IMAGES quarterly Meeting
June, 2017

Progress at University of Nottingham.

- Stability of packed beds
- Advancing WindTP
- Sign-Preserving Filters
- All-steel thermal stores
- Thinking forward to one more IMAGES event.

“The Stability of Packed Bed Thermoclines”

Conference paper to be presented at OSES 2017

“The Stability of Packed Bed Thermoclines”

T.R.Davenne, S.D.Garvey, B.Cardenas & J.P.Rouse

Key Points:

- Thermal front stability depends on two factors
    1. Temperature dependence of the resistance to flow (can drive unstable distortion of the thermal front)
    2. Transverse thermal diffusion (acts to spread out non-uniformities)
- The thermal front is inherently unstable when cooling a packed bed with factor 1 being more significant than factor 2
- Small non-uniformities in inlet flow or void fraction may cause significant disruption of the thermal front during discharge of a hot thermal store or charge of coolth store
- Packed bed thermal store models are generally 1D which does not allow for observation of this effect

"The Stability of Packed Bed Thermoclines"

Thermal Front Stability Criterion

Pressure drop in a packed bed: Coefficients A and B are temperature dependant

$$\frac{\Delta P}{L} = AM + BM^2 \qquad A = \frac{150\mu(1-\varepsilon)^2}{\rho d^2 \varepsilon^3} \qquad B = \frac{1.75\rho(1-\varepsilon)}{\rho^2 d \varepsilon^3}$$

Pressure drop in a partially charged thermal store: Subscripts 1 and 2 refer to charge and discharge temperatures, *R* is the fill ratio and assuming an ideal sharp thermal front then

$$\frac{\Delta P}{L} = (A_1 M + B_1 M^2)R + (A_2 M + B_2 M^2)(1-R) \qquad R = \frac{x}{L}$$

Finding $\frac{\partial M}{\partial R}$ >0 gives the following criteria for instability of the thermal front

$$\frac{\Delta P}{L}\big(A_2 - A_1 + 2M(B_2 - B_1)\big) + M^2(A_2 B_1 - A_1 B_2) > 0$$

“The Stability of Packed Bed Thermoclines”

Thermal Front Stability Criterion

Equivalent transverse thermal conductivity can be obtained from the following according to Ming et al.

Often a small effect

$$k_t = 0.04 k_f \frac{(1-\varepsilon)}{\varepsilon} Pe$$

with Peclet number as follows

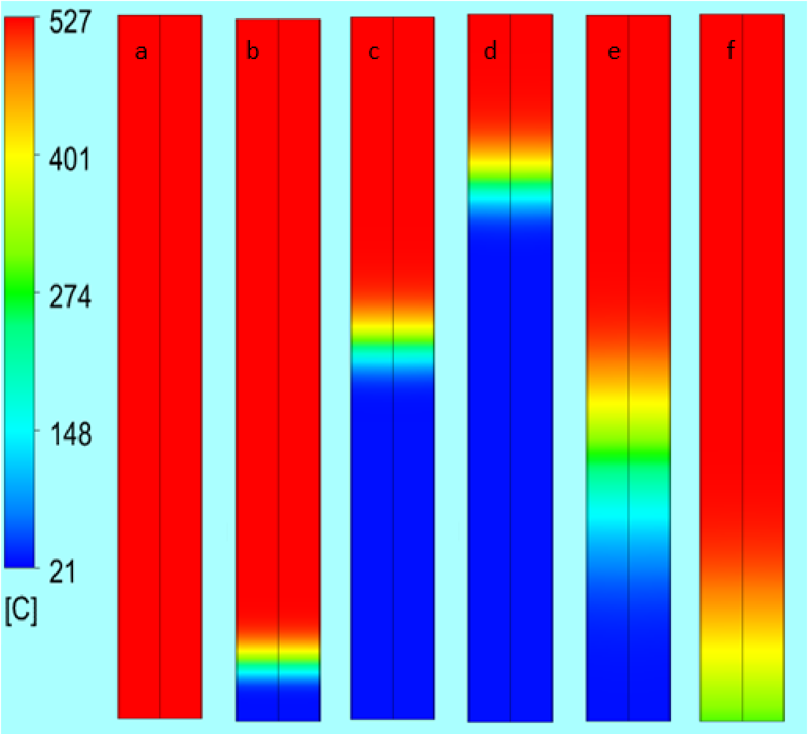
$$Pe = \frac{Vd}{\alpha}$$

and diffusivity being defined as

$$\alpha := \frac{k}{pc_p}$$

“The Stability of Packed Bed Thermoclines”

CFD simulations of a Packed bed thermal store (no perturbation)



Contour plots show rock temperature following discharging for 50000s and then subsequent charging for 50000s (a=initial condition, b= 6000s, c=35000s, d=50000s, e=75000s, f=100000s)

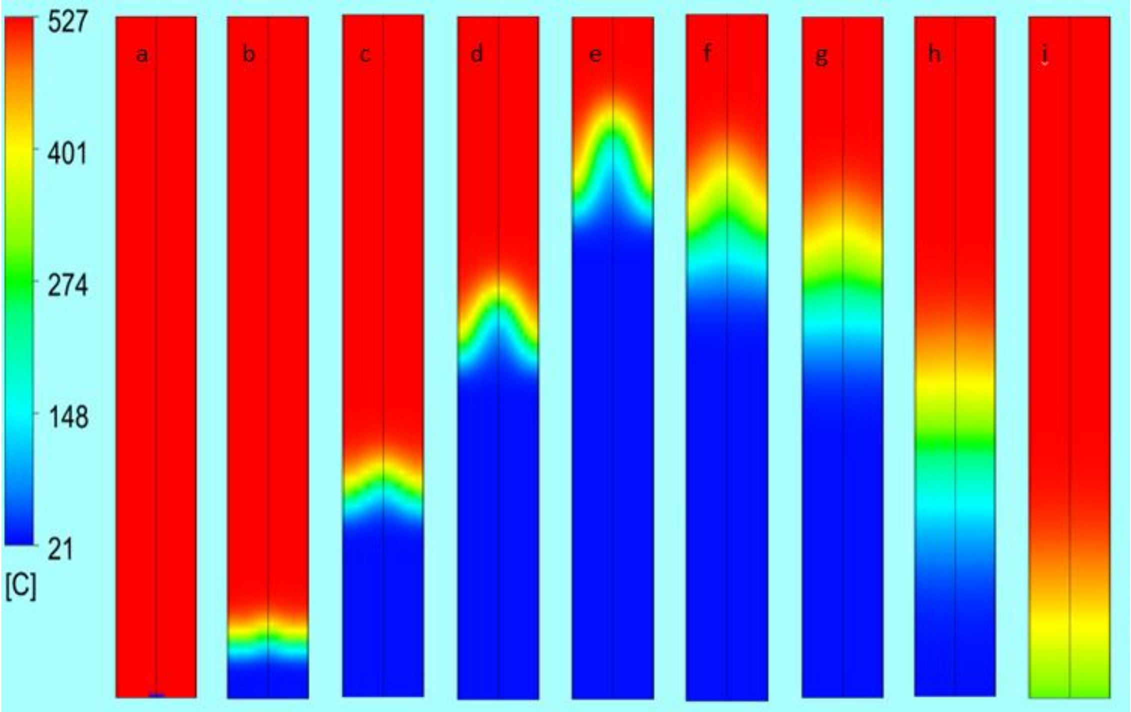
Note thermal front sharper on discharge than on charge – this is due to the thermal front velocity being sensitive to the temperature dependence of the heat capacity of the rock

$$c = \frac{Cp_g}{\rho_s Cp_s(1-\varepsilon)} M$$

“The Stability of Packed Bed Thermoclines”

CFD simulations of a Packed bed thermal store (with perturbation)

Unstable growth of a perturbation (cold spot) in the thermal front during discharge of a hot thermal store and stabilisation of the thermal front during subsequent charging.



Contour plots show rock temperature following discharging for 50000s and then subsequent charging for 50000s (a=initial condition with cold spot, b= 6000s, c=20000s, d=35000s, e=50000s, f=55000s, g=60000s, h=75000s, i=100000s) N.B. Exergy loss increased by 20% compared to uniform case on previous slide.

“The Stability of Packed Bed Thermoclines”

Ideas to minimise detrimental effects of instability

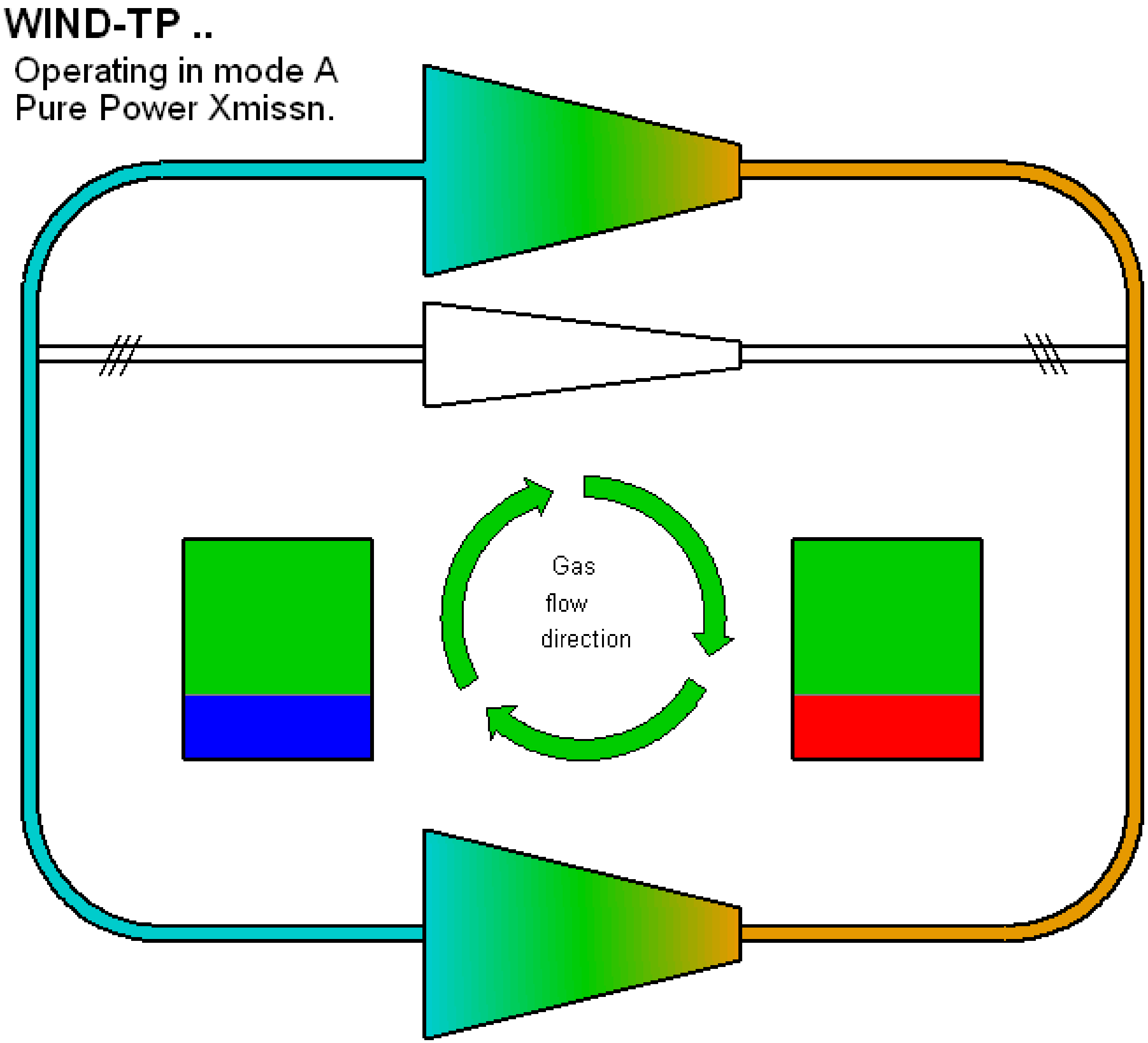
Careful manifold design to ensure uniform inlet and outlet flow across cross section of thermal store

Avoid local areas of high void fraction by packing with regular sized rocks (difficult)?

Significant areas of reduced void fraction exist at the walls. Deform a thin film on to the peripheral surface of the packed bed to remove this local high void fraction region.

Improve transverse diffusion by adding thermally conductive horizontal layers or waste metallic swarf or non unity aspect ratio rocks into the packed bed.

Advancing WindTP



Advancing WindTP

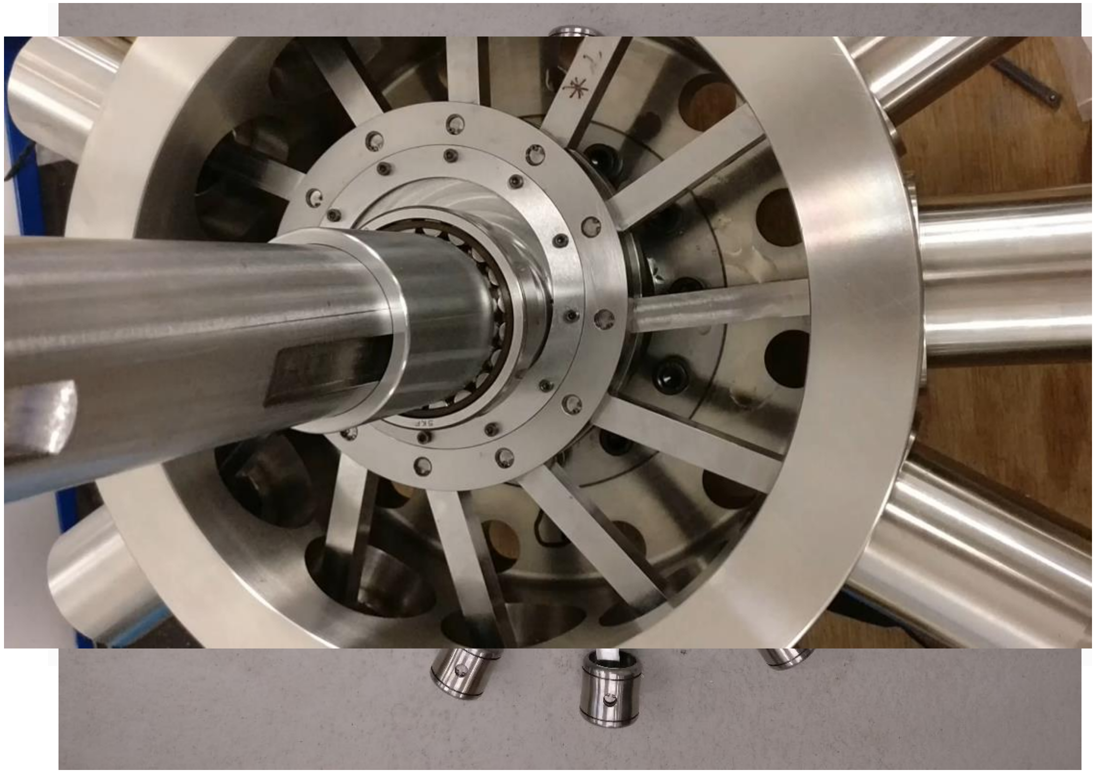
Undergraduate student Nathaniel Newman completed the detail design of the internal parts of the WindTP displacer.

