Institute of Energy and Sustainable Development

ADVANCES IN MODELLING AND MONITORING OF GSHP SYSTEMS

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GSHPA Research Seminar

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OVERVIEW

- Current work:
  - Numerical Modelling of BHE *(Candy He)*
  - Monitoring of a large Non-domestic GSHP installation *(Selvaraj Naicker)*
  - Modelling of Foundation Heat Exchanger systems *(Denis Fan)*

NUMERICAL MODELLING OF BHE

Model Development – A Dynamic 3D Model for BHE

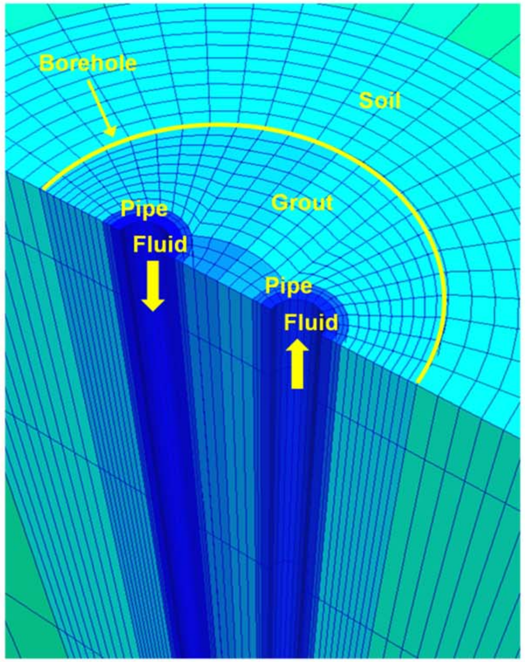


Fig. 2 Multi-block boundary fitted mesh.

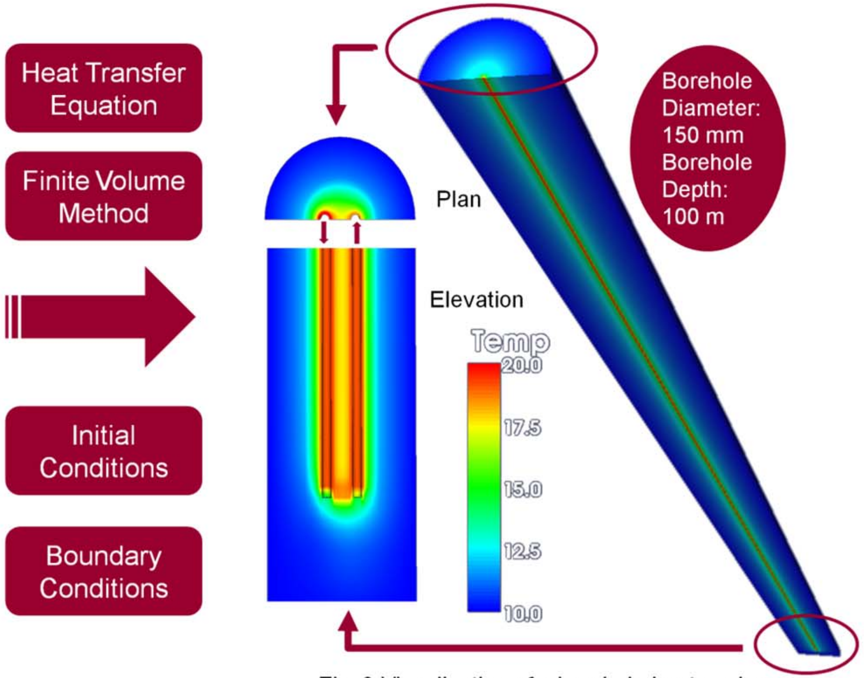


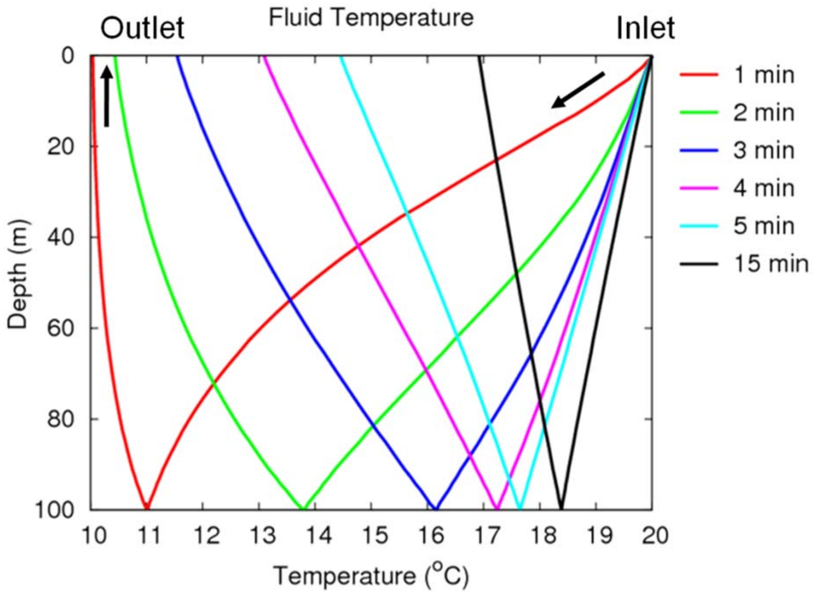
Fig. 3 Visualization of a borehole heat exchanger.

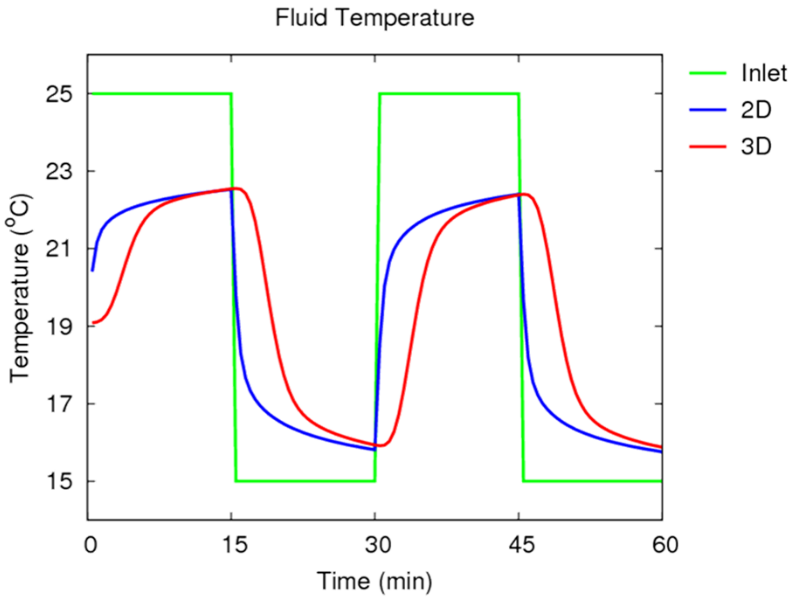
This new 3D model can:

- Simulate **transient fluid transport** along pipe loop.
- Apply **various boundary conditions** at the surface.
- Impose **initial vertical temperature gradients** of the ground.
- Model **different layers** of rock and soil.
- Obtain **temperature distribution** along borehole depth.
- Examine **heat transfer below the borehole**.

