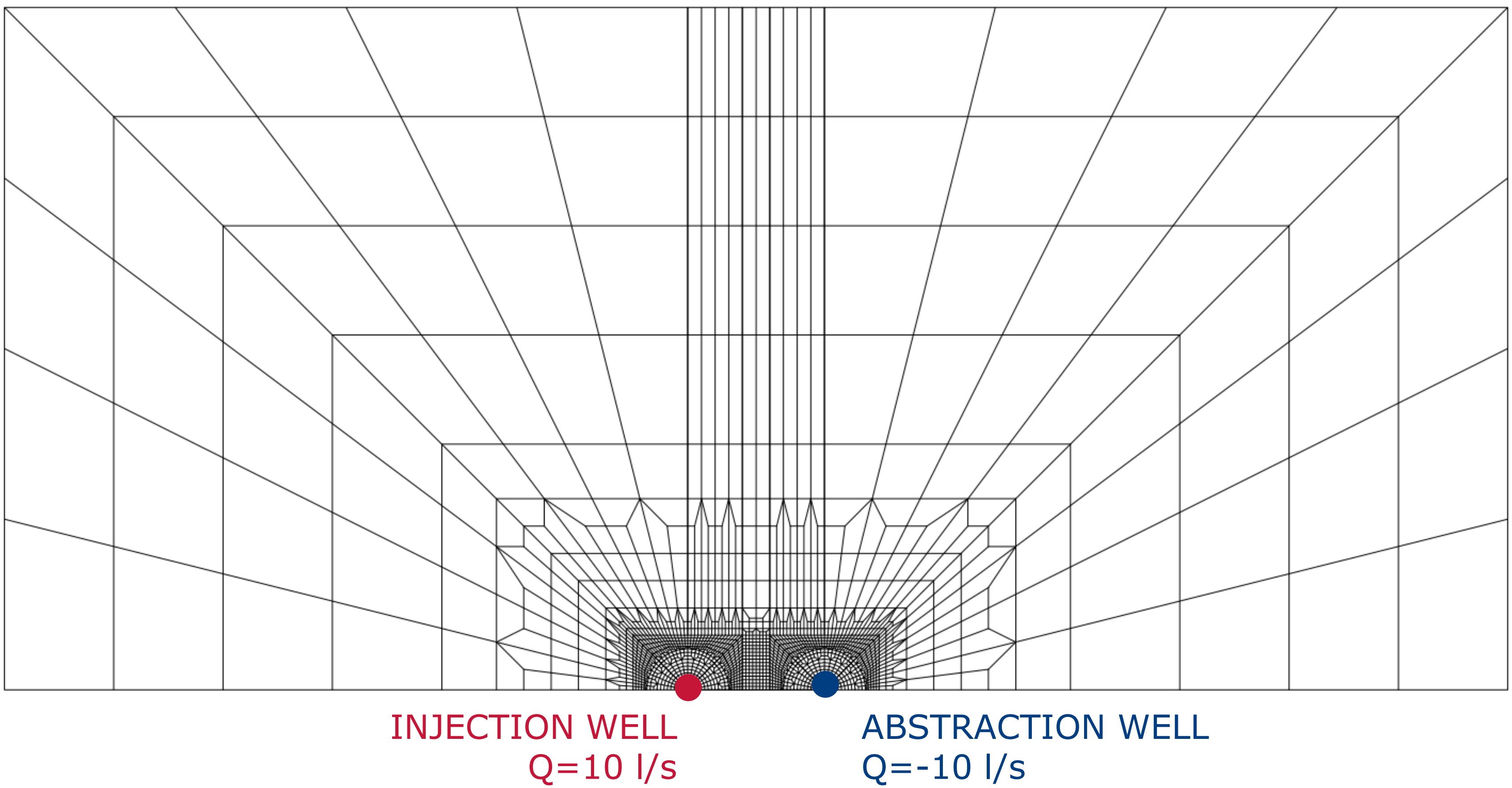
3) Application to open-loop GSES



Imperial College London

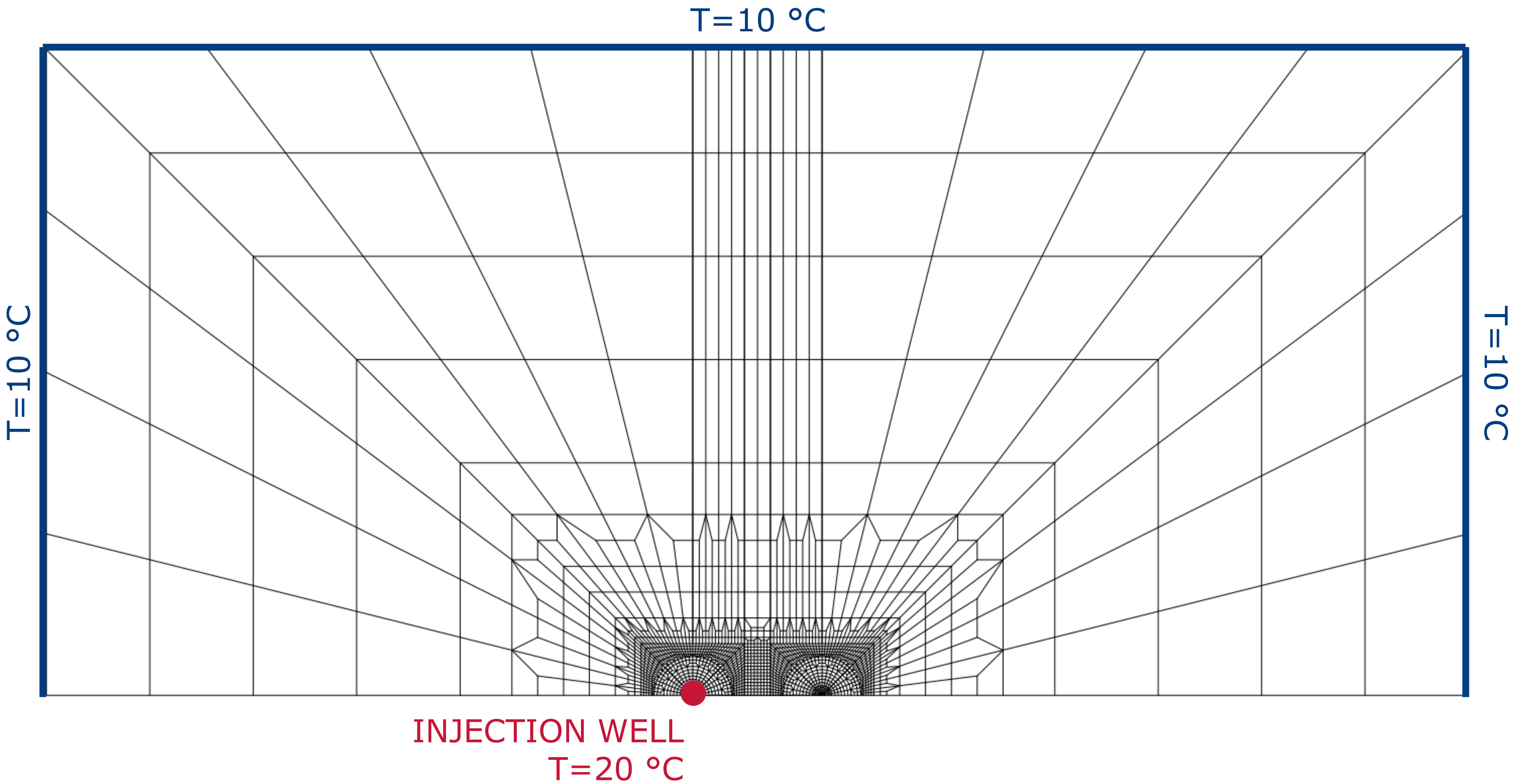
3) Application to open-loop GSES