He looked specifically at:

- Piston Profile
- Piston ring design

NN also addressed:

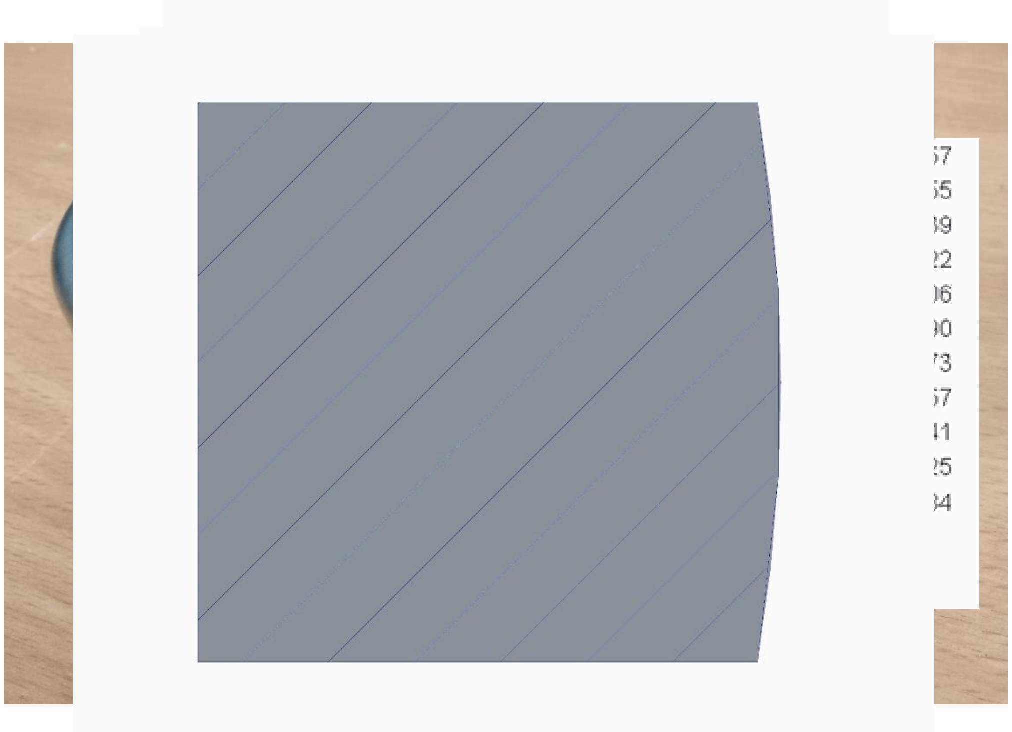
- Assembly of the displacer
- Testing of the displacer



Advancing WindTP

Detailed Design

- Piston features:
    - Two types – saves on parts count
    - Low pressure ∅ 52.07mm
    - High Pressure ∅ 36.24mm
    - Large corner radius
    - Waisted
    - Double acting
- Piston Ring design:
    - Primary concern was assembly - Cast Iron is brittle
    - Contact face also important – optimised to reduce friction



Advancing WindTP

Assembly of the Displacer

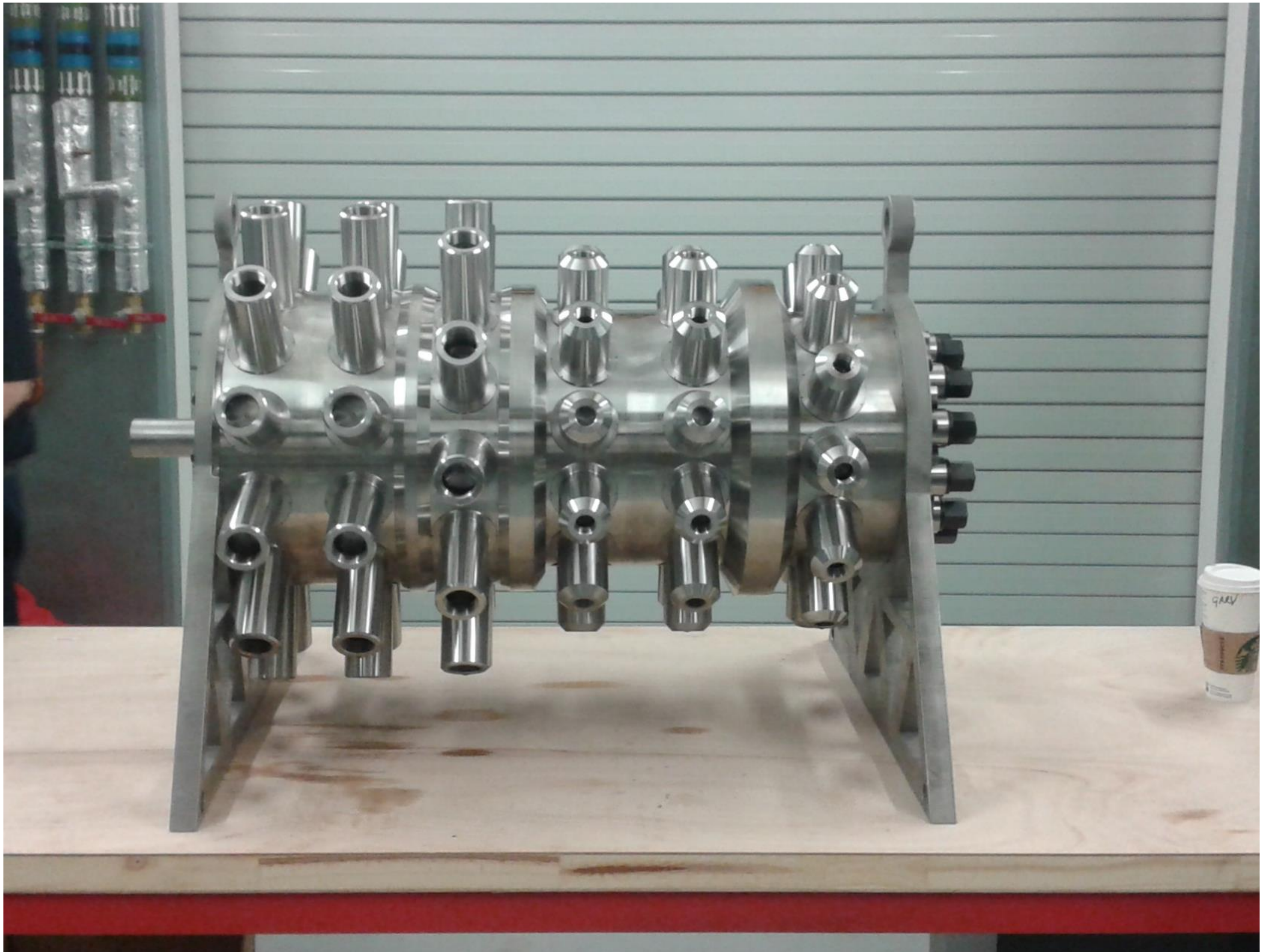
Advancing WindTP

Advancing WindTP

Testing of the Displacer

- Gather data to asses the friction of parts and features
- Four tests:
  - Torque test of each stage prior to cylinder honing without piston rings
  - Torque test of each stage post honing without piston rings
  - Torque test of each stage after honing with piston rings assembled
  - Pressure test of each stage after honing with piston rings assembled
- Future testing:
  - Torque test with pistons immersed in oil at ambient pressure
  - Torque test with pistons immersed in oil at high pressure

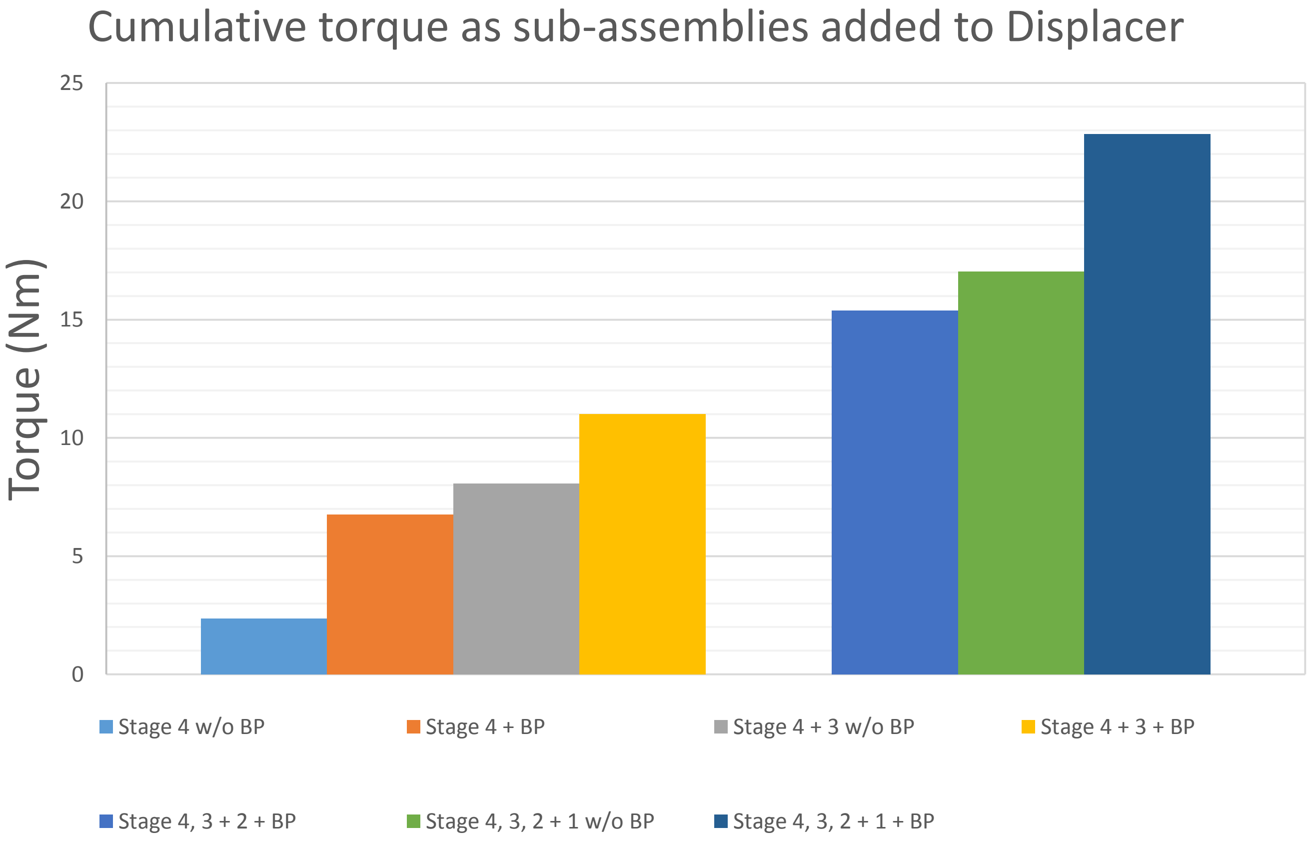
Advancing WindTP



Advancing WindTP

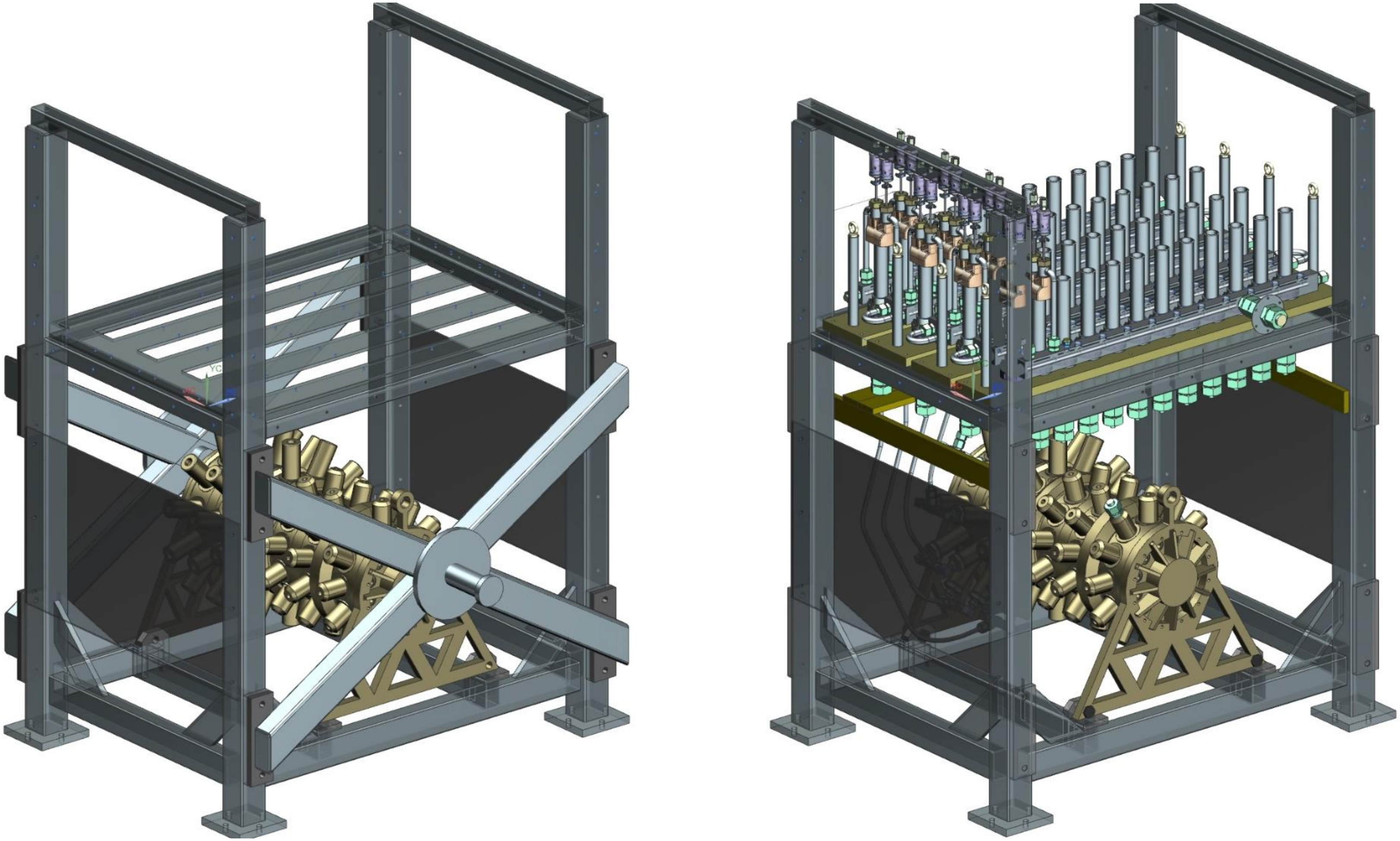
Advancing WindTP

Preliminary experience with the *displacer* seems very promising



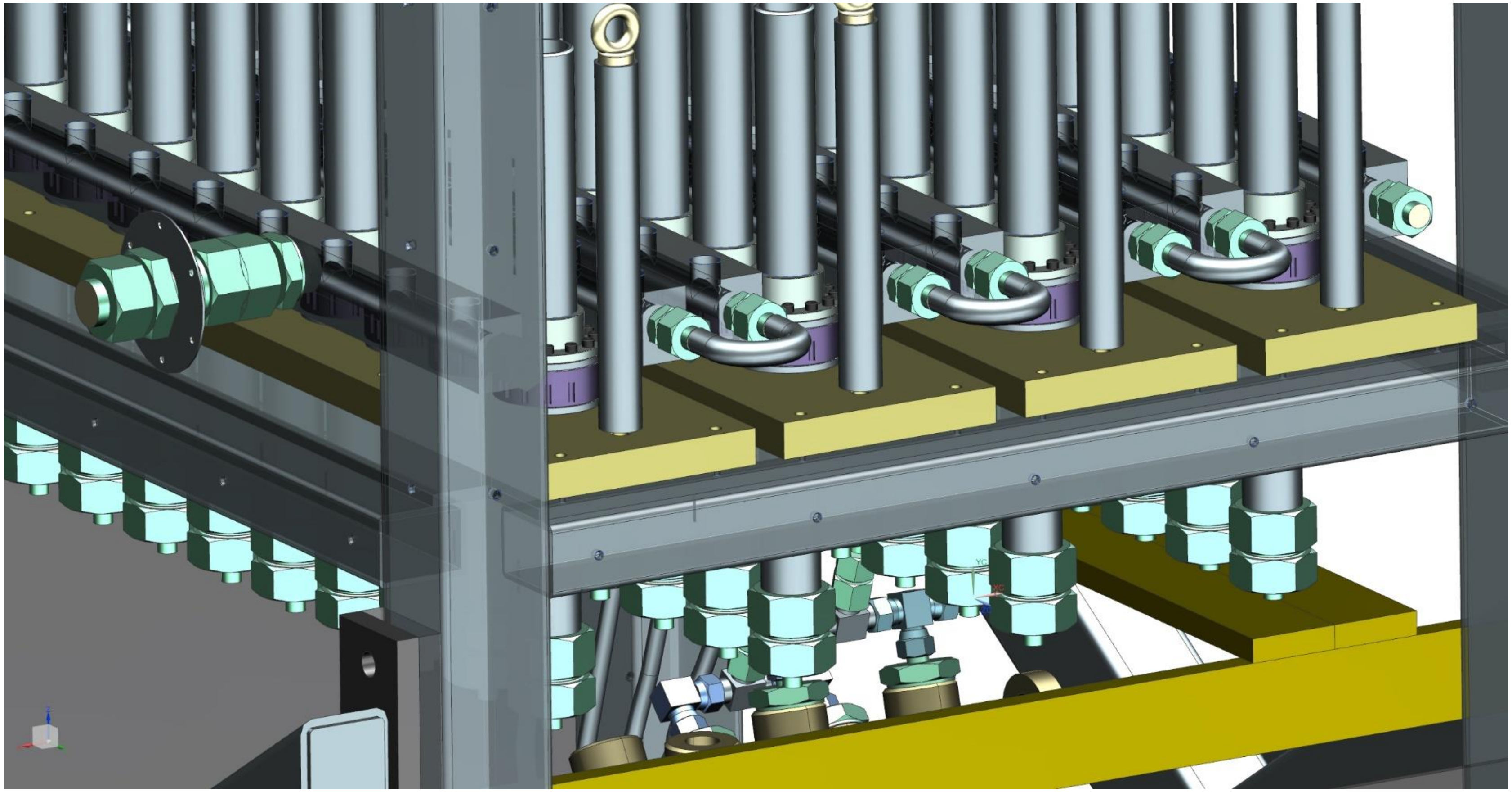
Advancing WindTP

The *Converter* design is almost complete.