NUMERICAL MODELLING OF BHE

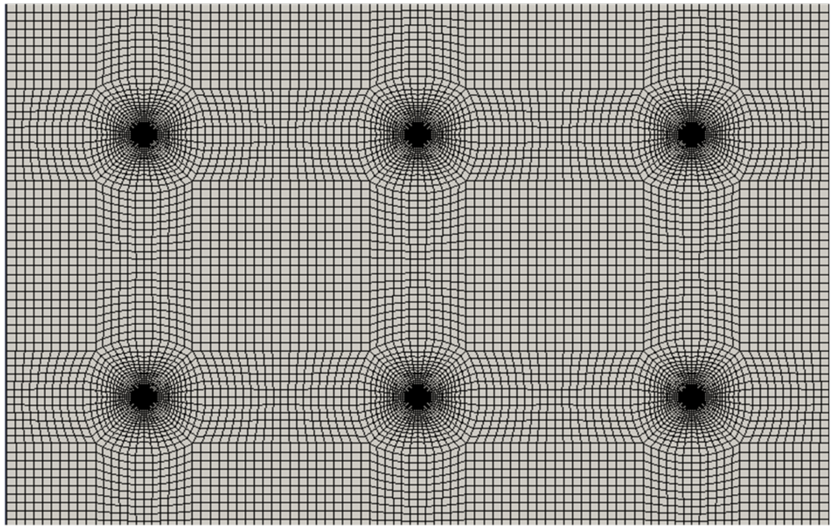
- A 3D Model allows analysis of borehole temperature and heat transfer variations with depth
- Modelling fluid circulation allows short-timescale response to be modelled

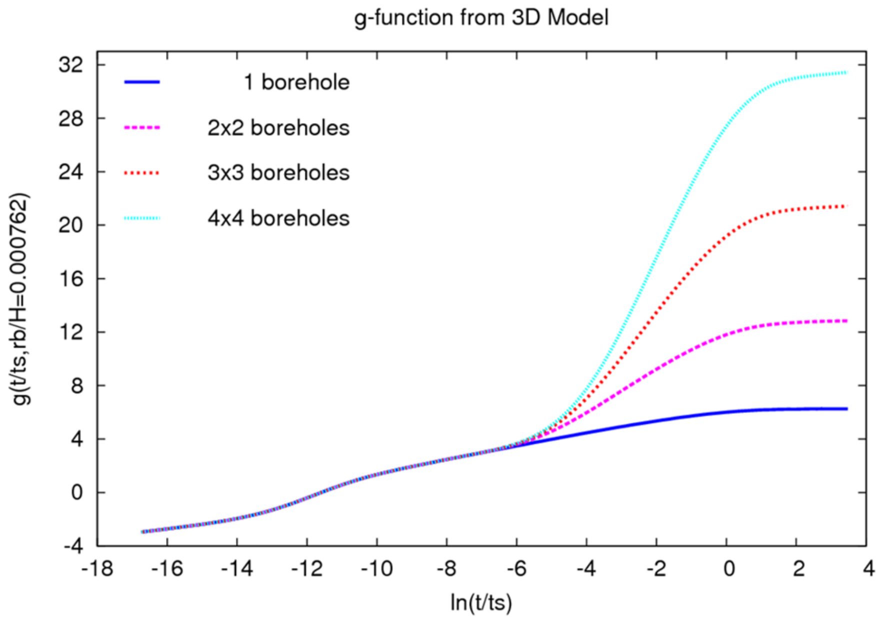




BOREHOLE FIELD RESPONSE

- Modelling the borehole components is important when trying to capture short timescale effects
- Modelling interaction and axial heat transfer is important when trying to capture long timescale effects