Hydraulic BC – injection of water



3) Application to open-loop GSES

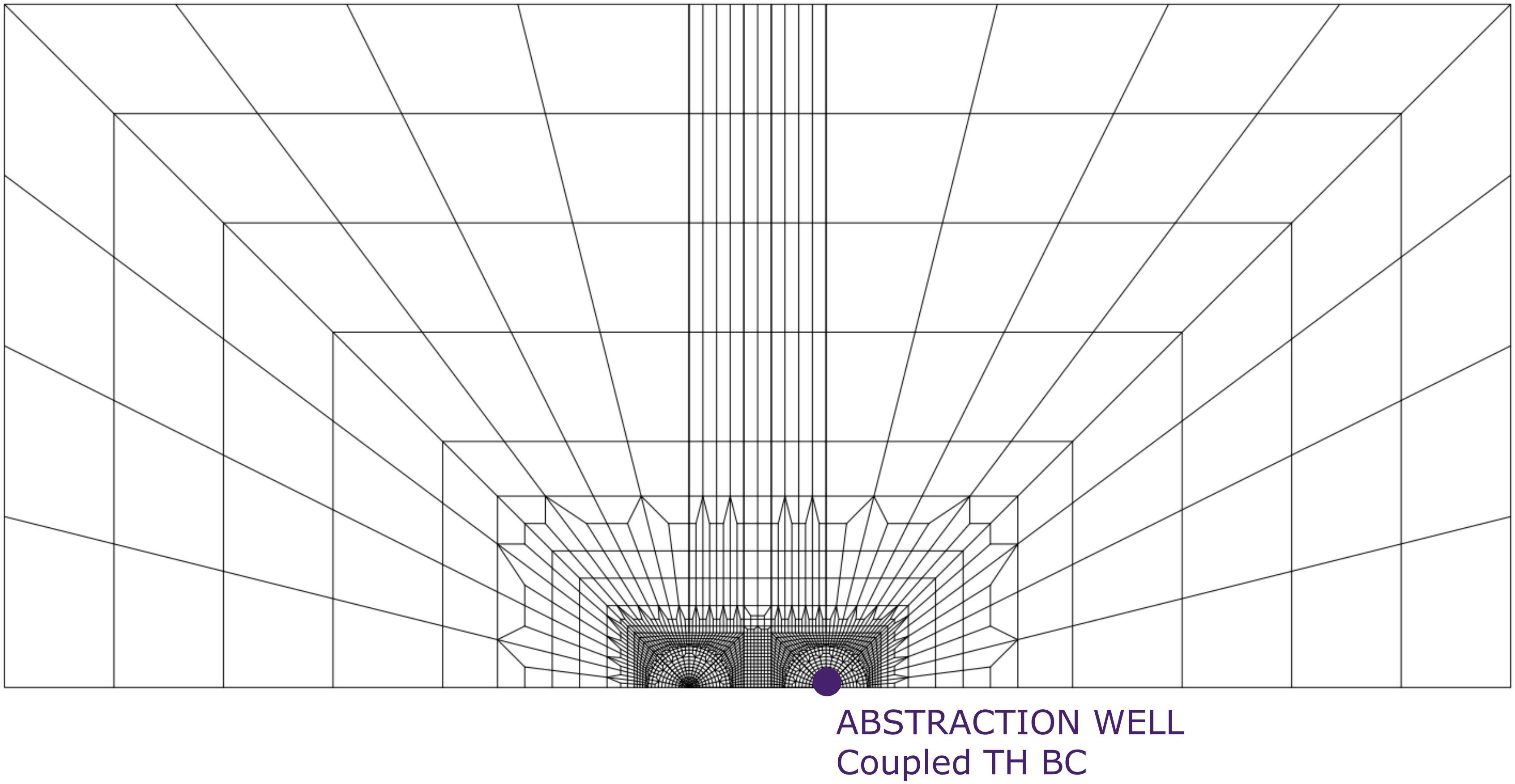
Thermal BC - prescribed temperature



Imperial College London