Advancing WindTP

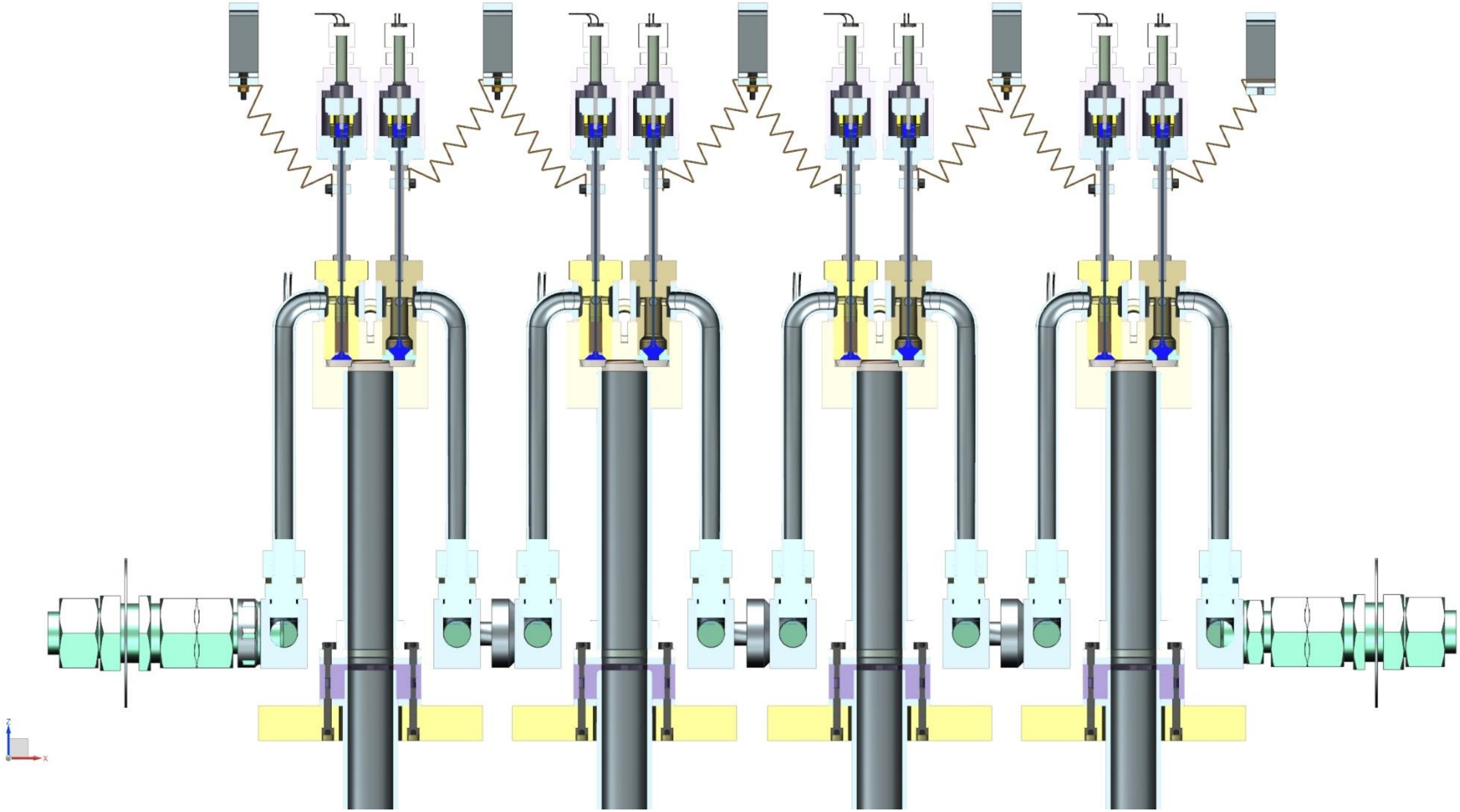
The *Converter* design is almost complete.



The University of Nottingham
UNITED KINGDOM · CHINA · MALAYSIA

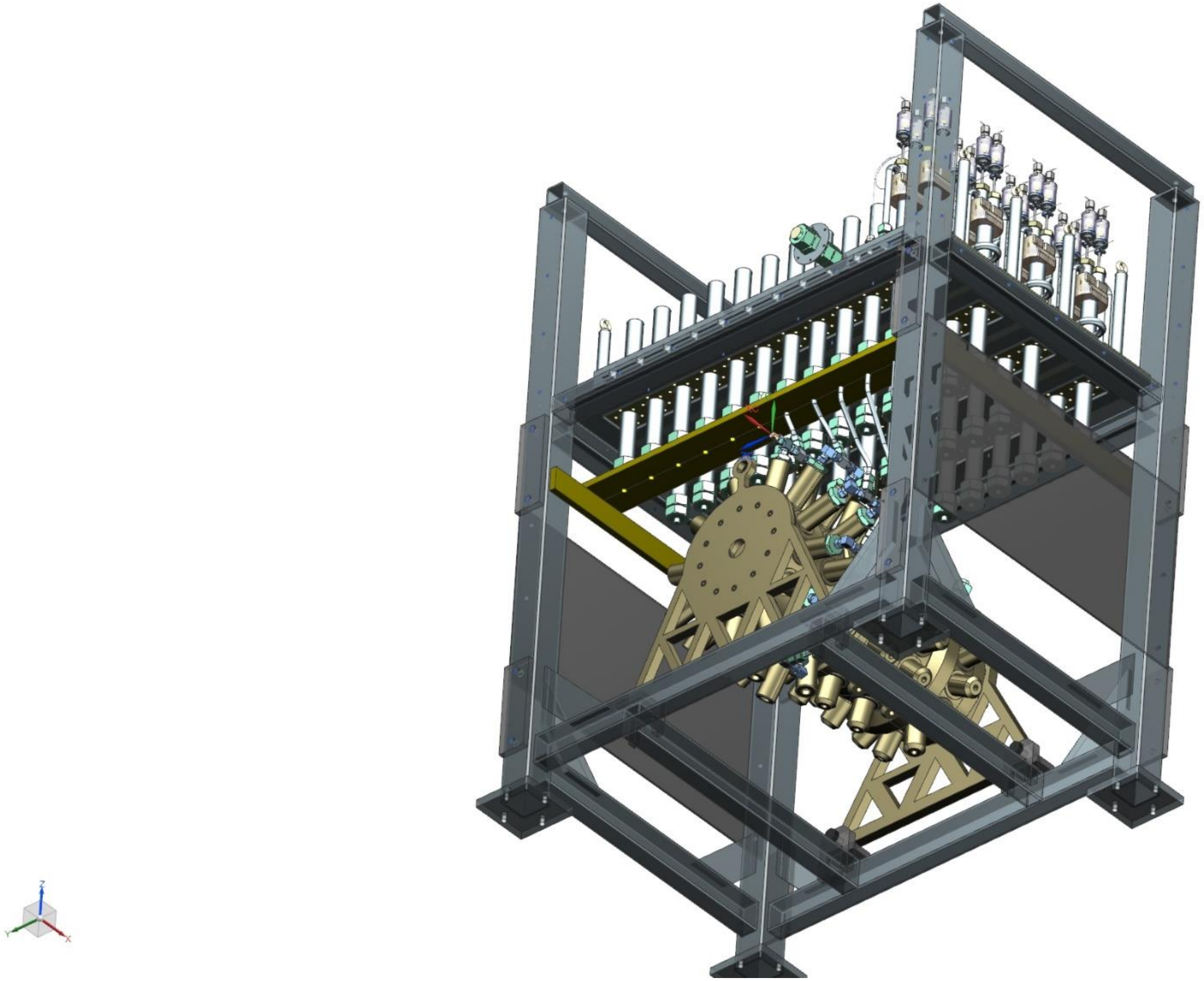
Advancing WindTP

The *Converter* design is almost complete.



Advancing WindTP

The *Converter* design is almost complete.



Sign-Preserving Filtering

“Problem Statement”:

Design of packed-bed thermal stores is a trade-off between pressure-drop and quality of heat transfer.

Relatively large rock sizes => small Δp but large ΔT

Relatively small rock sizes => larger Δp but smaller ΔT

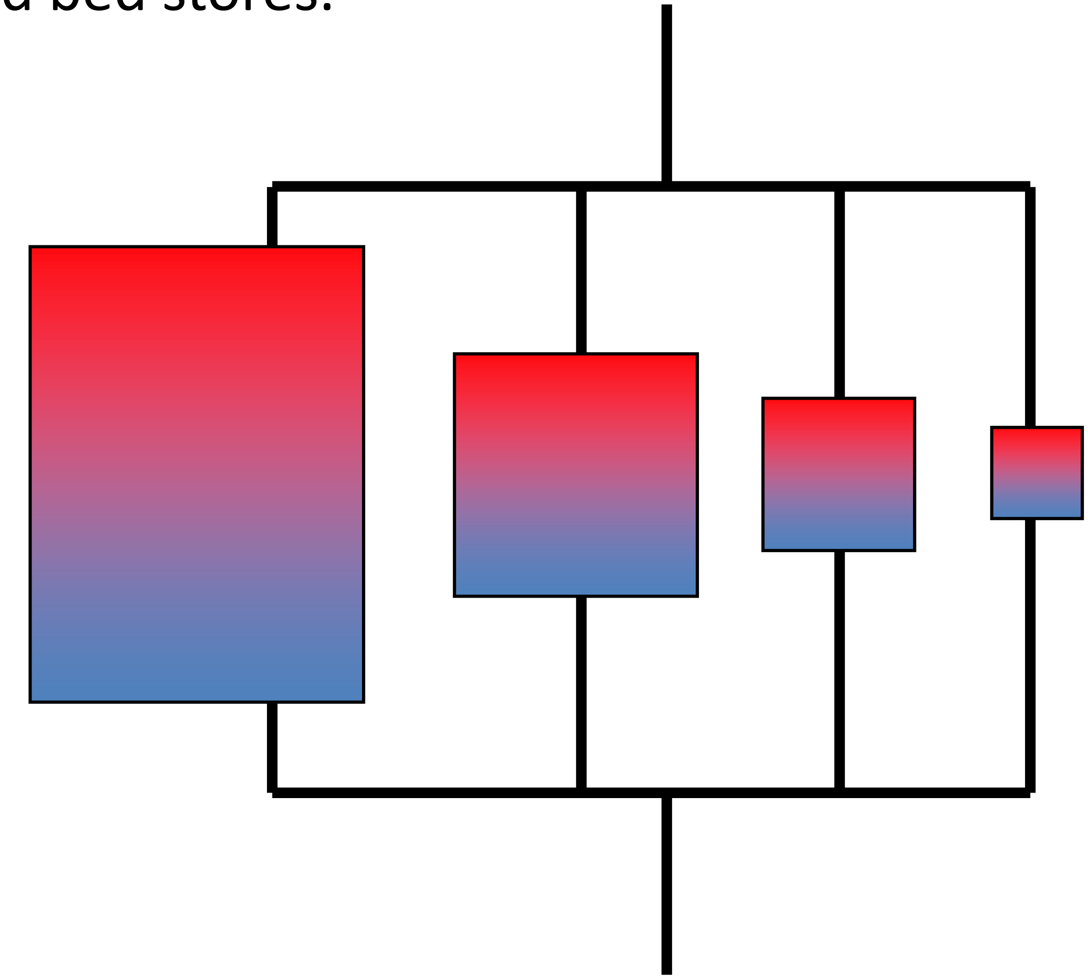
Conjecture:

Use parallel packed-bed stores with:

- small stores having small rock sizes for *high-frequency* components
- Larger stores with larger rock sizes for *low-frequency components*

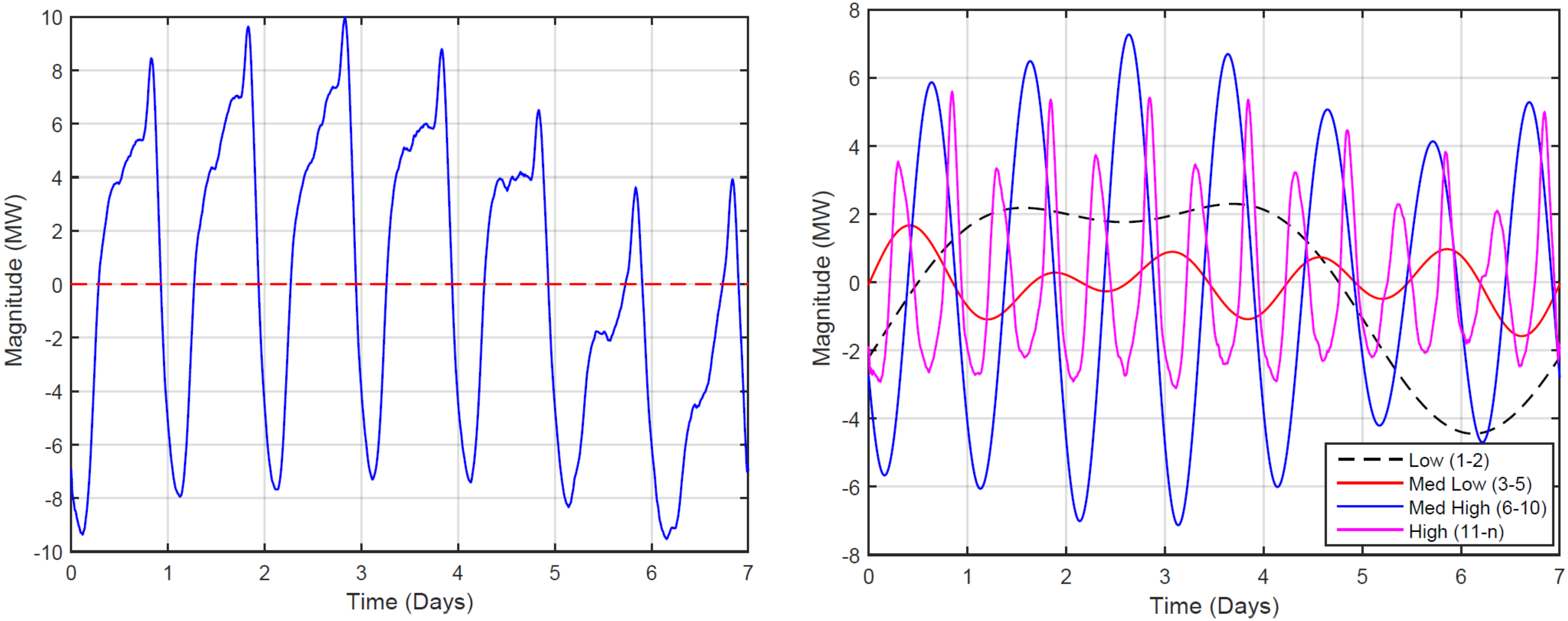
Sign-Preserving Filtering

Parallel packed bed stores.