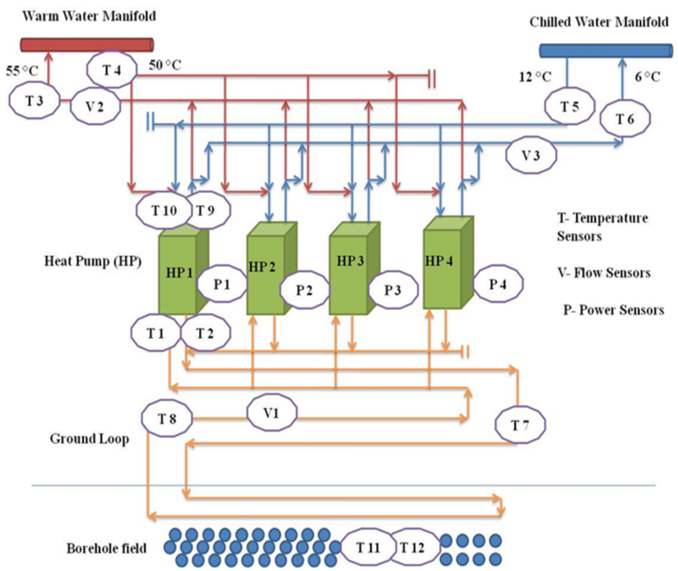




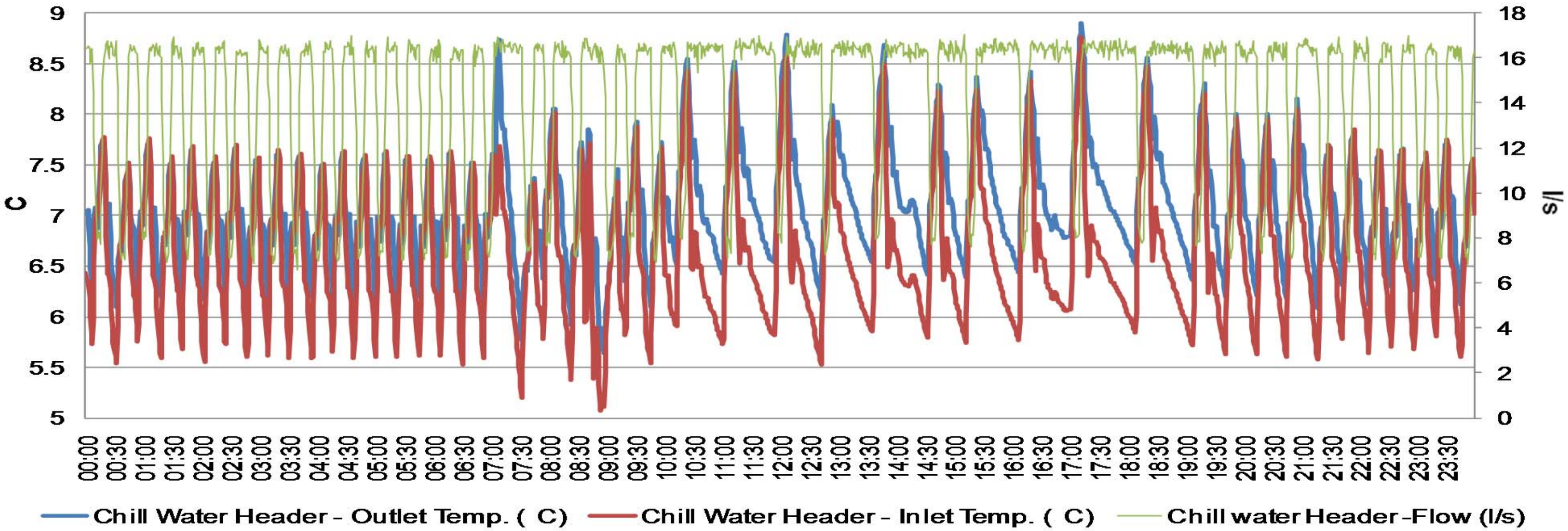
MONITORING OF A LARGE NON-DOMESTIC GSHP SYSTEM

DMU Hugh Aston Building System:

- A multi-use building (15,607 m$^{2)}$
- Monitored since opening in Jan. 2010
- GSHP system provides all AHU and FCU cooling (360 kW peak) and all underfloor heating (330 kW peak)
- Has Four Water Furnace two-stage reversible heat pumps
- 56 x 100m deep borehole heat exchangers, 125mm diameter. 30 l/s peak flow

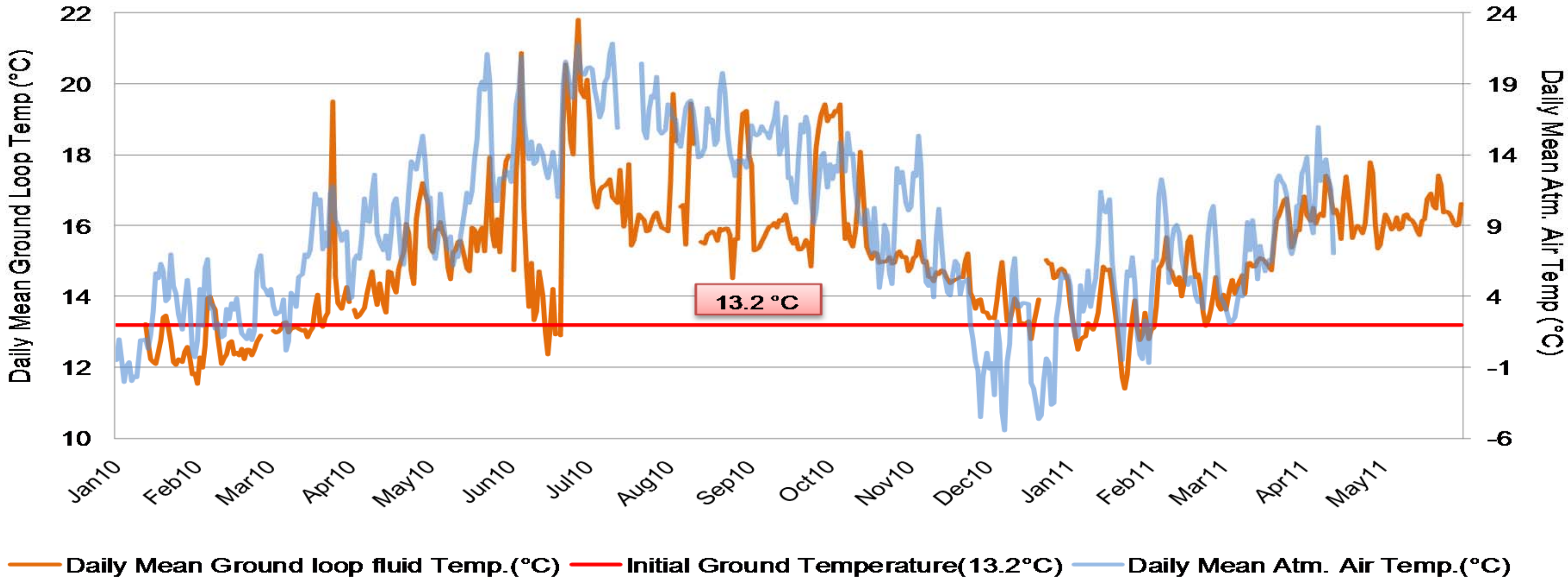


SYSTEM OPERATION



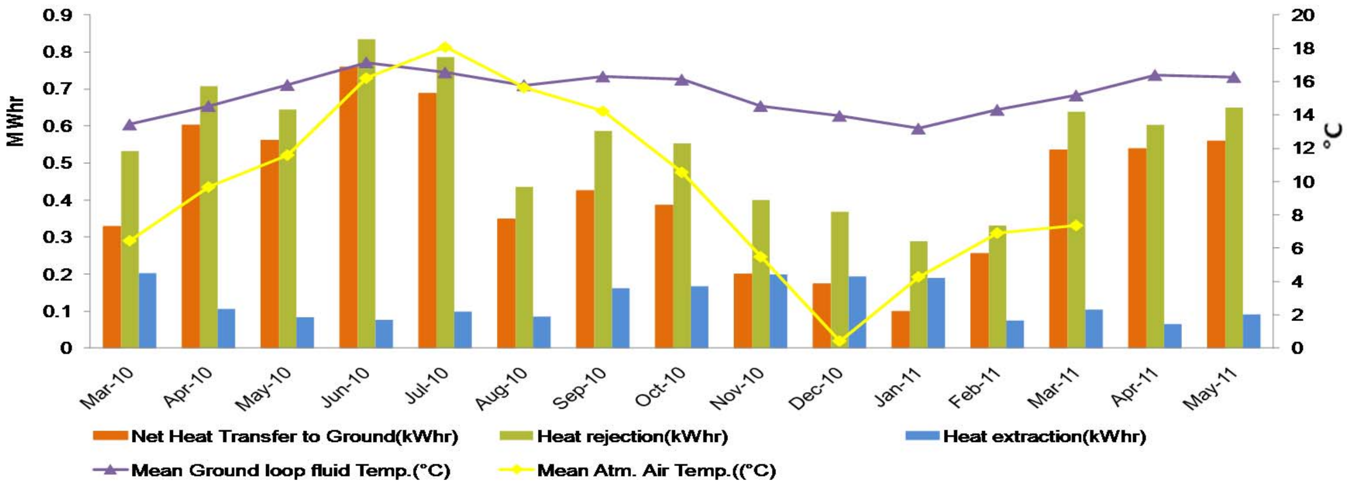
- Three loops – Ground , warm water , chill water – Three variable speed circulating pumps
- Flow rate depends on number of heat pumps under operation
- Four heat pumps – Eight compressor stages – number of stages depends on temperature difference in header and set point
- Chill water header – inlet temp. and outlet temp. varies between 5 to 7.5 and 6 to 8.5 respectively, flow rate varies between 7 to 17 l/s
- Operating cycle length is longer during day says higher cooling load