3) Application to open-loop GSES

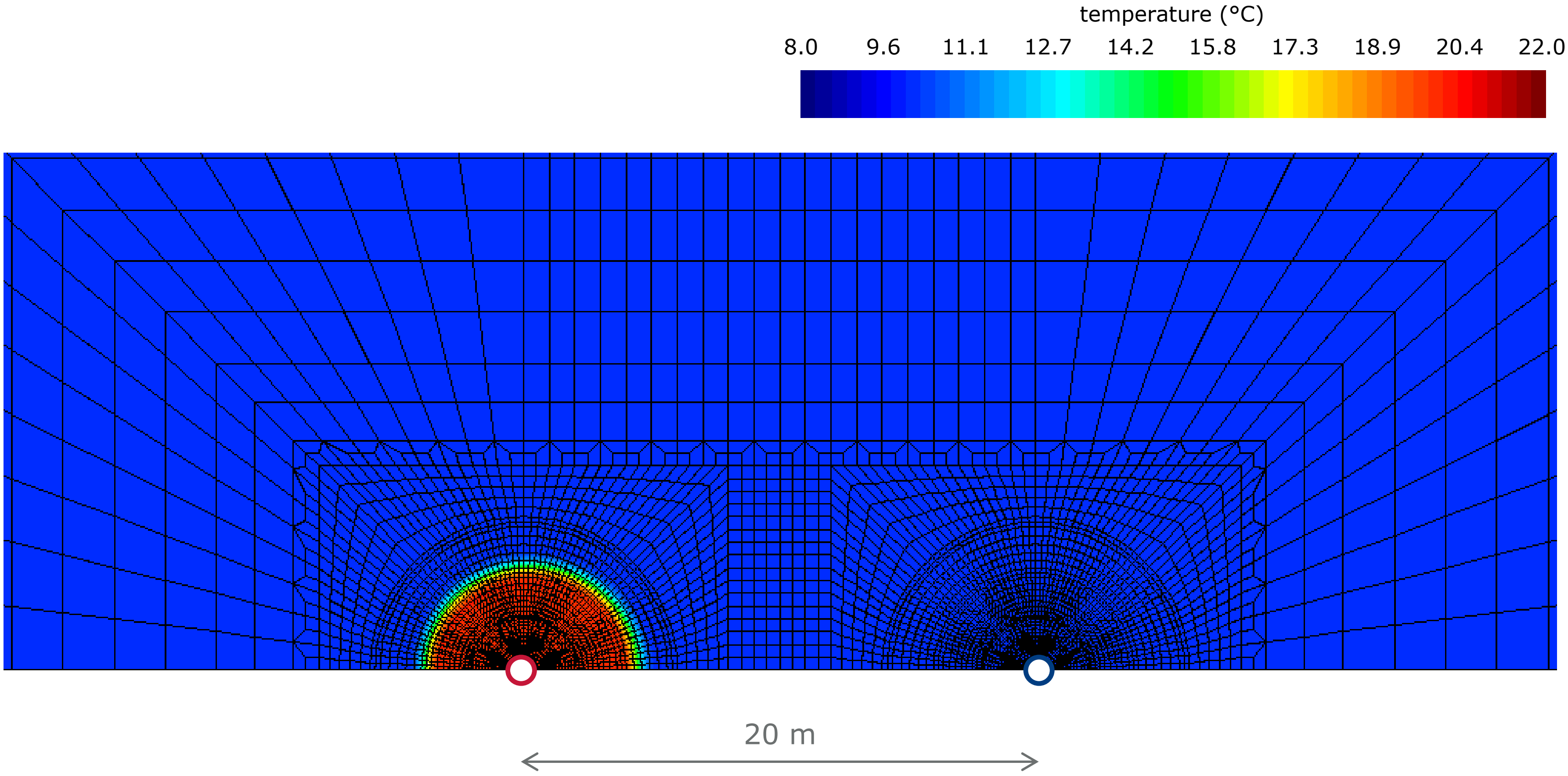
Coupled thermo-hydraulic BC



Imperial College London

3) Application to open-loop GSES