Sign-Preserving Filtering

Straightforward Fourier decomposition performs badly because flows in different packed beds are often in opposite directions.



Sign-Preserving Filtering

The *sign-preserving filtering* requirement can be expressed thus:

Split some original signal, $a(t)$, into two parts …

$$a(t) = b(t) + c(t)$$

such that

$b(t)$ … contains mainly “low-frequency” (i.e. smooth) content

$c(t)$ … contains mainly “high-freq.” (i.e. not-so-smooth) content

AND $$sign(a(t)) = sign(b(t)) = sign(c(t)) \qquad \forall \ t$$

Sign-Preserving Filtering

We have developed an approach based on adding/subtracting multiples of various different *wavelets*.

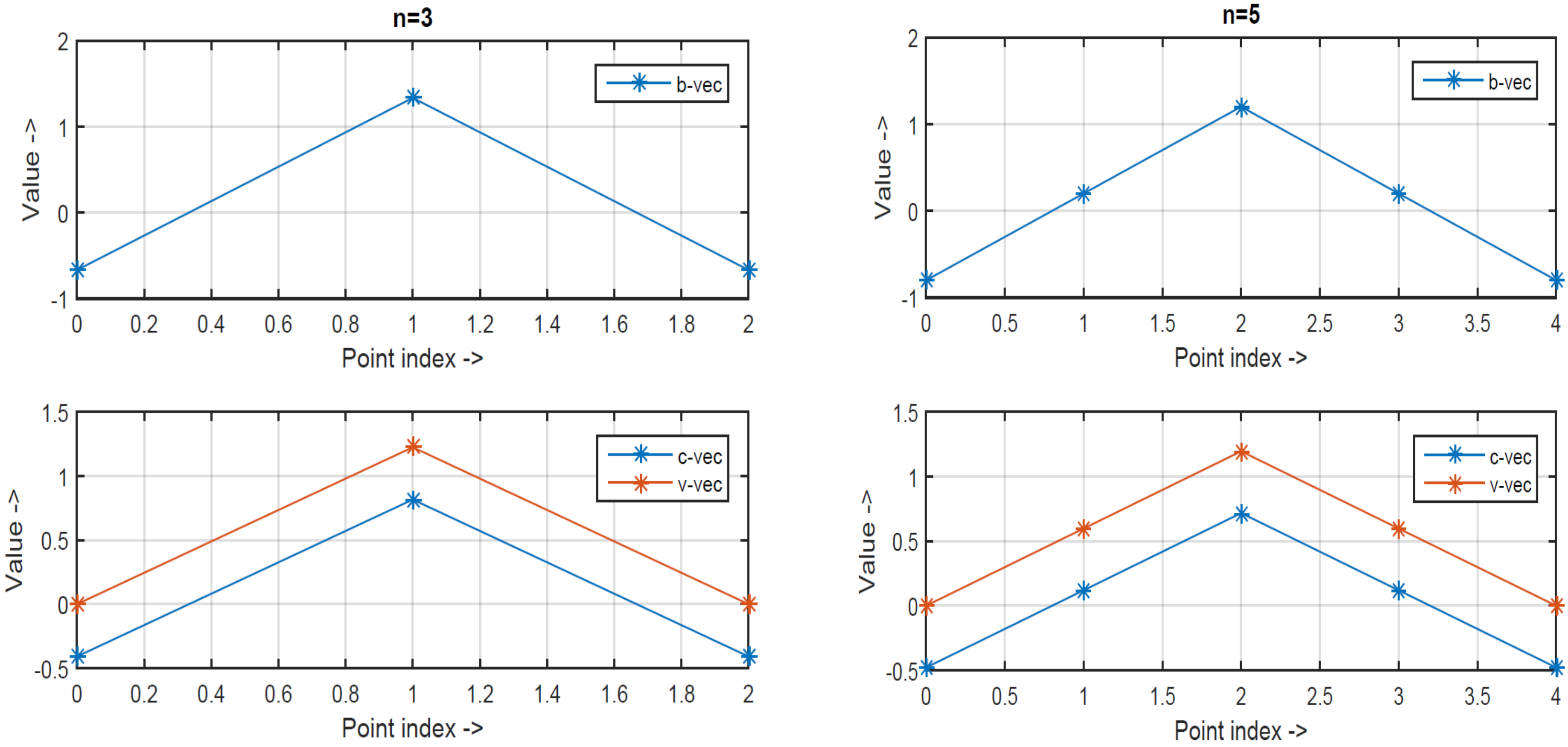
Initialisation: $b_0(t) = a(t)$ $c_0(t) = 0$

Iteration:

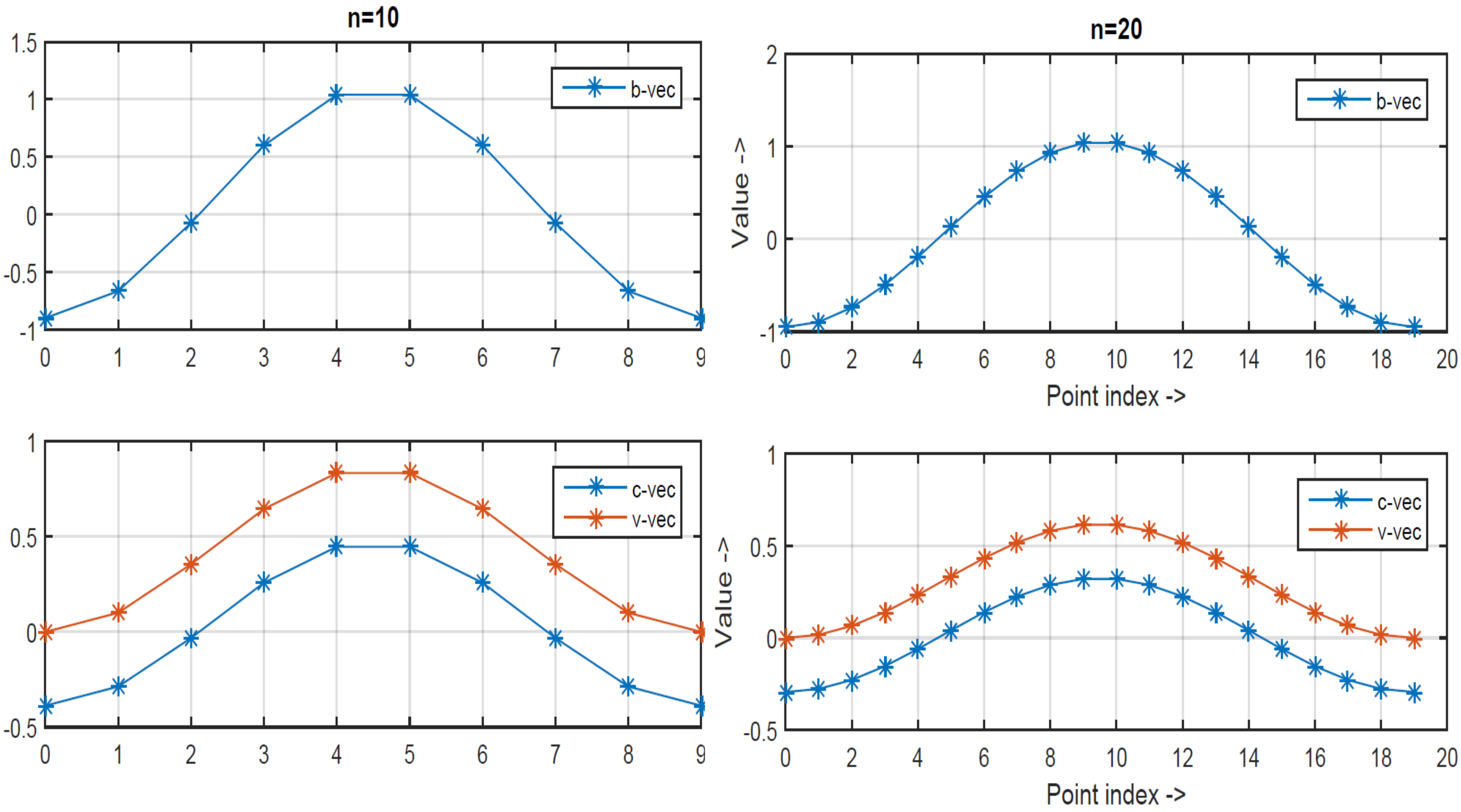
$$b_{k+1}(t) = b_k(t) - \alpha_k w(t)$$
$$c_{k+1}(t) = c_k(t) + \alpha_k w(t)$$

Sign-Preserving Filtering

Different *wavelets*.

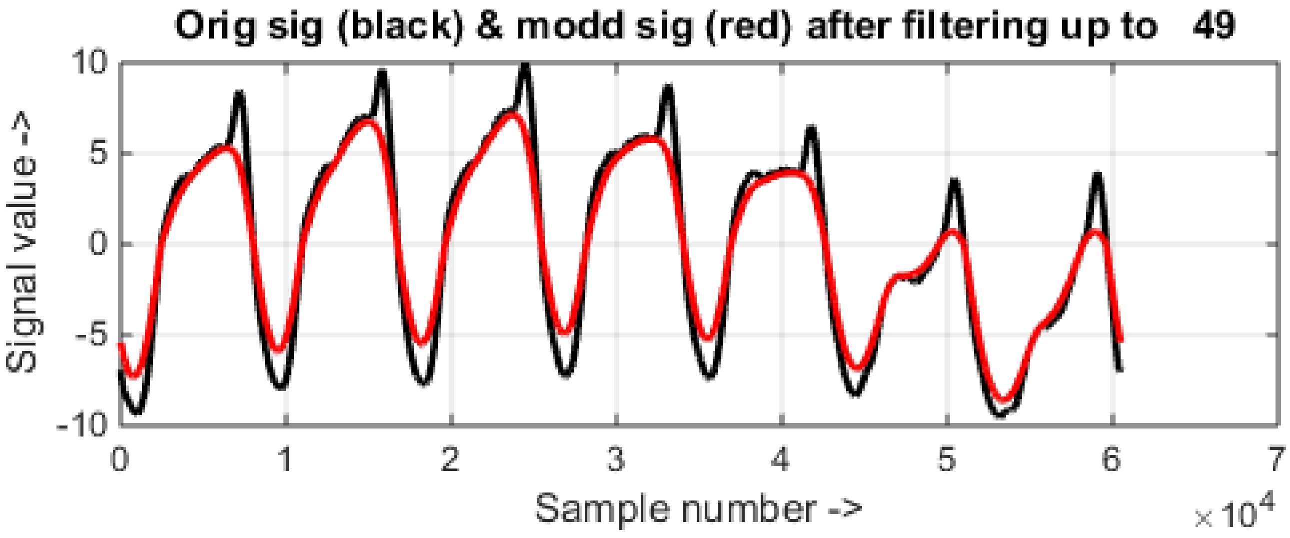


Sign-Preserving Filtering



Sign-Preserving Filtering

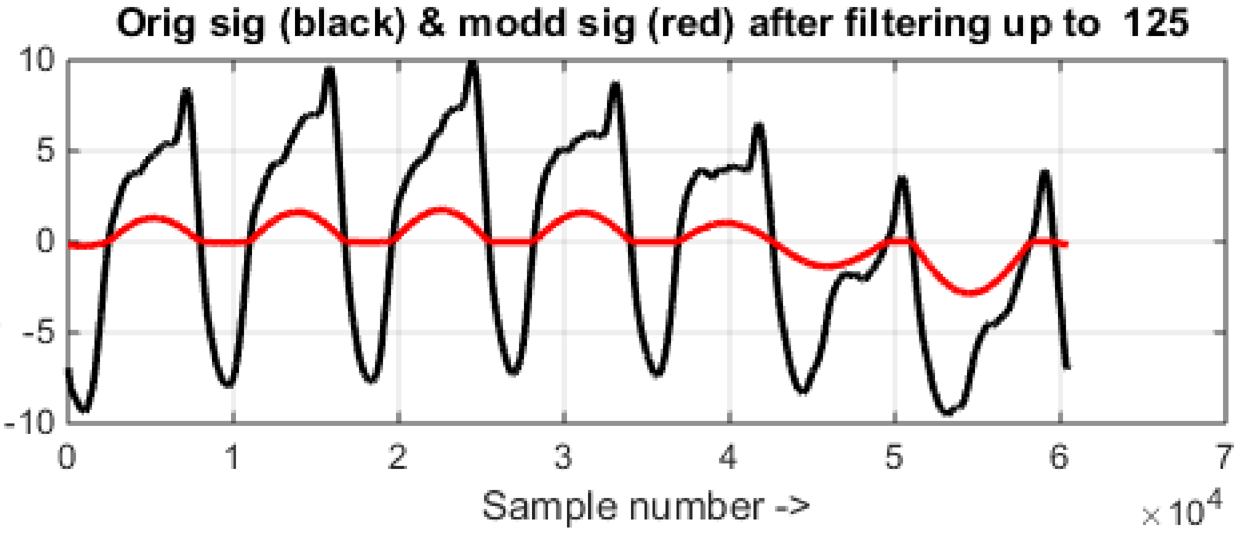
Two independent controls of the filter: (i) The maximum *width* of the wavelet and (ii) the number of *passes*



Here: maximum *width* of the wavelet = 49 points the number of *passes* is 3/15/30/100

Sign-Preserving Filtering

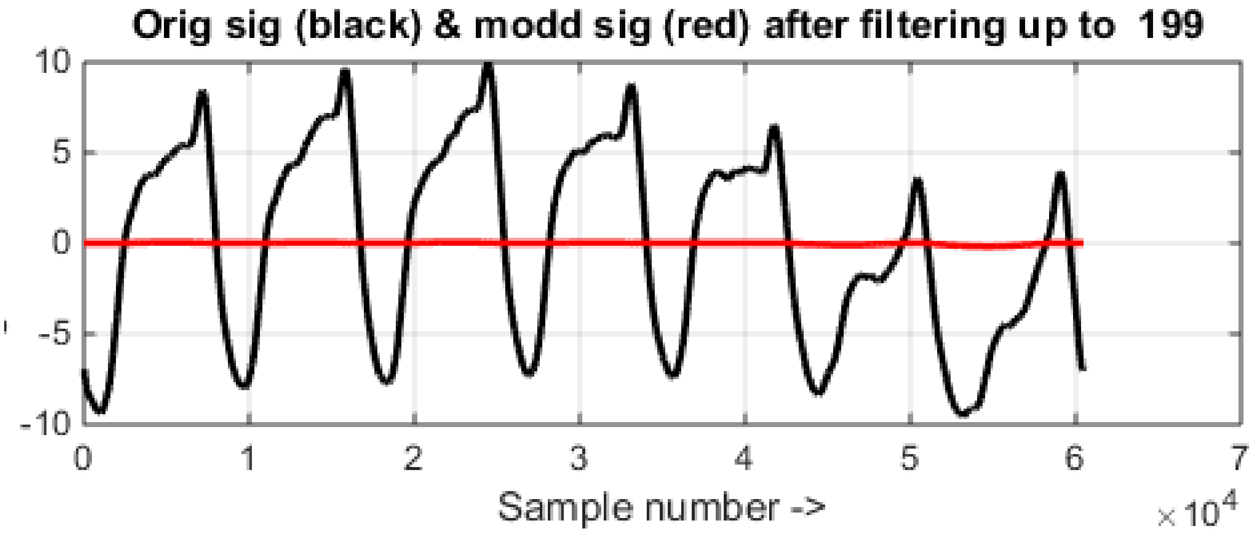
Two independent controls of the filter: (i) The maximum *width* of the wavelet and (ii) the number of *passes*



Here: maximum *width* of the wavelet = 49 points the number of *passes* is 3/15/30/100

Sign-Preserving Filtering

Two independent controls of the filter: (i) The maximum *width* of the wavelet and (ii) the number of *passes*