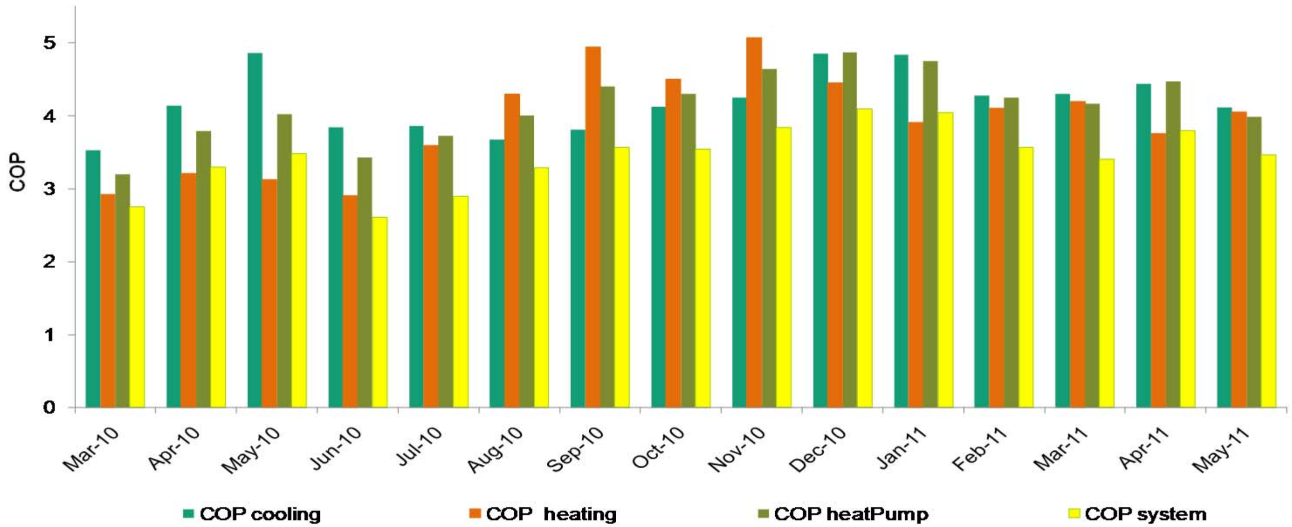
GROUND TEMPERATURES



- Cooling loads predominate.
- Ground loop temperature swings by 8K.
- External air temperature swings by 28K.
- There is some slight increase in temperature in the second year.