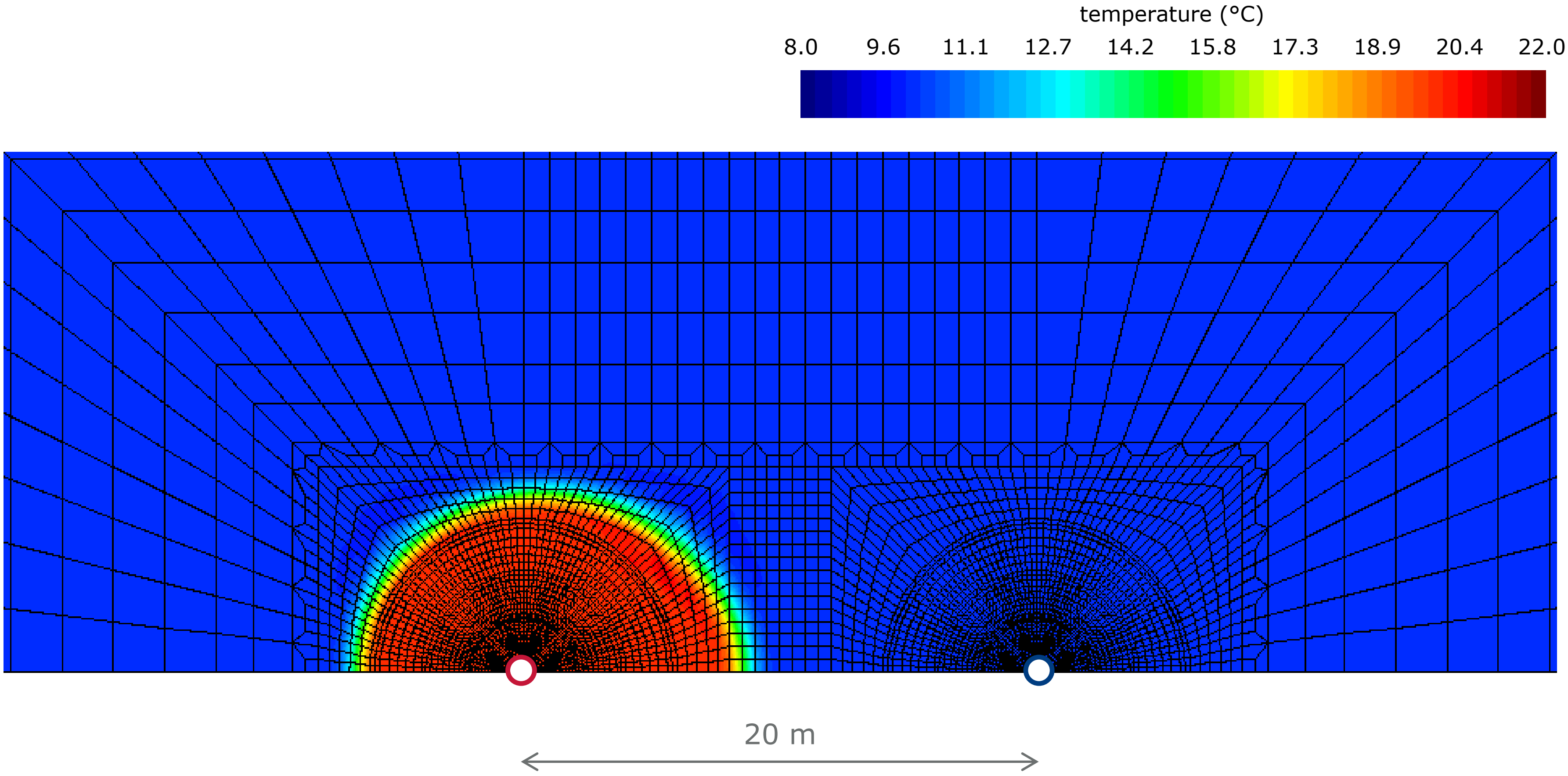
Analysis C - 2 days



Imperial College London

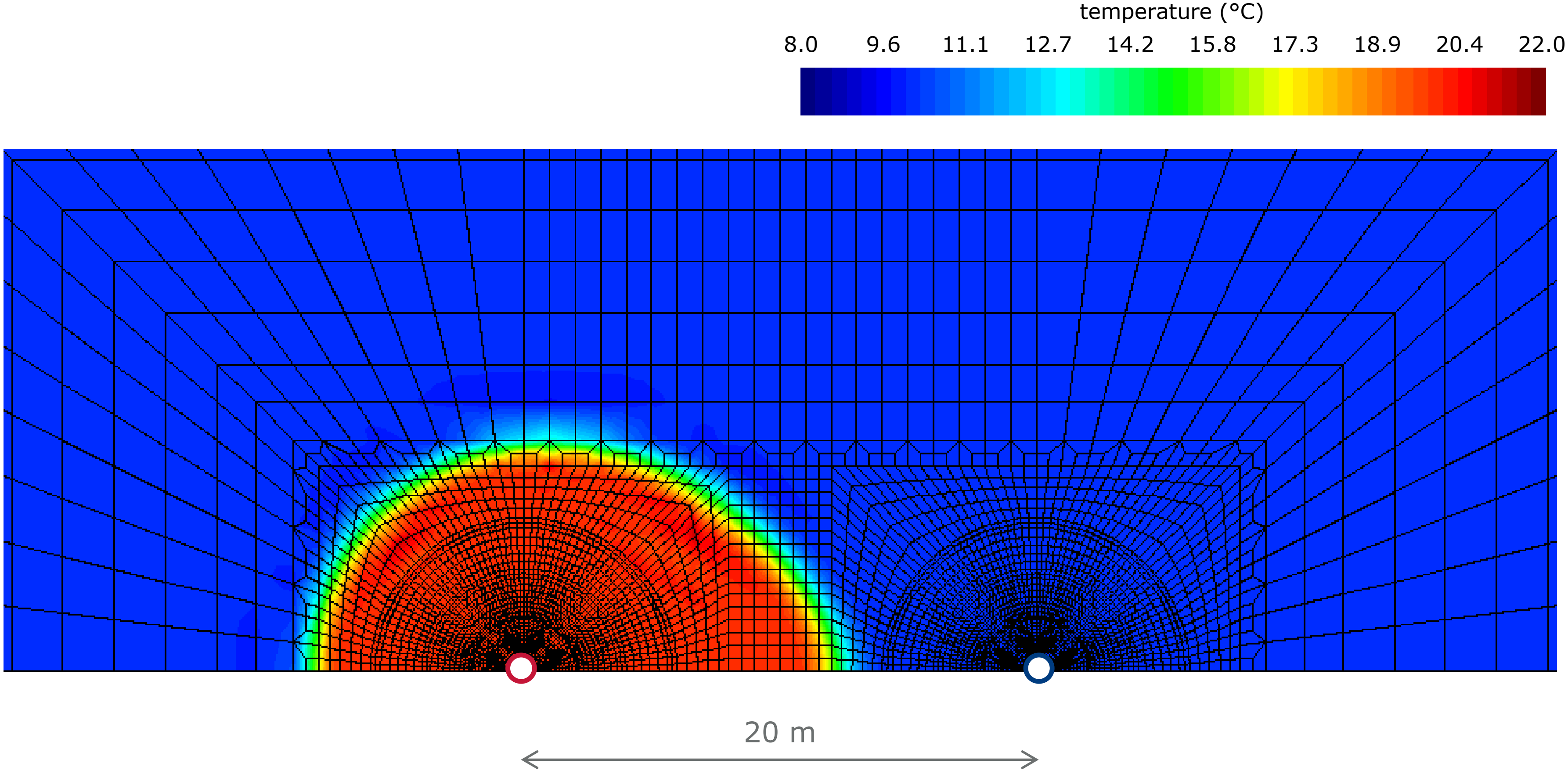
3) Application to open-loop GSES