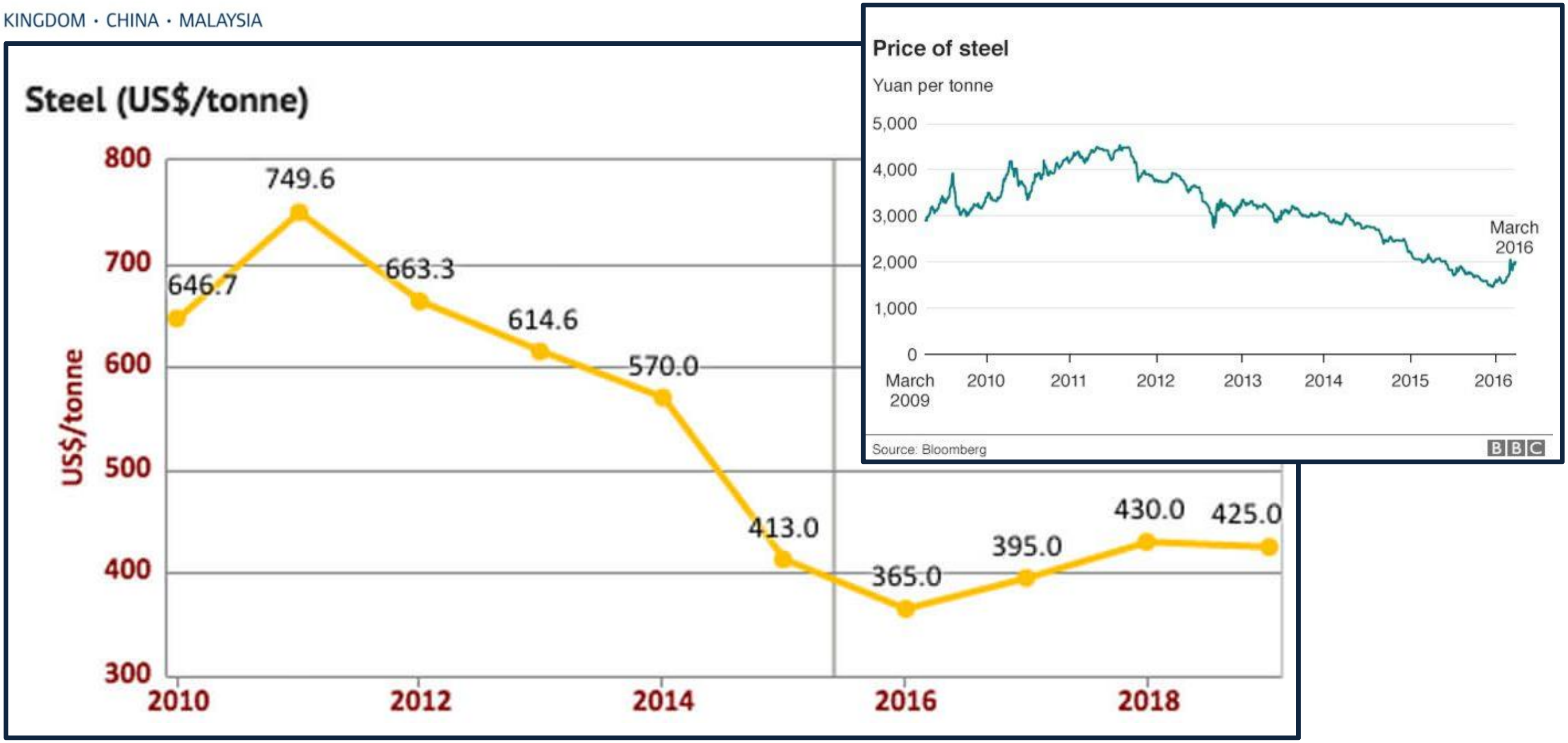


Here: maximum *width* of the wavelet = 49 points the number of *passes* is 3/15/30/100

All-Steel Thermal Stores

Proposition: One might use a steel structure as both heat exchanger and thermal store.

Storage costs – with steel



Source: Bloomberg

Falling Steel costs possibly prompt a re-examination of whether storage of high pressure air in steel could be cost-effective.

Steel pipe can be heat-exchanger <u>and</u> thermal store

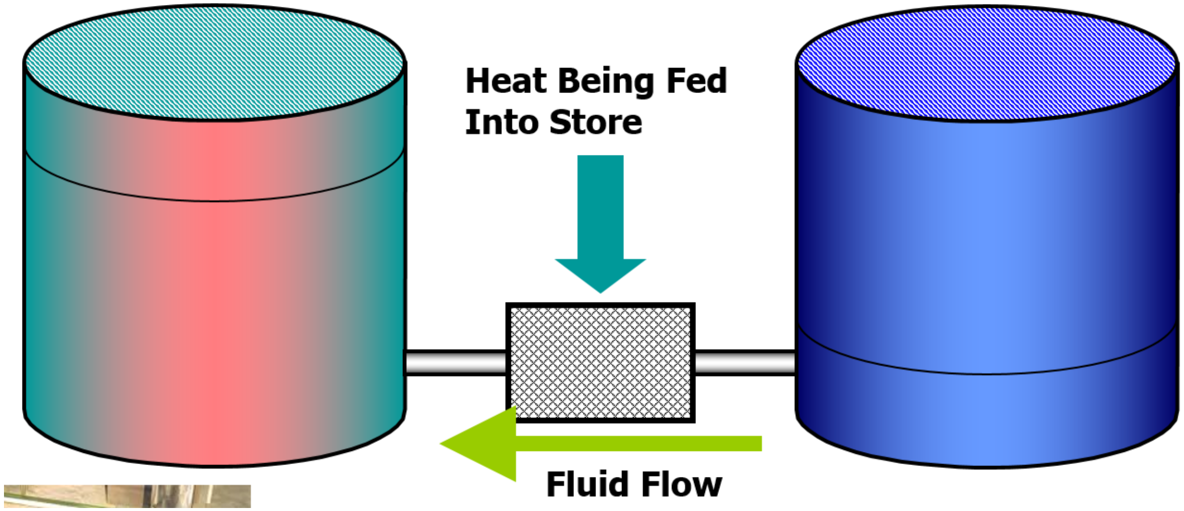
Storage costs – with steel

In all CAES systems, thermal management is essential.

In general, for every CAES system, some of the exergy is stored in the form of compressed air and some is stored in the form of heat.

Traditionally, we think of molten salts as an excellent choice of thermal storage medium. Costs <$20/kWh of exergy.

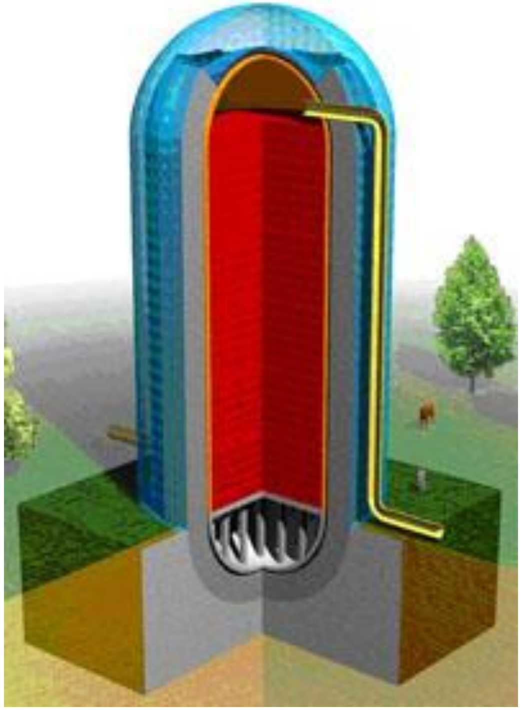
A 2-Tank system with molten salt gives consistent heating / cooling of pressurised air.

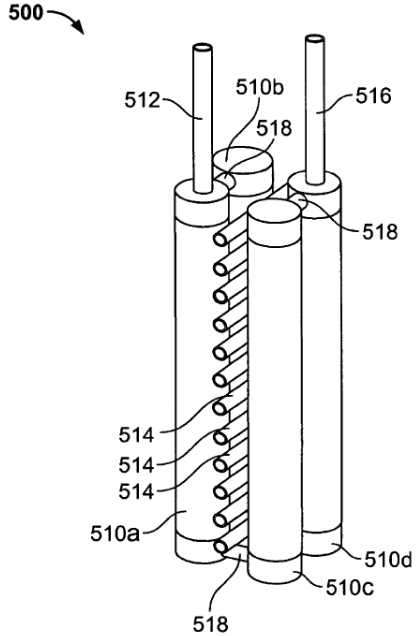


Storage costs – with steel

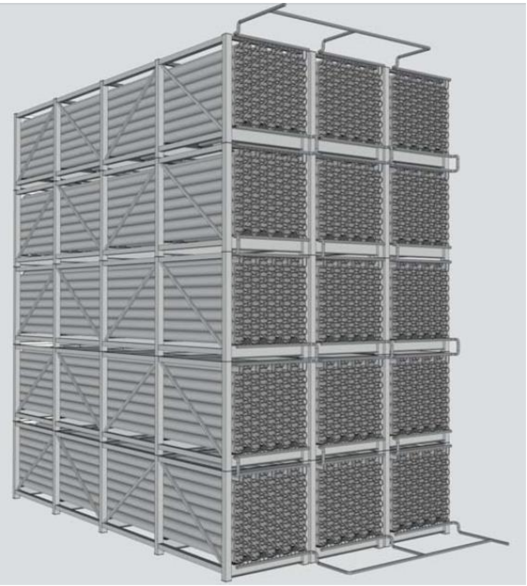
CONJECTURE:: It might be economically feasible solid steel pipes as the thermal store with no other material!

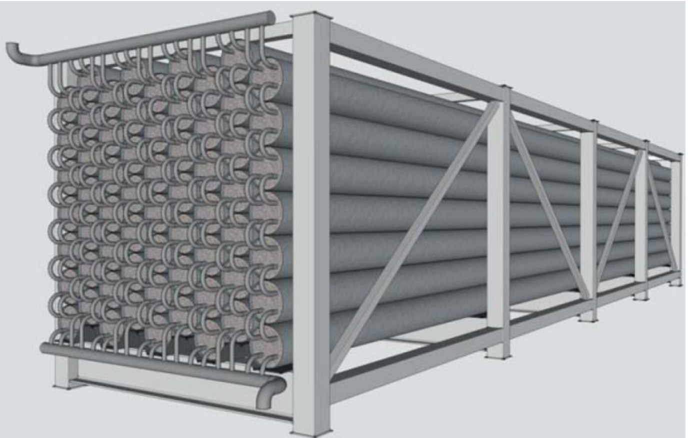
Solid thermal stores are already being considered with steel pipes but also some other medium.





US2006/0107664





Storage costs – with steel

A basic sanity-check is required.

Assume:

- Steel has constant Cp of 500 J/kgK
- Steel costs ~$600/ton (stainless steel ~$2000/ton)
- We can operate between 50°C and 600°C

Cost per kWh of heat = $600 / $((1000 \times 500 \times 550)/3.6\times10^6)$

= $7.9/kWh (heat)

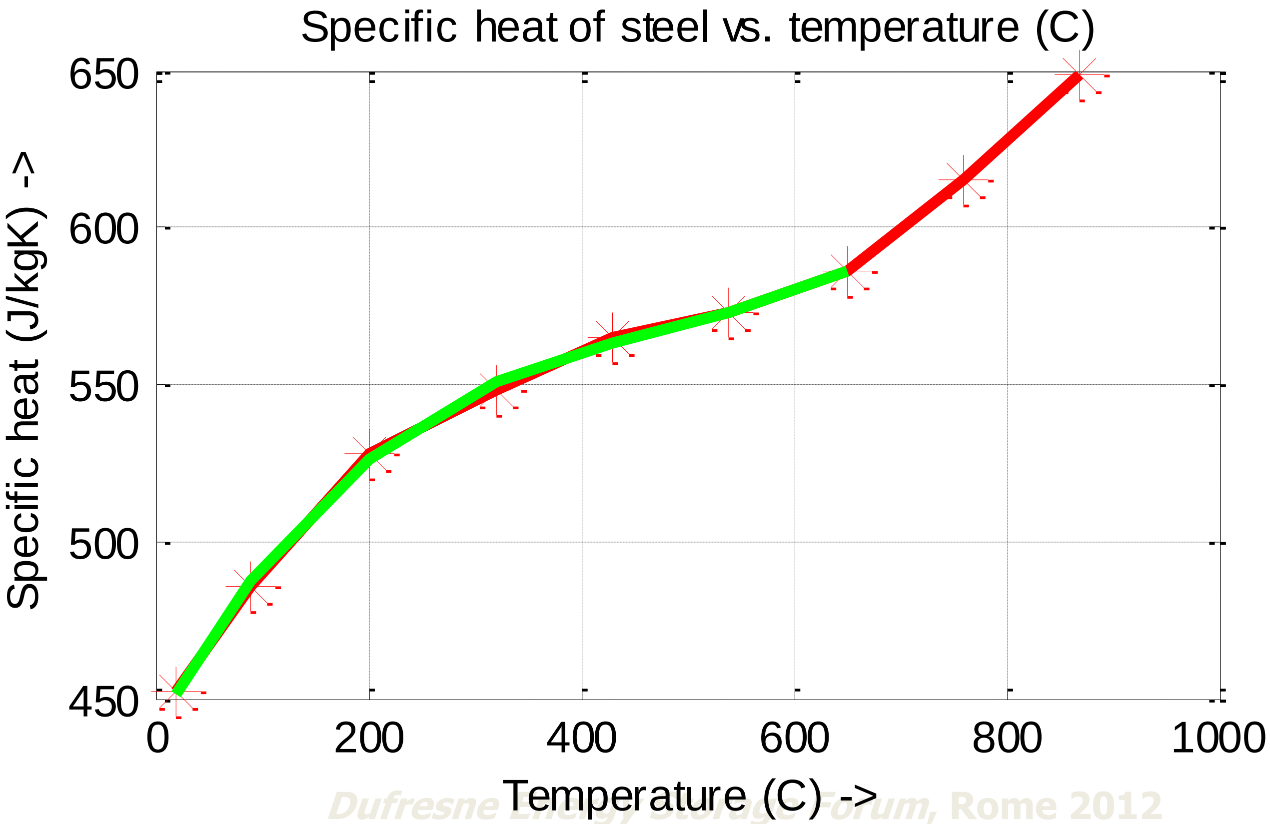
Cost per kWh of thermal exergy ~ = $15/kWh (exergy)

Storage costs – with steel

A more detailed calculation is justified!