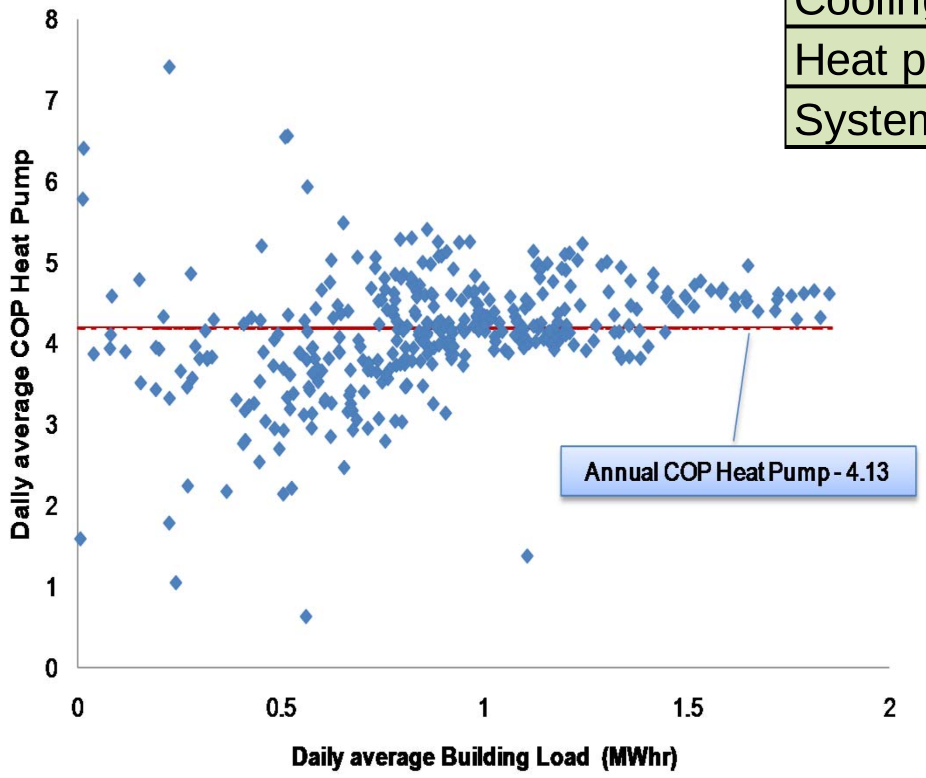
MONTHLY PERFORMANCE





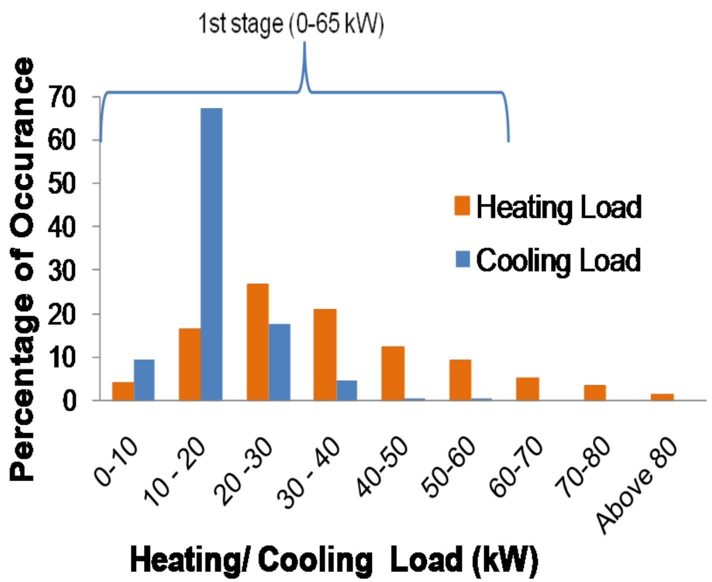
ANNUAL PERFORMANCE

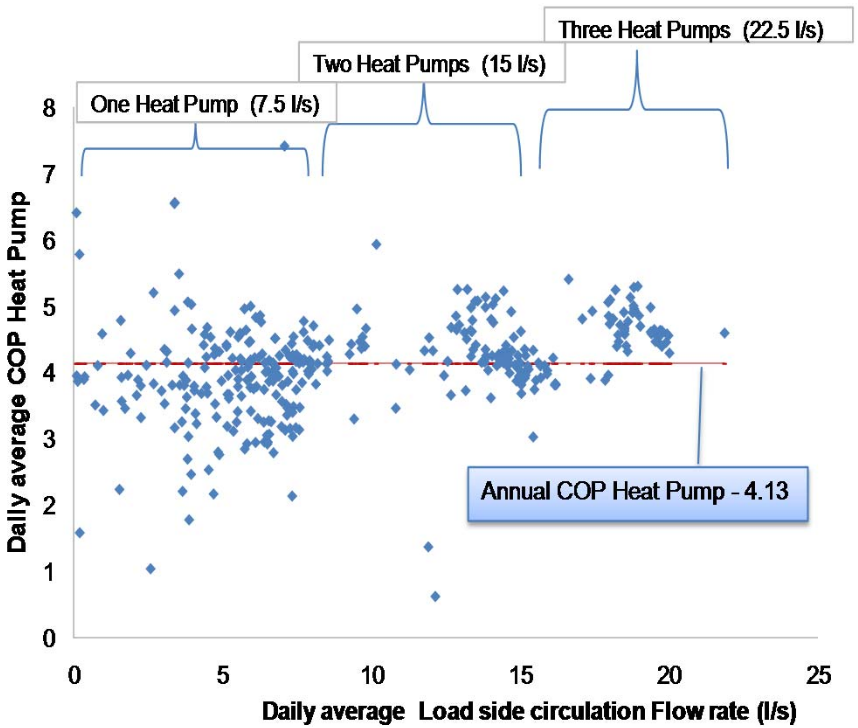
Operation	COP
Heating COP	3.93
Cooling COP	4.19
Heat pump COP	4.13
System Seasonal COP	3.41



$$COP\ system = \frac{Total\ Building\ Load}{Total\ Compressor\ work\ input + Total\ circulating\ Pump\ power}$$

VARIATIONS IN EFFICIENCY





FOUNDATION HEAT EXCHANGER (FHX) MODELLING

- FHX are new type of ground heat exchanger for residential buildings.
- Makes use of excavations created for basement, foundations or external services to accommodate horizontal closed loop pipes.
- FHX can significantly reduce the installation cost as no additional excavation is required.
- Detailed numerical models have been developed by DMU in a US Department of Energy funded project in partnership with OSU and Oak Ridge National Lab

OAK RIDGE National Laboratory

OKLAHOMA STATE UNIVERSITY

FHX Experimental Houses

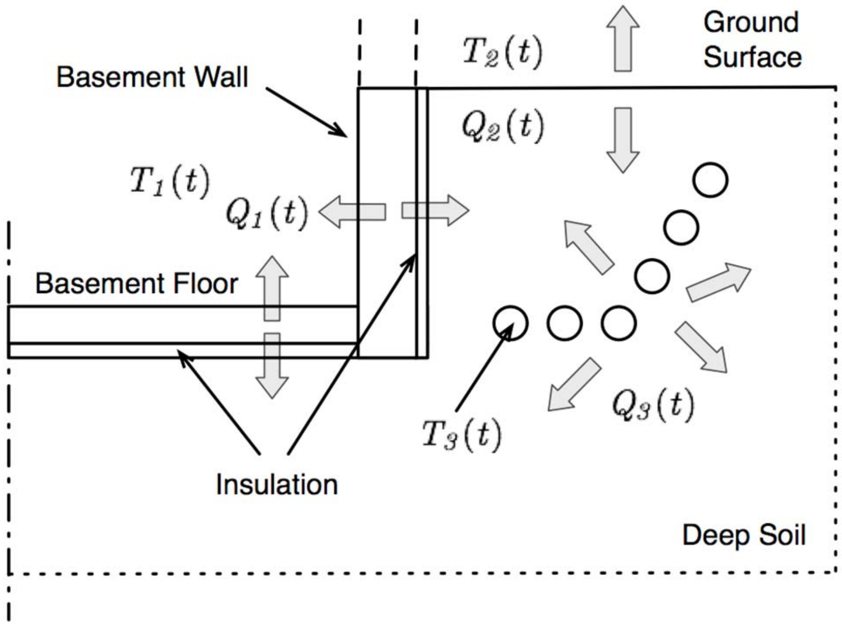
- Four low energy residential buildings have been constructed at Oakridge, Tennessee, USA.
- Two of them have FHX and heat pumps and have been extensively instrumented.
- Data collected over a one year period has been use to validate a number of design tools and simulation models

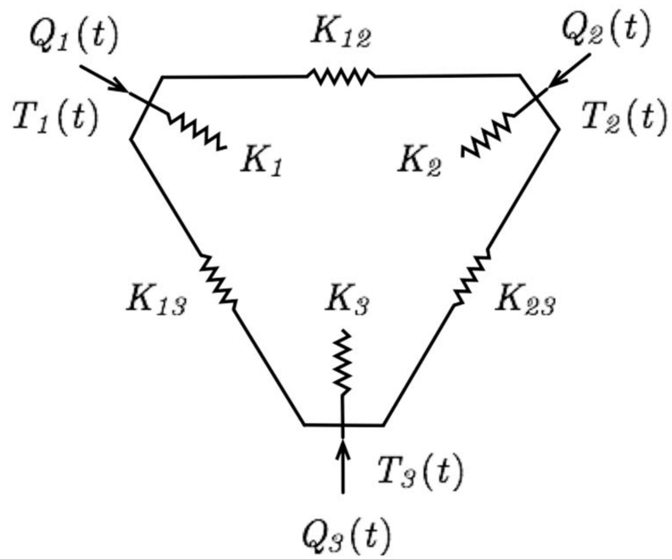
DYNAMIC THERMAL NETWORKS (DTN)

- Two approaches – a 3D Finite Volume Model and a Dynamic Thermal Network Model
- The Dynamic Thermal Network approach:
  - A form of response factor method in which conduction heat transfer processes are represented as a network
  - Conduction fluxes are conceived as the sum of an admitted and a transmitted component.
  - Can be applied to any combination of multi-layer surfaces of arbitrary geometry.
  - Much more efficient that a 3D numerical model
- The method was originally developed by Claesson and Wentzel at Chalmers University, Sweden.