Analysis C - 6 days



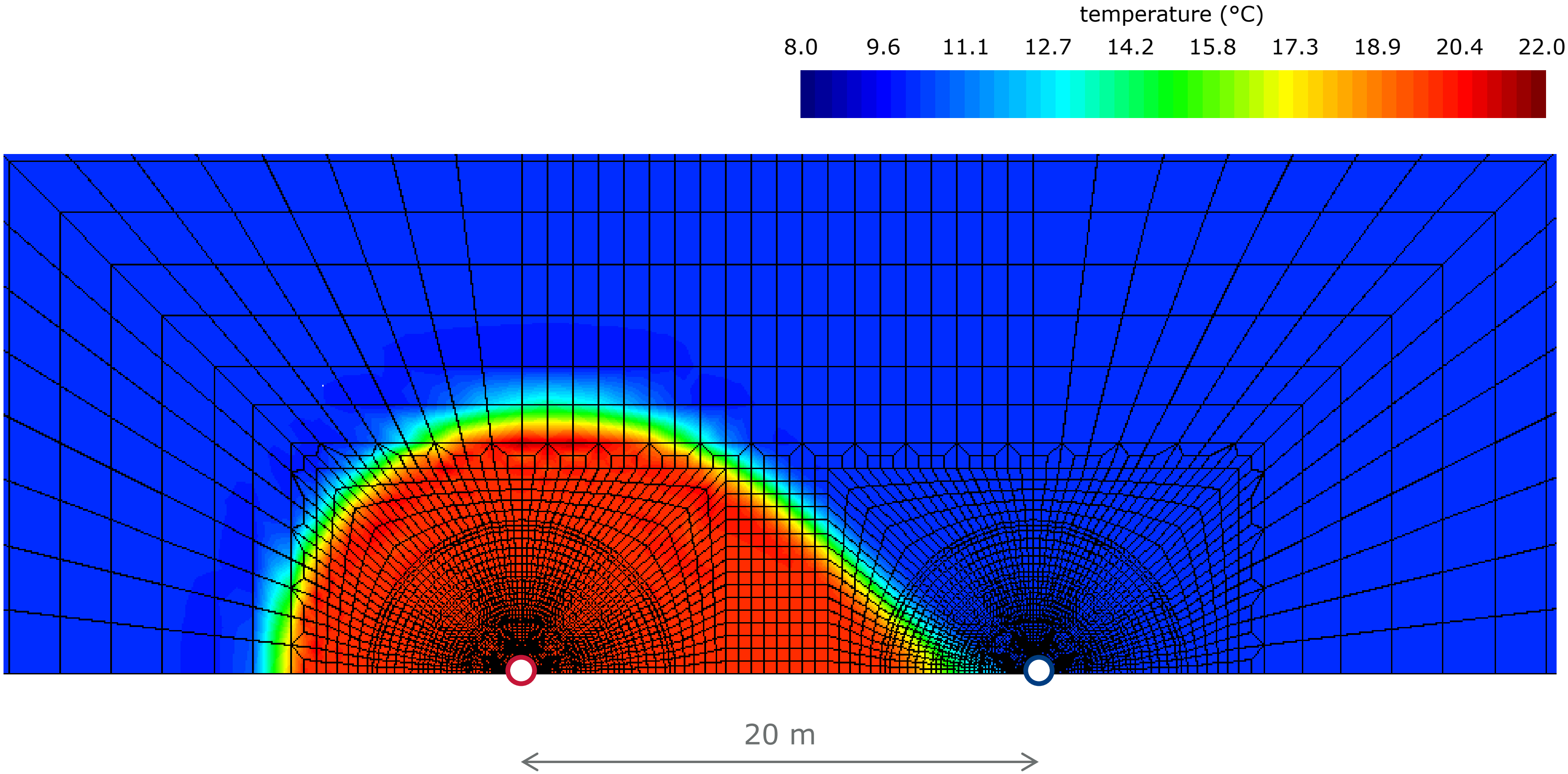
3) Application to open-loop GSES

Analysis C - 10 days



3) Application to open-loop GSES

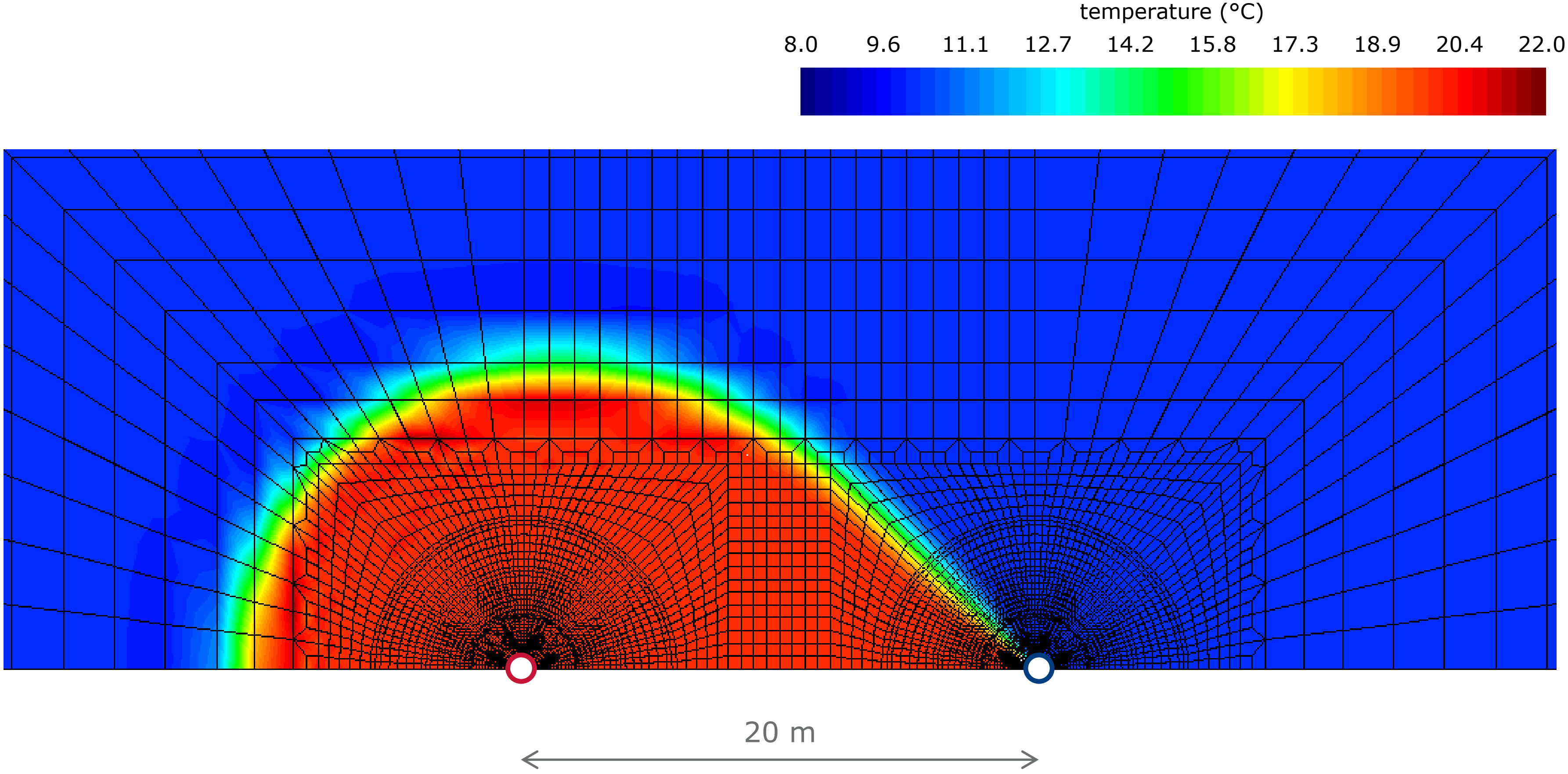