Determine c_p for a suitable steel (stainless) as a continuous function of temperature.

$$c_{p,steel} = 439.8 + 618.4\times10^{-3}\times T(C) - 1089\times10^{-6}\times T(C)^2 + 744\times10^{-9}\times T(C)^3$$

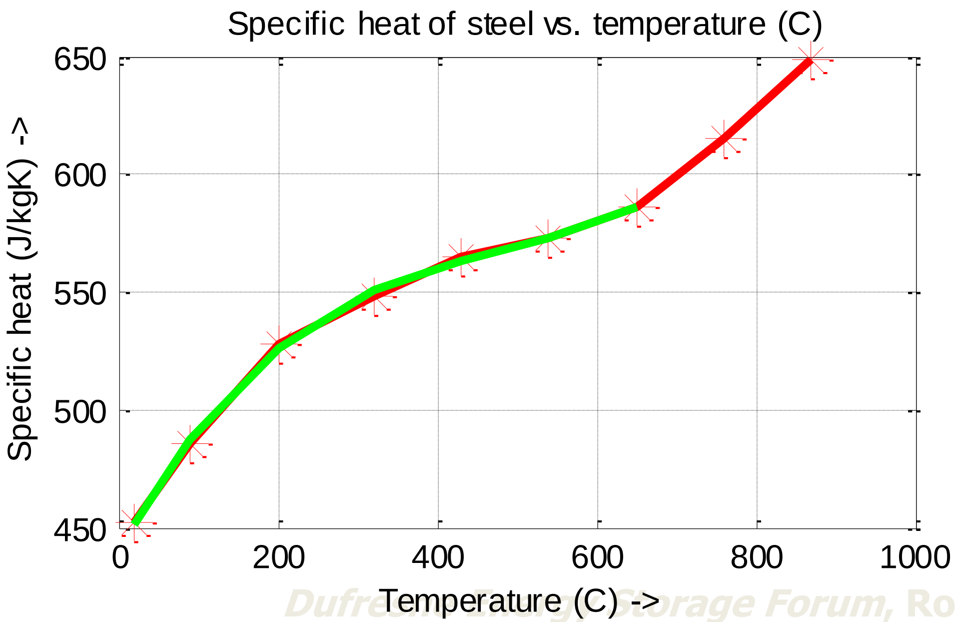


Storage costs – with steel

Then numerically integrate for *Q* and *B*

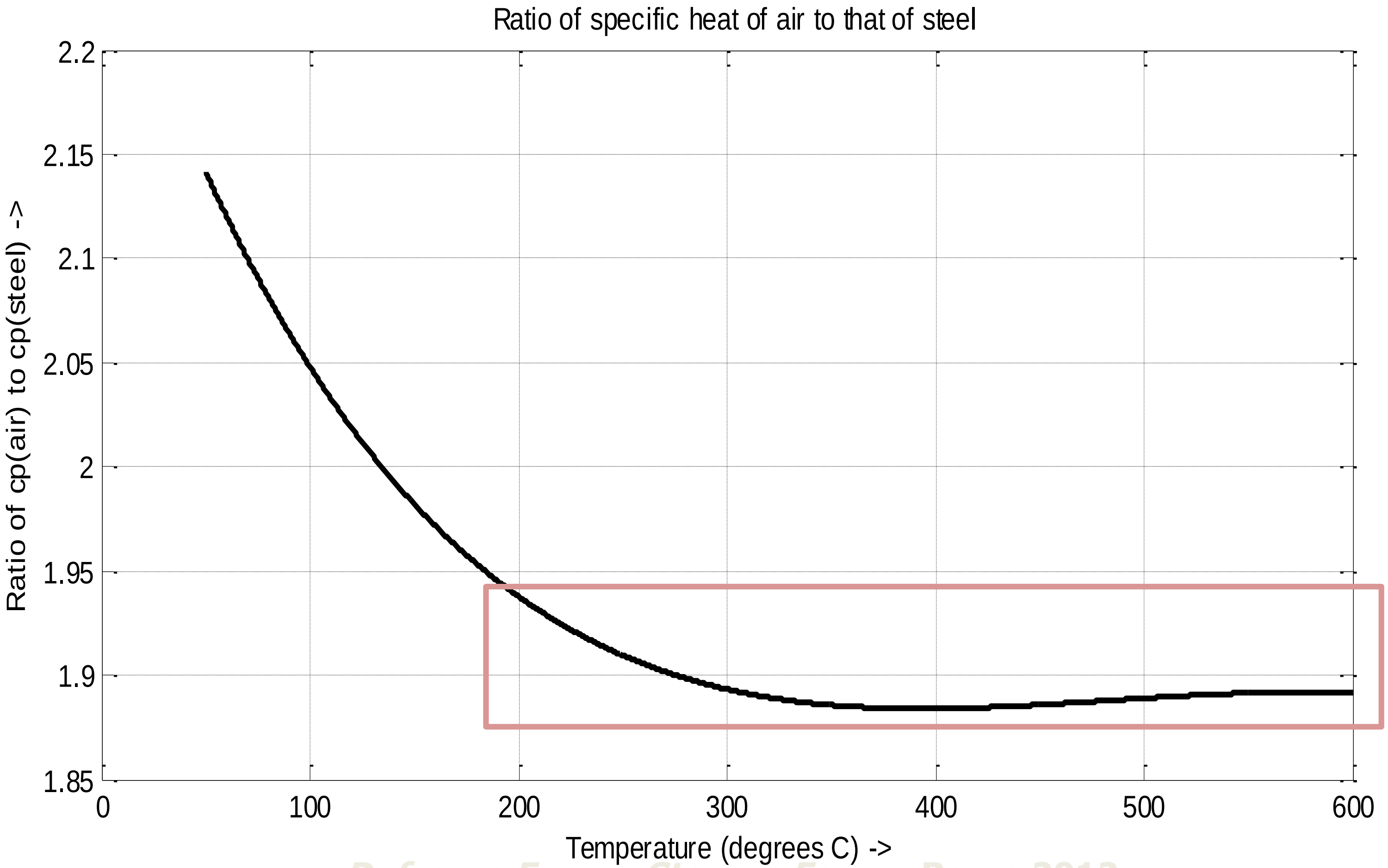
$$Q_{p.u.m.} = \int_{323}^{873} c_{p,steel}(T).dT = 507kJ/kg$$

$$B_{p.u.m.} = \int_{323}^{873} c_{p,steel}(T) \times \left(1 - \frac{T_{ref}}{T}\right).dT = 267\,kJ/kg$$



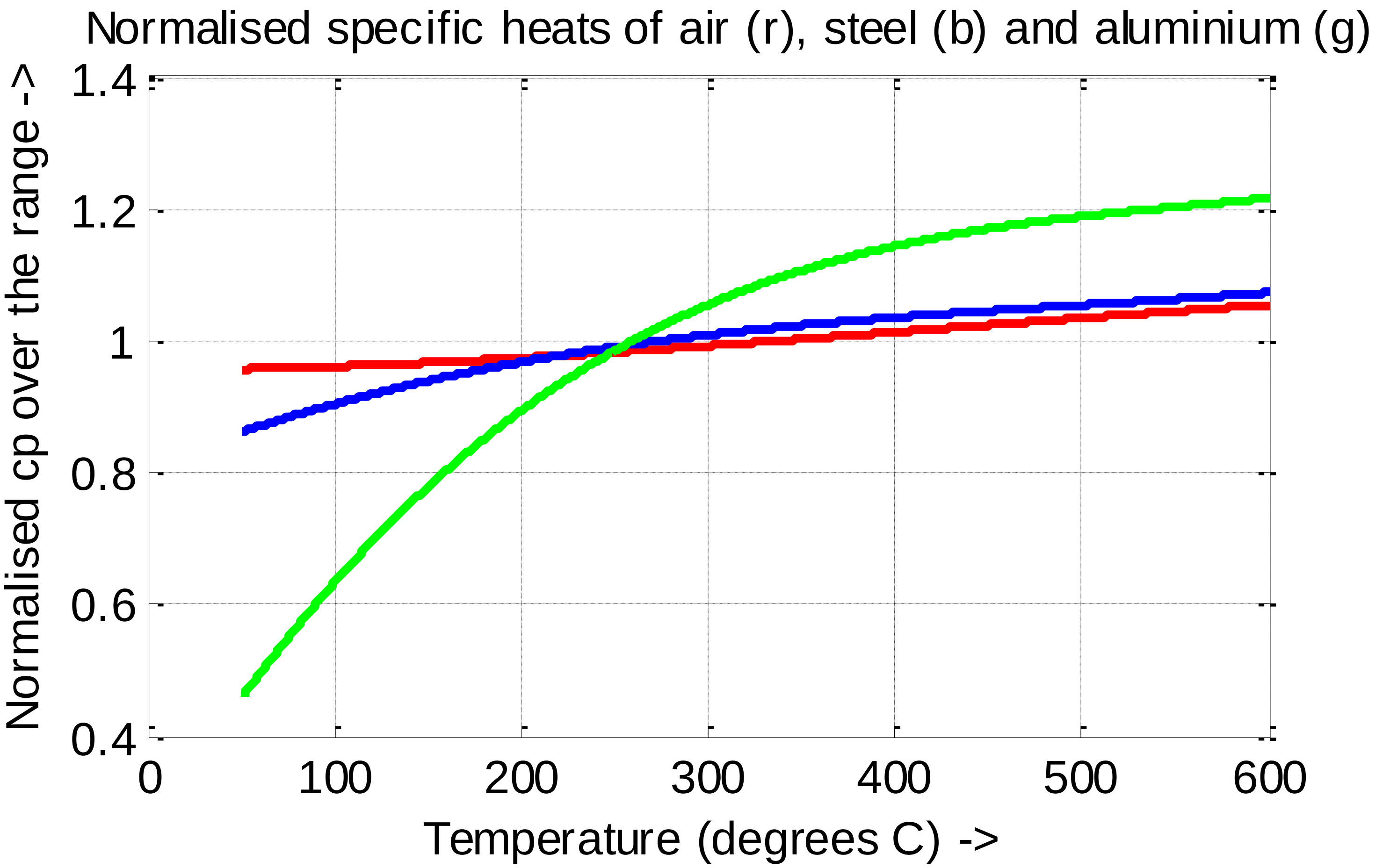
Storage costs – with steel

Steel c_P is not a perfect match to air – but not terrible.
It is especially good in the range 200°C to 600°C



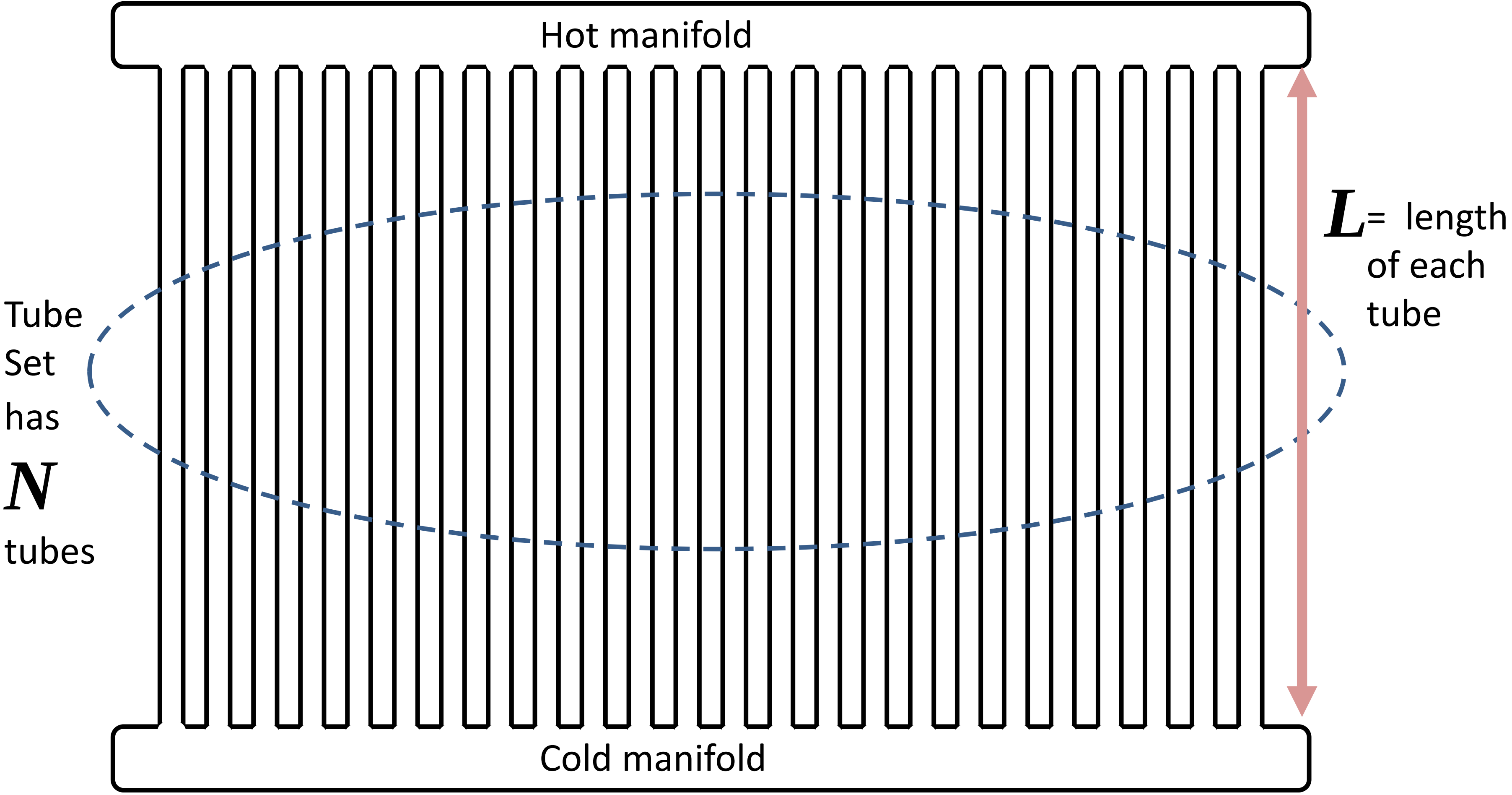
Storage costs – with steel

It is useful to contrast the match of specific heats by using another material – Aluminium here.



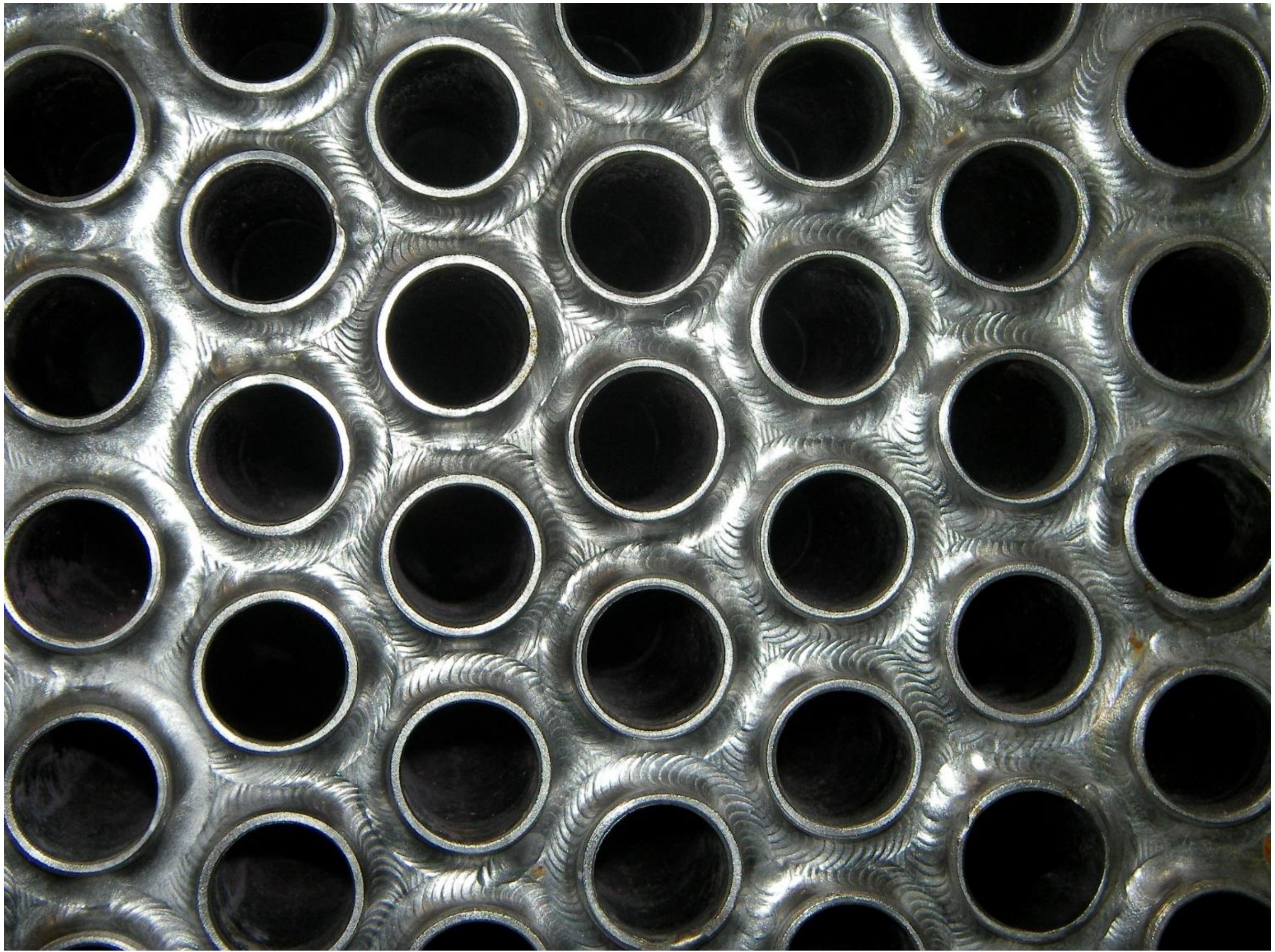
All-Steel Thermal Stores

The thermal store will comprise N identical pipes in parallel.