DTN General Formulation

- We consider the modelling of FHX as a 3 surface DTN problem.
- In the FHX model surface 1 is the basement, surface 2 is the ground surface and surface 3 is the pipe surface





DTN General Formulation

Boundary fluxes are defined as the sum of admitted and transmitted components. For a three-surface problem:

$$Q_1(t) = K_1 \cdot [T_1(t) - \overline{T}_{1a}(t)] + K_{12} \cdot [\overline{T}_{1:2}(t) - \overline{T}_{2:1}(t)] + K_{13} \cdot [\overline{T}_{1:3}(t) - \overline{T}_{3:1}(t)]$$

$$Q_2(t) = K_2 \cdot [T_2(t) - \overline{T}_{2a}(t)] + K_{12} \cdot [\overline{T}_{2:1}(t) - \overline{T}_{1:2}(t)] + K_{23} \cdot [\overline{T}_{2:3}(t) - \overline{T}_{3:2}(t)]$$

$$Q_3(t) = \underbrace{K_3 \cdot [T_3(t) - \overline{T}_{3a}(t)]}_{\text{Absorbed component components}} + \underbrace{K_{13} \cdot [\overline{T}_{3:1}(t) - \overline{T}_{1:3}(t)] + K_{23} \cdot [\overline{T}_{3:2}(t) - \overline{T}_{2:3}(t)]}_{\text{Transmitted}}$$

Absorbed component components

Transmitted

DTN GENERAL FORMULATION (2)

$$Q_1(t) = K_1 \cdot [T_1(t) - \overline{T}_{1a}(t)] + K_{12} \cdot [\overline{T}_{1:2}(t) - \overline{T}_{2:1}(t)] + K_{13} \cdot [\overline{T}_{1:3}(t) - \overline{T}_{3:1}(t)]$$

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3 Surface Conductances

DTN General Formulation (2)

$$Q_1(t) = K_1 \cdot [T_1(t) - \overline{T}_{1a}(t)] + K_{12} \cdot [\overline{T}_{1:2}(t) - \overline{T}_{2:1}(t)] + K_{13} \cdot [\overline{T}_{1:3}(t) - \overline{T}_{3:1}(t)]$$

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3 Transmittive Conductances

DTN General Formulation (2)

$$Q_1(t) = K_1 \cdot [T_1(t) - \overline{T}_{1a}(t)] + K_{12} \cdot [\overline{T}_{1:2}(t) - \overline{T}_{2:1}(t)] + K_{13} \cdot [\overline{T}_{1:3}(t) - \overline{T}_{3:1}(t)]$$

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$$[T_n(t) - \overline{T}_{na}(t)] = T_n(t) - \int_0^\infty \kappa_{na} \cdot T_n(t-\tau)\,d\tau \qquad [n = 1,2,3]$$

Current Boundary Temperature

DTN General Formulation (2)

$$Q_1(t) = K_1 \cdot [T_1(t) - \overline{T}_{1a}(t)] + K_{12} \cdot [\overline{T}_{1:2}(t) - \overline{T}_{2:1}(t)] + K_{13} \cdot [\overline{T}_{1:3}(t) - \overline{T}_{3:1}(t)]$$

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Absorption Weighting Functions

DTN GENERAL FORMULATION (2)

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Temperature History Backwards to time τ

DTN General Formulation (2)

$$Q_1(t) = K_1 \cdot [T_1(t) - \overline{T}_{1a}(t)] + K_{12} \cdot [\overline{T}_{1:2}(t) - \overline{T}_{2:1}(t)] + K_{13} \cdot [\overline{T}_{1:3}(t) -- \overline{T}_{3:1}(t)]$$

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$$[\overline{T}_{n:m}(t) - \overline{T}_{n:m}(t)] = \int_0^\infty \kappa_{nm} \cdot [T_n(t-\tau) - T_m(t-\tau)] d\tau \qquad \begin{bmatrix} n = 1,2,3; m = 1,2,3 \\ n \neq m \end{bmatrix}$$

Transmittive Weighting Functions

DTN General Formulation (2)

$$Q_1(t) = K_1 \cdot [T_1(t) - \overline{T}_{1a}(t)] + K_{12} \cdot [\overline{T}_{1:2}(t) - \overline{T}_{2:1}(t)] + K_{13} \cdot [\overline{T}_{1:3}(t) - \overline{T}_{3:1}(t)]$$

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Temperature Histories Backwards to time τ

DTN Discrete Formulation

- The formulation can be expressed in discrete form in an exact way for piecewise linear varying boundary conditions.
- For the absorptive weighting function the discrete weighting factor series (length ρ) can be found from a step response heat flux calculation:

$$\kappa_{\mathrm{na},\rho} = \frac{\overline{Q}_{na}(\varphi) - \overline{Q}_{na}(\omega)}{\overline{\overline{K}}_{n}} \qquad \begin{bmatrix} n = 1,2,3 \\ \varphi = (vh - h), \omega = vh \\ v = 1,\ldots,\rho \end{bmatrix}$$

- Similarly for the transmitted weighting factors:

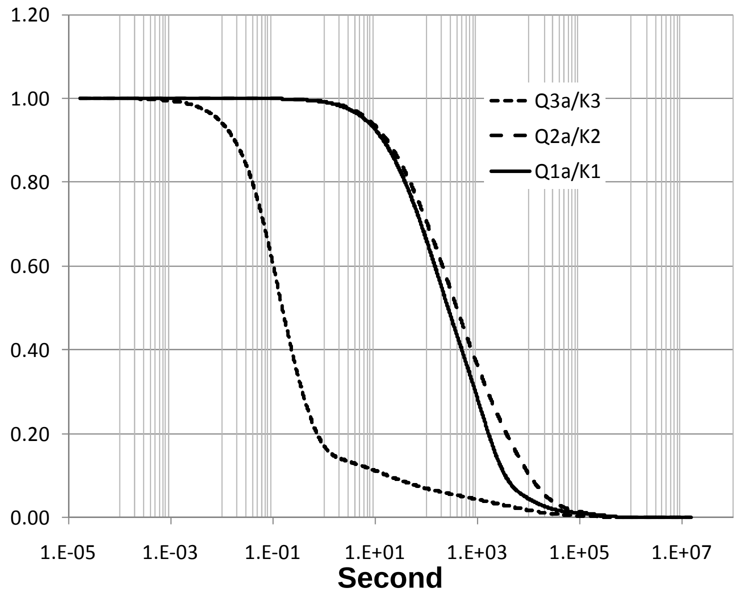
$$\kappa_{\mathrm{nm},\rho} = \frac{\overline{Q}_{nm}(\omega) - \overline{Q}_{nm}(\rho)}{\overline{\overline{K}}_{nm}} \qquad \begin{bmatrix} n = 1,2,3; m = 1,2,3; n \neq m \\ \varphi = (vh - h), \omega = vh \\ v = 1,\ldots,\rho \end{bmatrix}$$

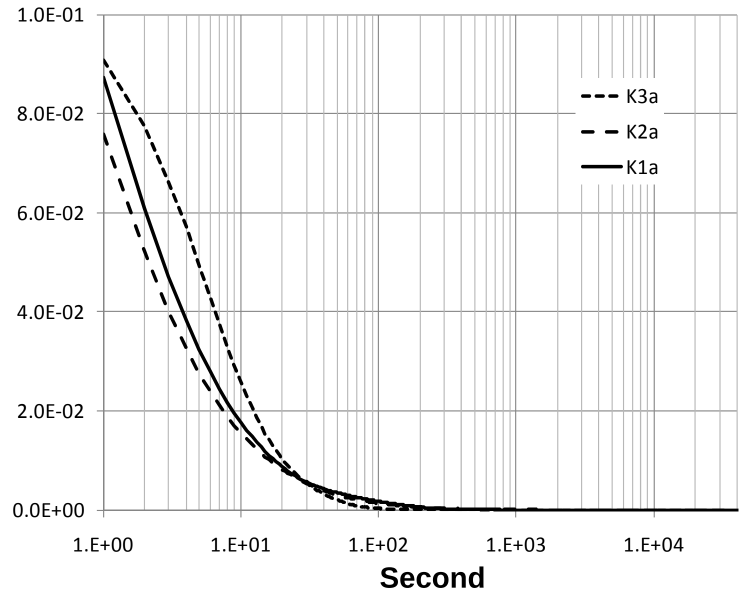
DTN NUMERICAL IMPLEMENTATION

Generation of the Step Response

- Available approaches:
  - Analytical solutions for simple geometries, e.g. Multi-layer walls (*Claesson, 2003*).
  - Use a Finite Difference Method with fixed time steps for more complex geometries (*Wentzel, 2005*).
- Our approach:
  - Apply Finite Volume Method (FVM) using 2D and 3D FHX meshes and variable time steps (2nd order accurate).

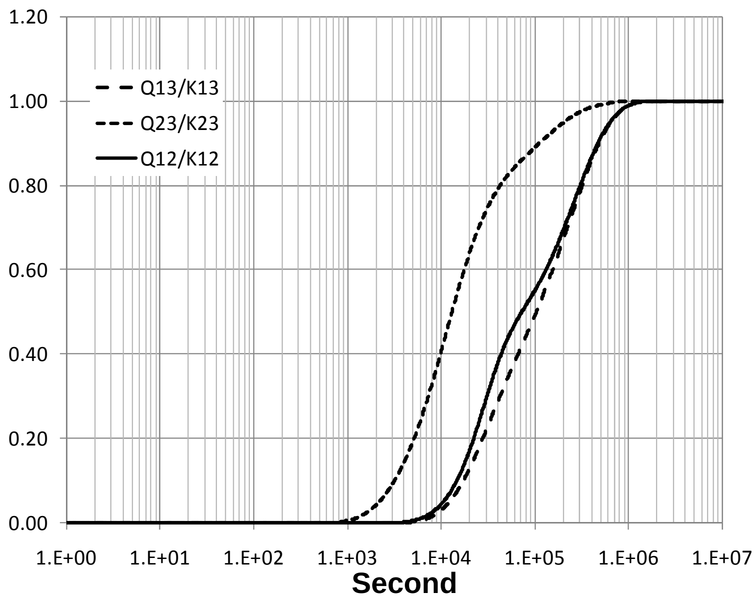
EXAMPLE ABSORBTIVE WEIGHTING FUNCTIONS

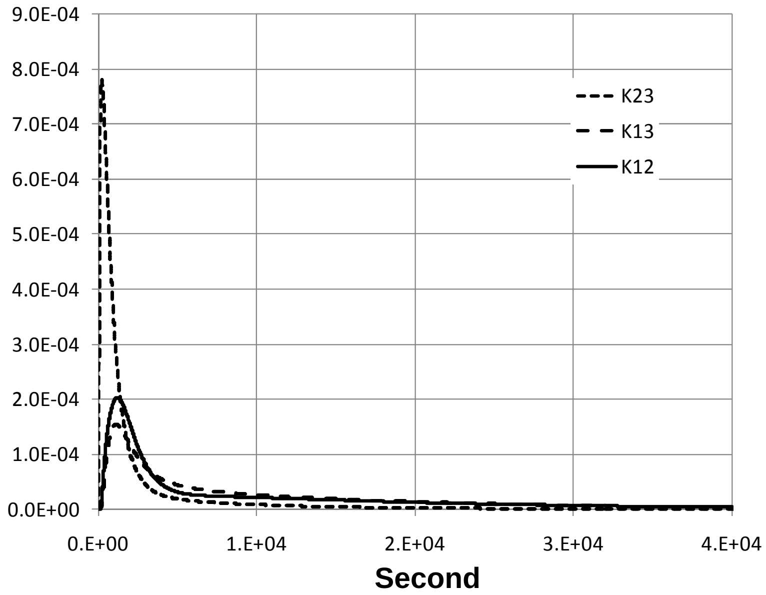




	Decay Period		Fallen to 50% of Maximum
Q_{1a}	0.001 sec – 15 hrs	K_{1a}	~ 5 hrs
Q_{2a}	6 min – 15 hrs	K_{2a}	~ 8 hrs
Q_{3a}	6 min – 15 hrs	K_{3a}	~ 2.5 hrs