Analysis C - 14.5 days



Imperial College London

3) Application to open-loop GSES

Analysis C - 21 days

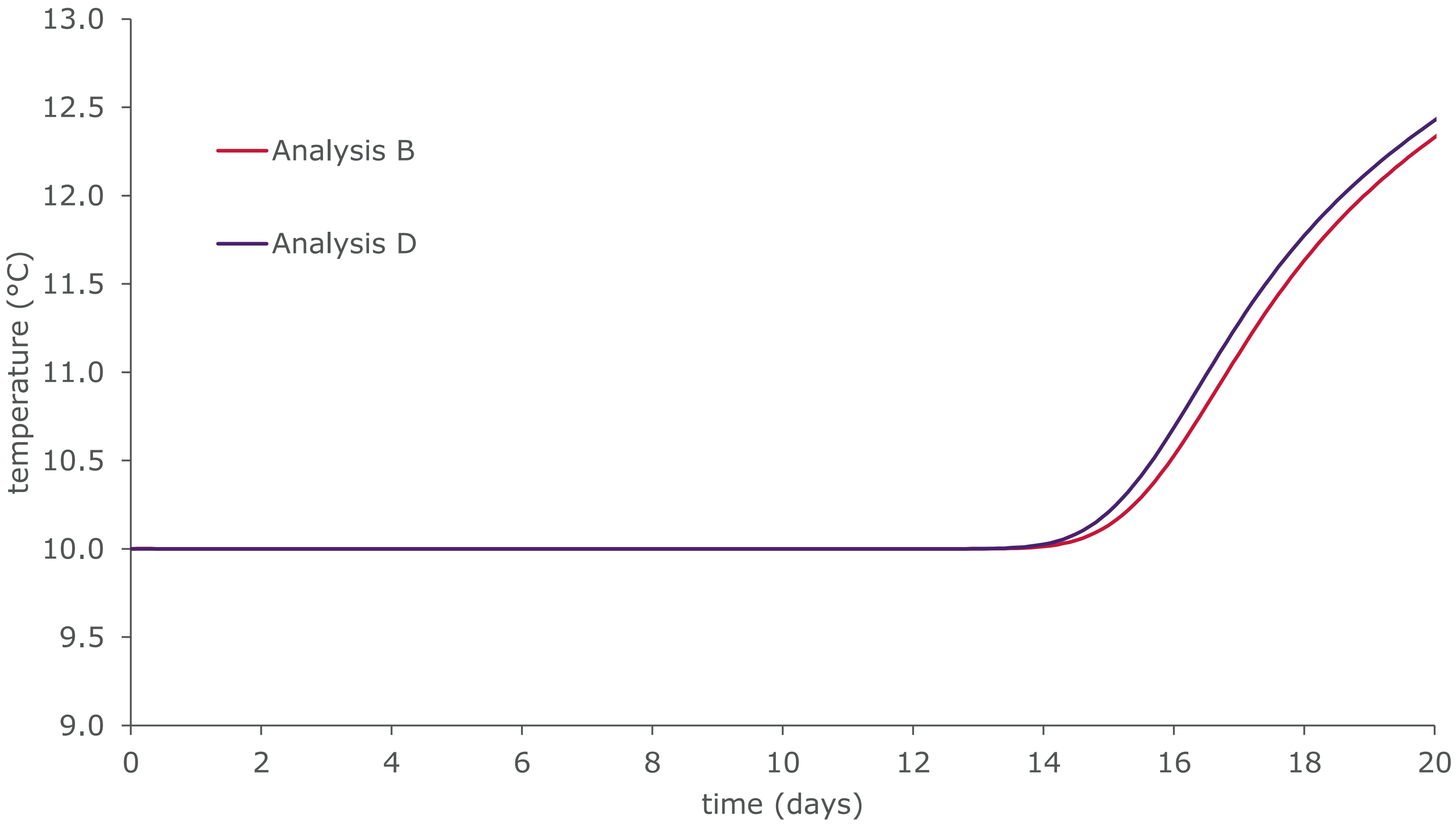


Imperial College London

3) Application to open-loop GSES

Effect of element size

Analysis B: quadratic elements, **coarse mesh**
Analysis D: quadratic elements, **fine mesh**