All-Steel Thermal Stores

Orbital welding already very standard practice!

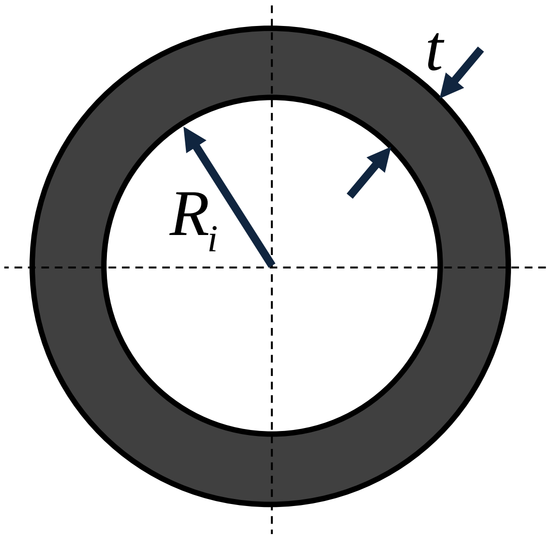


All-Steel Thermal Stores

We look at $N \in \{10, 20, 50, 100, 200, 500, \ldots\}$

For each value of N, we can choose a total tube length, L.

Choosing L determines the tube maximum bore since



$$R_i \times p_{\max} = t \times \sigma_{\max}$$

For stainless steel at 600°C …

$$\sigma_{\max} \cong 50MPa \quad (?)$$

All-Steel Thermal Stores

For a given N, larger L causes higher pressure drops but achieves better heat transfer.

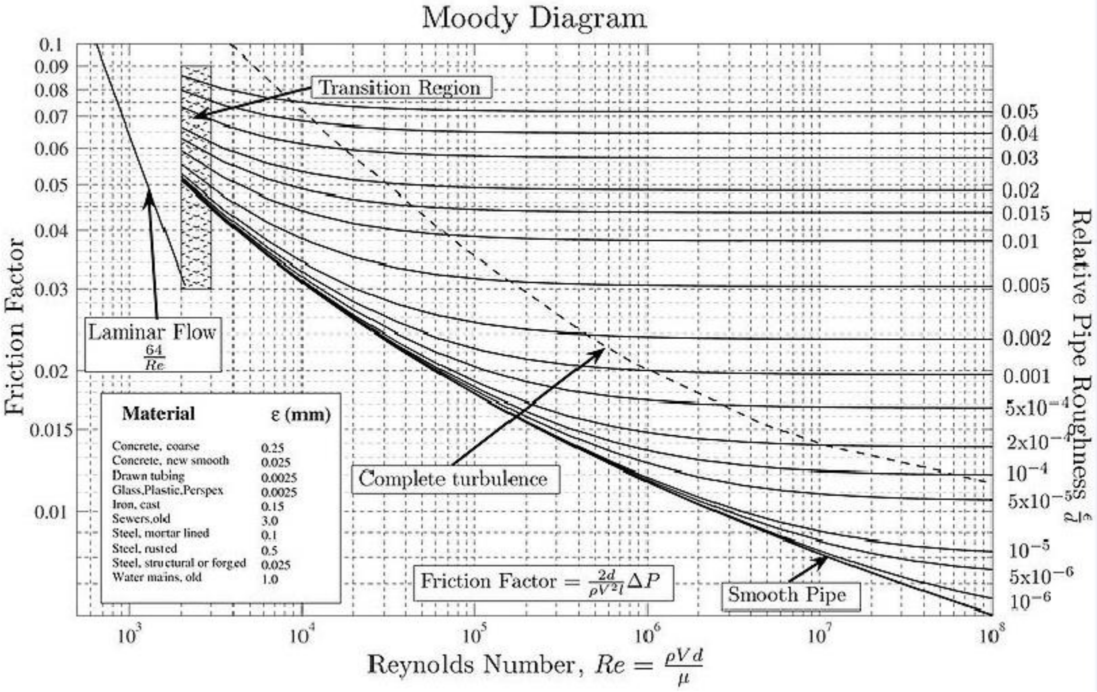
For a good initial choice of L, find pressure drop when the tube is fully hot and when it is fully cool. Get the average of these two pressure drops to be ~1% of max pressure.

$$\Delta p = f \times \left(\frac{L}{D_I}\right) \times \left(\frac{\rho v_m^{\ 2}}{2}\right)$$

$$\left(\frac{1}{\sqrt{f}}\right) = -2\log_{10}\left(\frac{(\varepsilon/D_I)}{3.7} + \frac{2.51}{Re_D\sqrt{f}}\right)$$

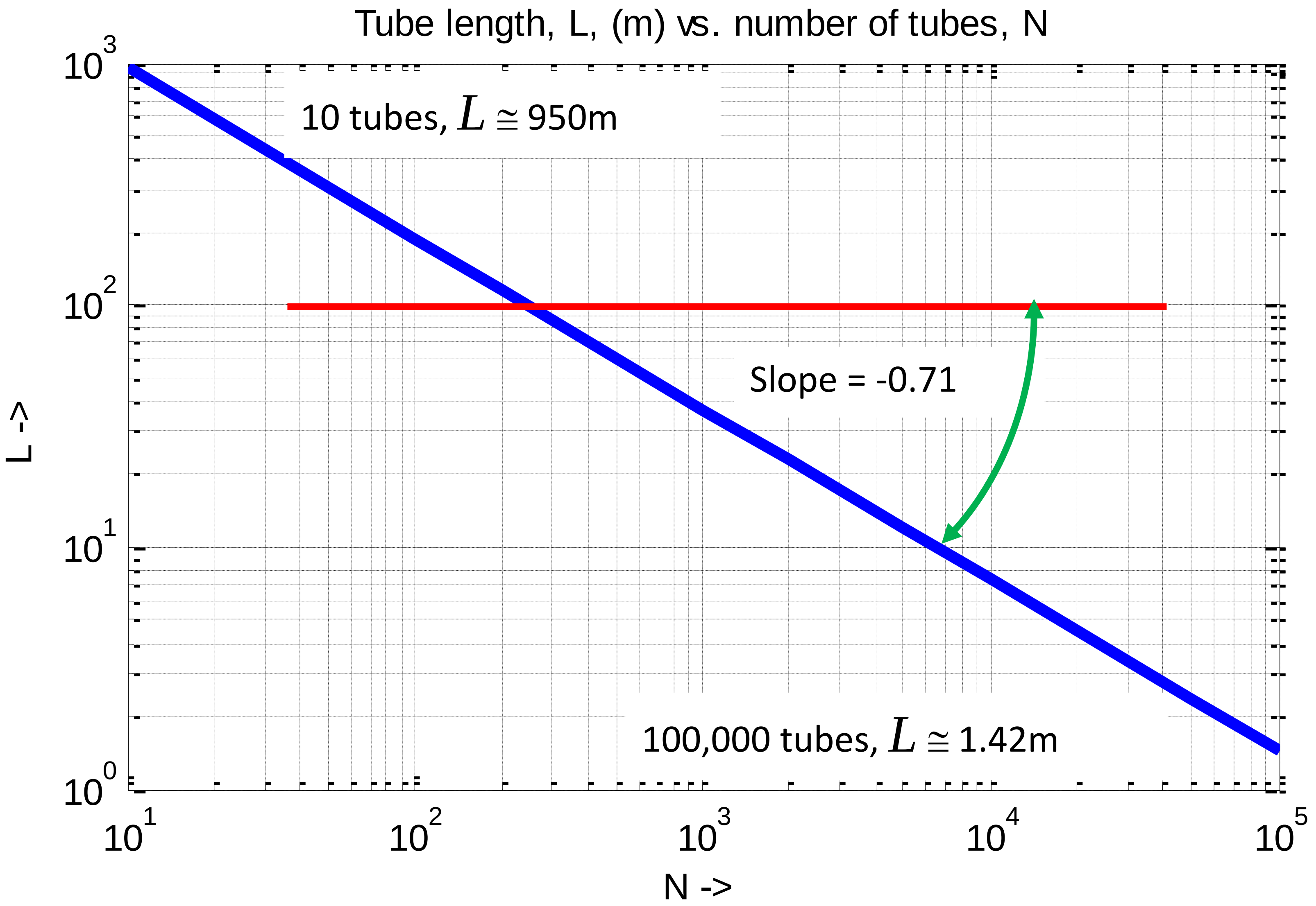
(Colebrook equation for *f*).

Moody Diagram

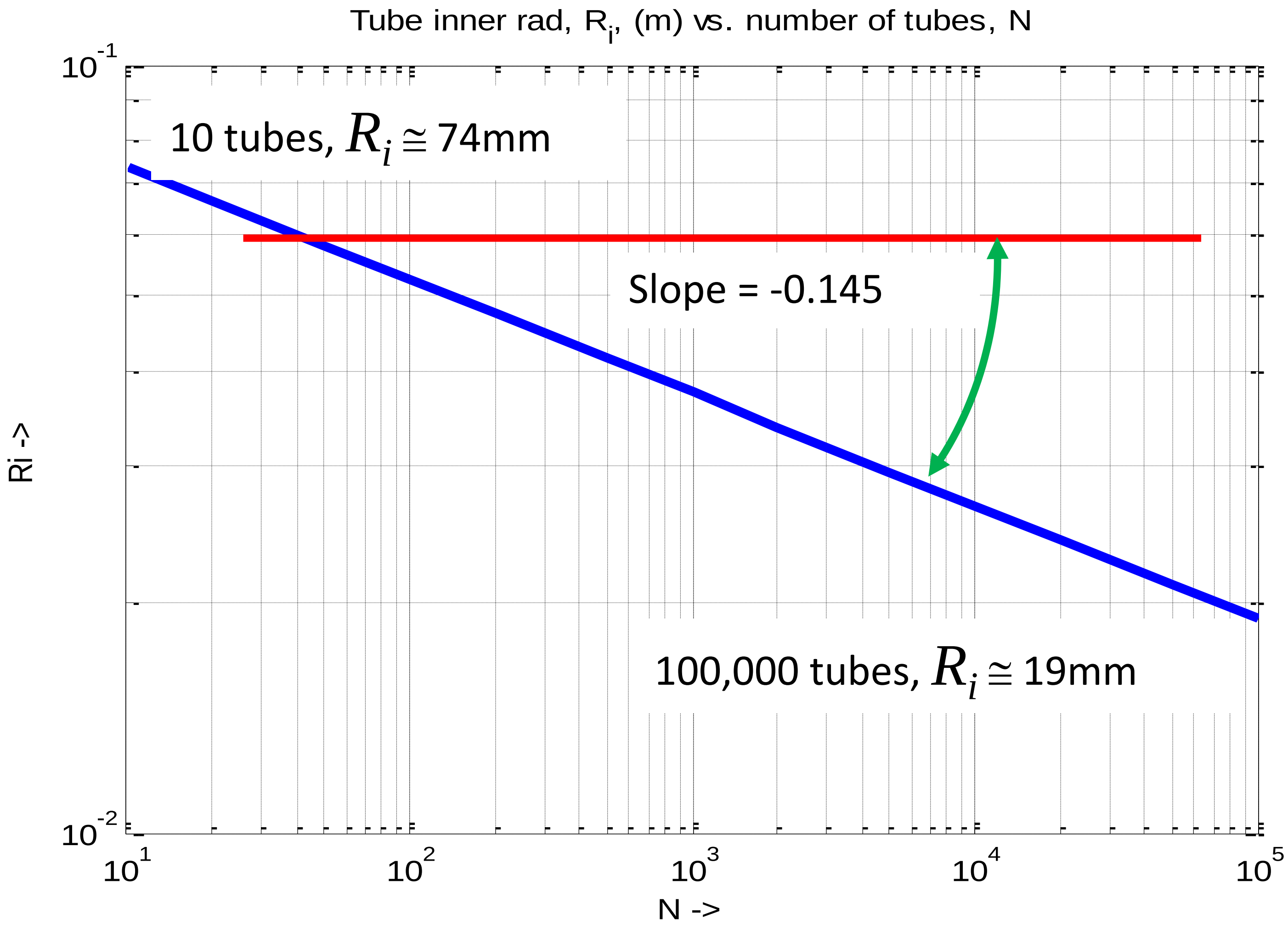


Material	ε (mm)
Concrete, coarse	0.25
Concrete, new smooth	0.025
Drawn tubing	0.0025
Glass,Plastic,Perspex	0.0025
Iron, cast	0.15
Sewers,old	3.0
Steel, mortar lined	0.1
Steel, rusted	0.5
Steel, structural or forged	0.025
Water mains, old	1.0

All-Steel Thermal Stores



All-Steel Thermal Stores



10 tubes, $R_i \cong 74\text{mm}$

Slope = -0.145

100,000 tubes, $R_i \cong 19\text{mm}$

All-Steel Thermal Stores

Heat transfer for the inner surface of the steel tubes determined from standard methods (*Colburn Correlation**).

$$Nu_D = 0.023 \times Re_D{}^{0.8} \times Pr^{0.33}$$

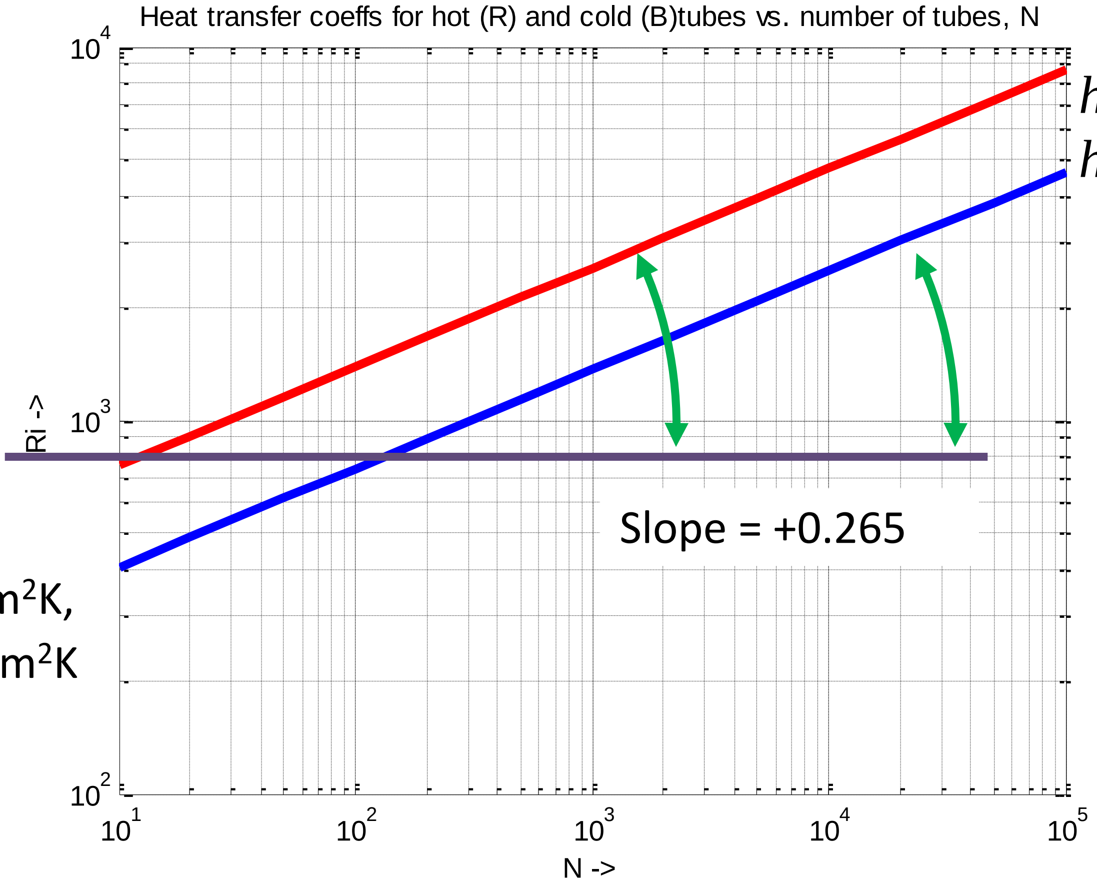
$$Pr = \frac{\mu_{air}(T) \times c_p(T)}{k_{air}(T)}$$

$$h = \frac{Nu_D \times k_{air}(T)}{D_I}$$

* Lienhard JH & Lienhard JH. *A Heat Transfer Textbook. 3rd Edition*. Phlogiston Press, Cambridge MA. 2004