EXAMPLE TRANSMITTIVE WEIGHTING FUNCTIONS



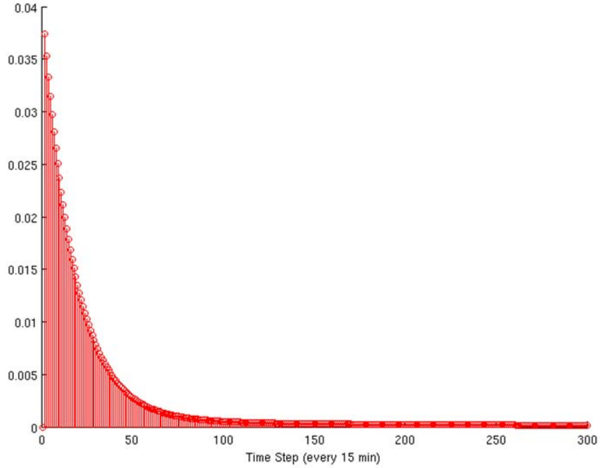


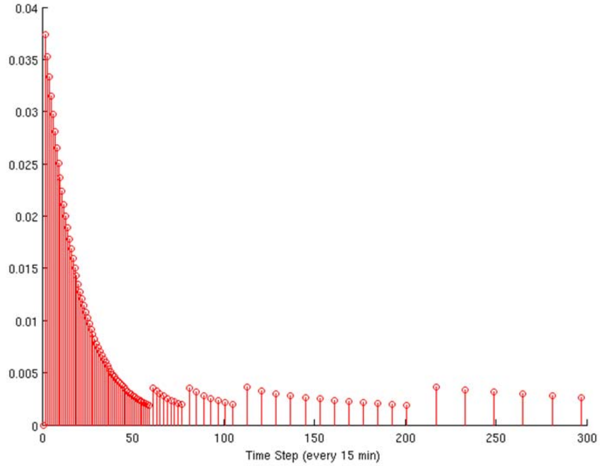
	Steady-state	Rise to 20% of Steady-state		Time to Maximum
Q_{12}	~ 6 years	~ 16 hours	K_{12}	~ 15 hours
Q_{13}	~ 6 years	~ 25 hours	K_{13}	~ 13 hours
Q_{23}	~ 5 years	~ 25 hours	K_{23}	~ 3 hours

DTN Weighting Factor Calculation

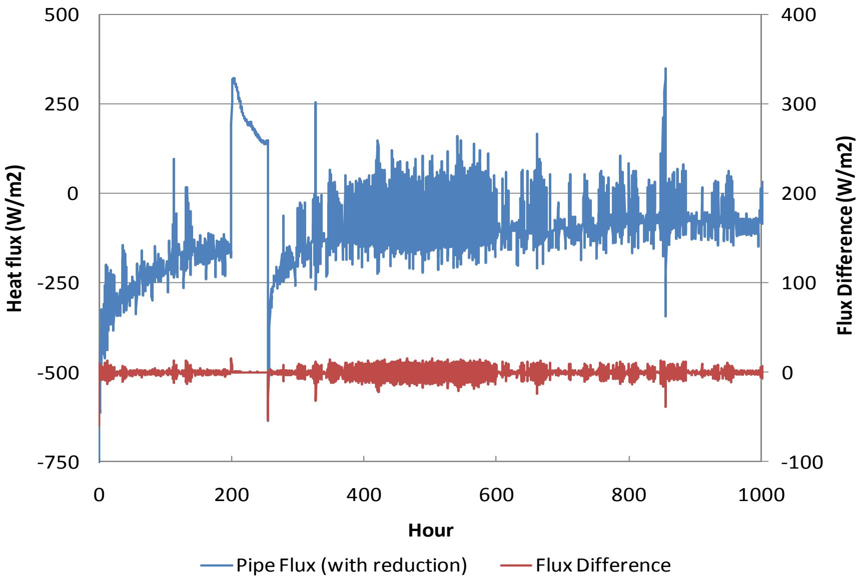
Weighting Factor Reduction

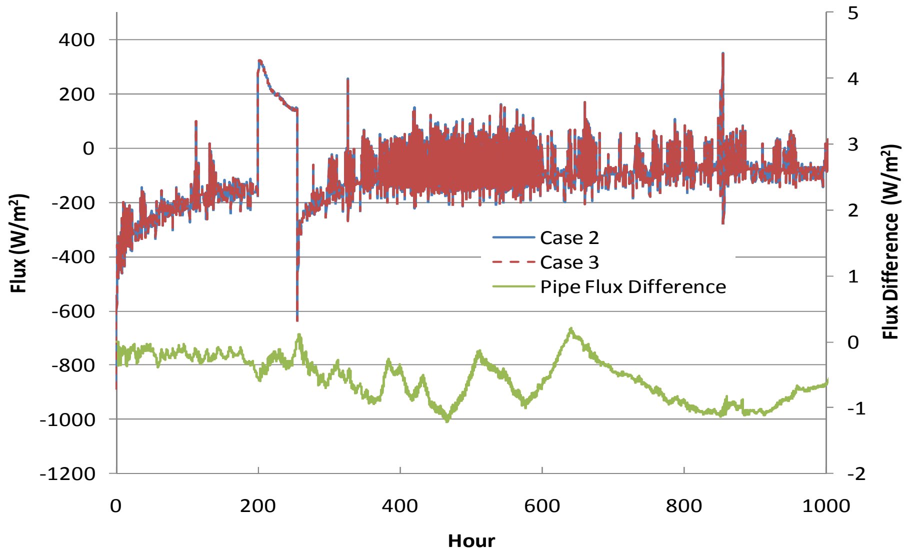
- Temperature histories for FHX can be up to a hundred thousand values, e.g. for 1 hour intervals.
- Approx. 2 days to complete an annual FHX simulation.
- Wentzel's (*2005*) reduction strategy was implemented to reduce this computation cost – time intervals are progressively doubled.
- More aggressive reduction strategies have been developed to improve efficiency further





DTN Method Verification





- Acceptably Close agreement between the DTN prediction & results from the Finite Volume solver.
- Reduction of the weighting factors introduces insignificant errors

SUMMARY

- DTN allows complex 3D multi-layer components to be simulated efficiently
- Practical implementation of the DTN approach has required:
  - Automated mesh generation
  - Variable time step numerical calculations to find the step response
  - Aggressive response factor reduction
- The result is that annual simulation of the 3D FHX geometry can be completed in less than 10 seconds
- DTN has great potential for heat exchangers such as piles:
  - Surface 1 = pipe
  - Surface 2 = exposed ground
  - surface 3 = below building

THANK YOU FOR LISTENING

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