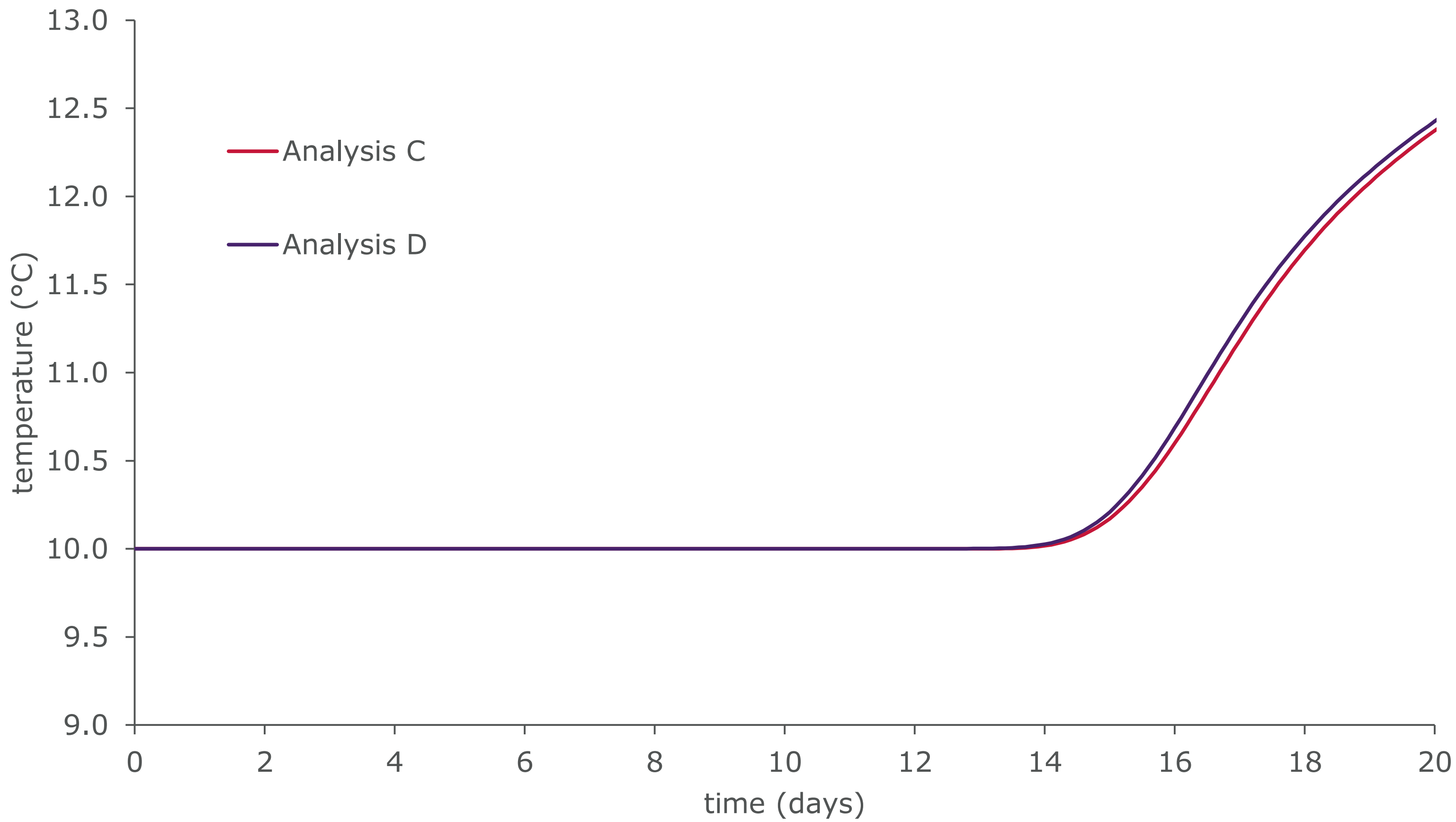


Imperial College London

3) Application to open-loop GSES

Effect of element type

Analysis C: **linear elements**, fine mesh
Analysis D: **quadratic elements**, fine mesh



3) Application to open-loop GSES

Summary of results

Analysis	Element type	Maximum Péclet number	Time to thermal breakthrough (days)
A	Linear	60	13.7
B	Quadratic	60	13.1
C	Linear	16	13.4
D	Quadratic	16	12.9
Analytical model (Banks, 2011)			12.7

Presentation outline

1) Numerical facilities in Imperial College Finite Element Program (ICFEP)

2) Finite element analysis of highly convective heat transfer

3) Application to open-loop ground source energy systems

4) Conclusions

Imperial College London

4) Conclusions

Coupled thermo-hydraulic FE analysis

- The coupled thermo-hydraulic boundary condition balances the energy associated with water flow through a boundary

- ICFEP is capable of modelling coupled thermo-hydraulic problems

Imperial College London

4) Conclusions

FE analysis of highly convective heat transfer

- Péclet number is a useful indication of the significance of convective heat transport
- Péclet number can be used as a measure of the element size required to avoid oscillations in the results
- When coupled thermo-hydraulic boundary condition is used, non-oscillatory results are observed with higher Péclet number

4) Conclusions

Numerical modelling of open-loop GCES

- Oscillations occur after thermal breakthrough, therefore Péclet number (element size) does not affect the predicted time to thermal breakthrough

- Element type does not affect the predicted time to thermal breakthrough

- Times to thermal breakthrough obtained numerically agree with the analytical solution

- **However**, if thermo-mechanical coupling is considered, the oscillations may affect the mechanical solution

Investigations on numerical analysis of coupled thermo-hydraulic problems in geotechnical engineering

W. Cui, K.A. Gawecka, D.M. Potts, D.M.G. Taborda and L. Zdravković