All-Steel Thermal Stores

Heat transfer coefficients were calculated for each design characterized by a different N and a mean Δp = 1% of p_1



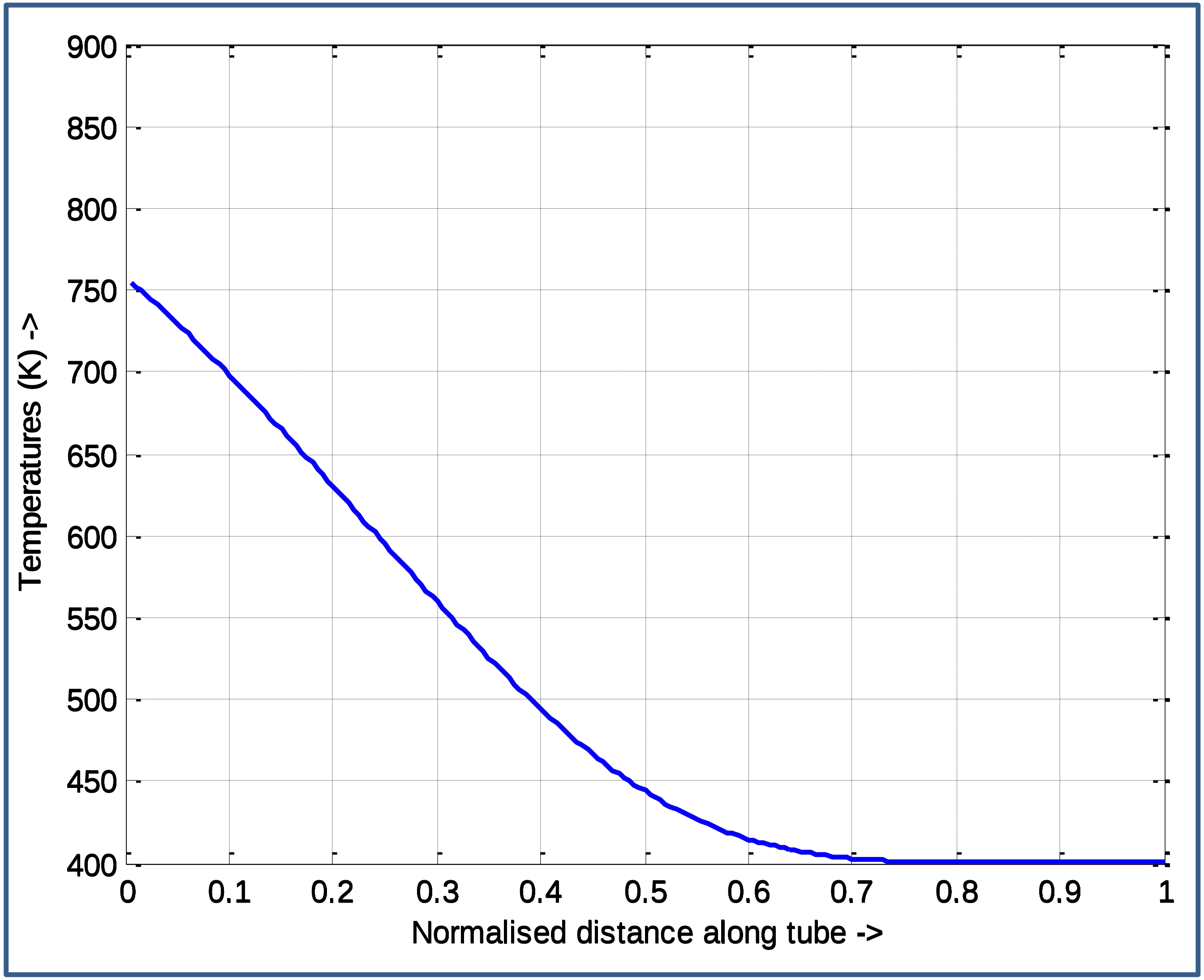
Slope = +0.265

With N=100,000,
h_{hot} = 8667 W/m^{2}K,
h_{cold} = 4618 W/m^{2}K

With N=10
h_{hot} = 722 W/m^{2}K,
h_{cold} = 403 W/m^{2}K

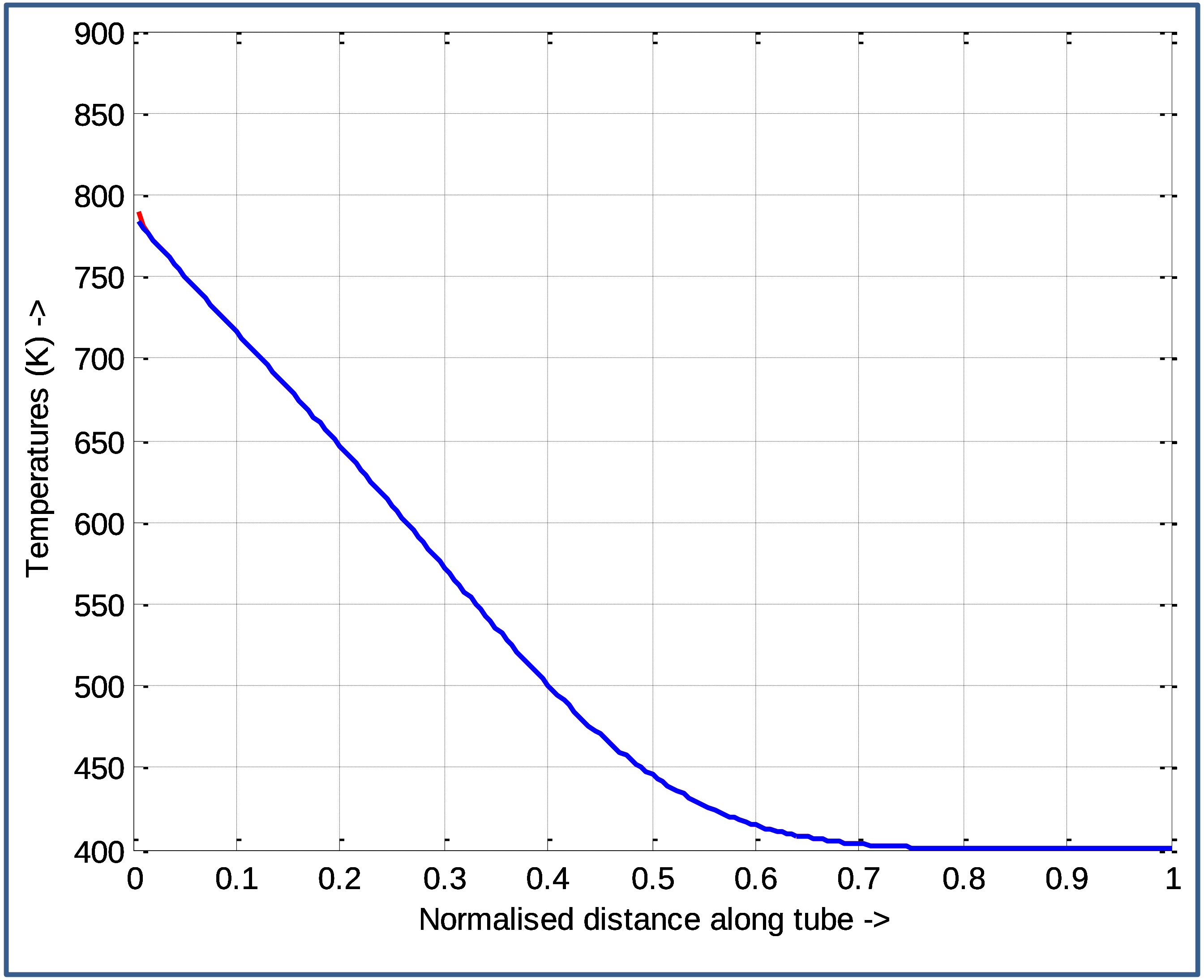
All-Steel Thermal Stores

$(N = 10)$



All-Steel Thermal Stores

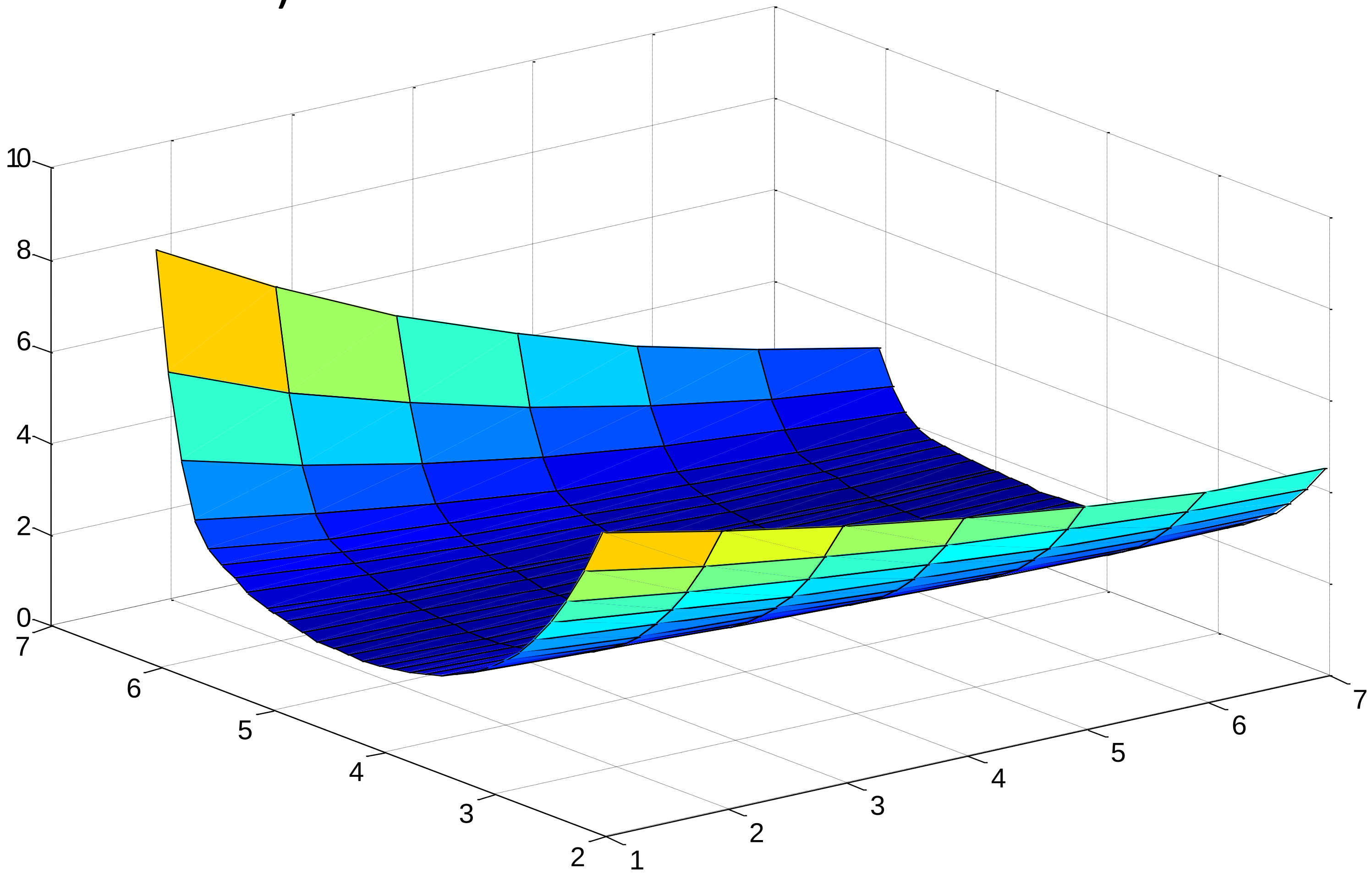
$(N = 10{,}000)$



The University of Nottingham
UNITED KINGDOM · CHINA · MALAYSIA

All-Steel Thermal Stores

Illustration of total exergy loss (%) vs log(N) and *length index* (for a 250bar case)



All-Steel Thermal Stores

Interesting outcome: large sets of steel tubes used as thermal stores for CAES plant contain significant volumes of HP air!!

One significant consequence is that “mass flow rate” is not a constant throughout the thermal store … iterations required in each individual step.

A second significant consequence is the “negative volume effect”. A fully-charged thermal store has (average) low-density air in it at storage pressure, p_S. A fully-discharged store has (average) high-density air in it at storage pressure, p_S. The thermal store “sucks in” mass of air as the air store discharges …. Bad!

Publications:

Presentation to STFC on March 30th (Generation-Integrated ES)

Presentation to 7th China International Energy Storage Conference April 24-26.

4 Papers at OSES2017
Davenne et al: Instabilities in packed bed thermal stores
Cardenas et al: optimisation of packed bed thermal stores
(particle size, aspect ratio and ~)
Rouse et al: Serial Hybrid Kinetic Energy Storage Systems
Garvey et al: All steel thermal stores.

Hybrid Energy Storage Workshop

Some ideas of people to invite:

Andrew Smallbone (Newcastle Uni) National Facility for Pumped Heat Energy Storage and Centre for energy systems integration (Total of £22M of EPSRC funding)

Lee Wai Chong (UoN Malaysia) Wrote a paper on Hybrid Energy Storage Systems and control strategies for stand-alone renewable energy power stystems

Alex White (Cambridge) presenting at OSES17 on the topic of PTES + LAES

Simone Zavatonni (University of Applied Sciences Switzerland) published work for ALACAES (Airlight Energy) who demonstrated a pilot ACAES plant in 2016 in Biasca Switzerland

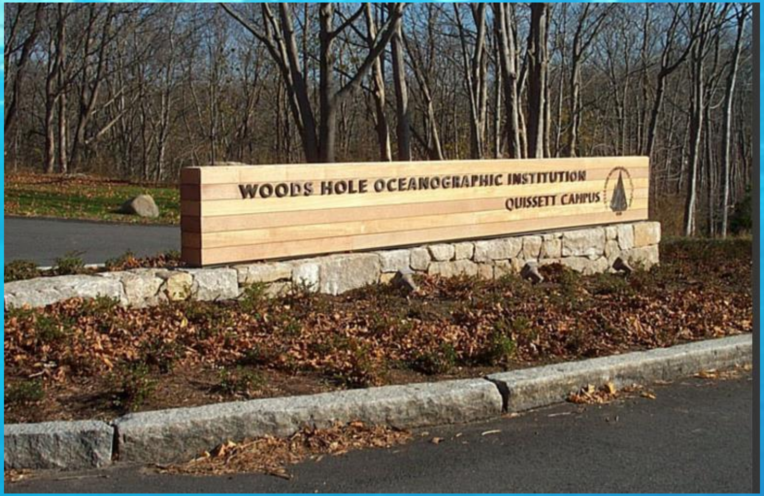
EERA had a workshop on Hybrid Energy and Energy Storage Systems in March 17. Interesting participants include

- Marcos Lafoz CIEMAT (WECs with ES)
- Atle Harby SINTEF(wind & pumped ydro & desalination & diesel)
- Juan Ignacio Perez Diaz UPM (flywheels and wind)
- Anna Stoppato University of Padova (PTES)

The University of Nottingham
UNITED KINGDOM · CHINA · MALAYSIA

This year's OSES conference

OSES2014: Windsor, Canada, OSES2015: Edinburgh, UK
OSES2016: Malta, OSES2017: WHOI, Boston



The University of Nottingham
UNITED KINGDOM · CHINA · MALAYSIA

THE UNIVERSITY of EDINBURGH

UNIVERSITY OF MALTA
L-Università ta' Malta

University of Windsor

UNIVERSITY OF LEEDS

Thanks for listening.

Seamus.Garvey@nottingham.ac.uk