Institute of Refractories Engineers

Thermal Gradient Modelling

Training Day 2016

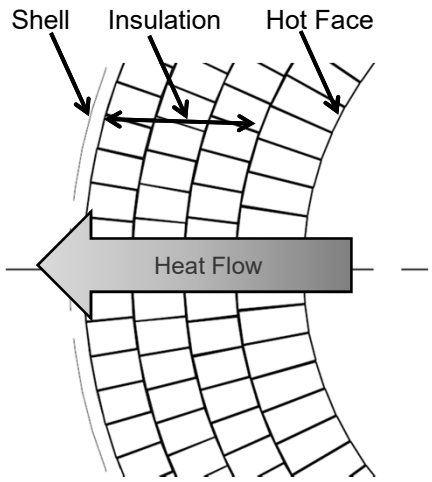
Sheffield
13 October 2016

Steady State

Means

- Constant hot face temperature
- Constant ambient conditions (temperature, wind etc)
- Energy flowing into hot face of lining is same as energy lost from hot face
- Temperature gradient is not changing with time
- Temperature at any point in lining is highest possible for a given hot face temp
- Takes hours or days to be reached depending on lining
- Simple to model and useful for design

Typical Lining



Heat energy flows from inside to hot face

Heat Flows through lining

Heat energy passes through lining and shell

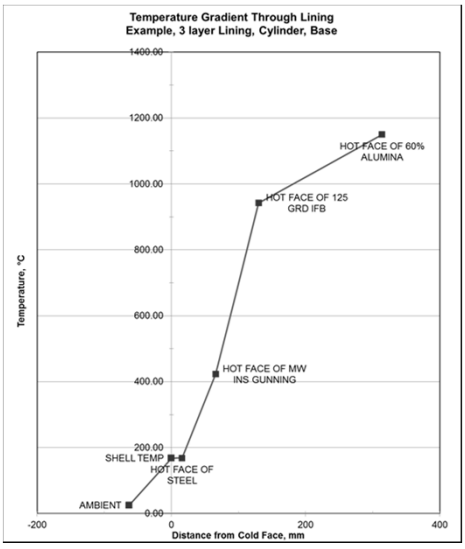
Temperature gradient through lining

Area of successive layers is different

Temperature Gradient

Automated models
- Quick Calculation
- Simple to use

- Reliability of result
  - Data used
  - Is steady state reliable?



How models work – 1 - Hot Face

Hot face temperature

- Assume steady process temperature
  - Melt temperature
  - Gas temperature
  - Flame temperature
  - Average from temp measurements

- Either
  - Assume hot face of refractory is at process temp
- Or
  - Apply a heat transfer coefficient between hot face and process

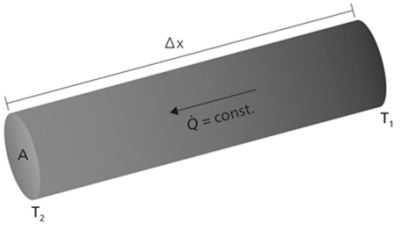
How models work –2- Flow through Lining

Thermal Conductivity

$$W = k A \Delta T/\Delta x$$

where

- W = Heat flow
- k = Thermal conductivity
- A = Area
- $\Delta T/\Delta x$ = Temperature Gradient

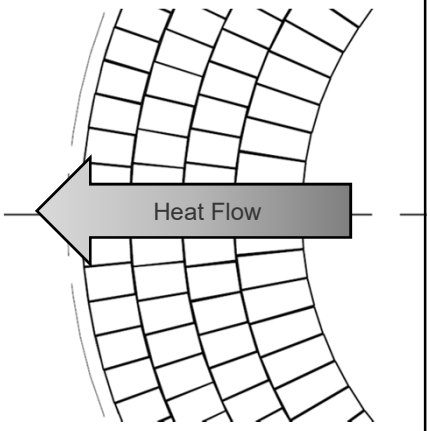


How models work –2- Flow through Lining

Most linings made up of several layers, each layer has

- different thickness $-\Delta x$
- different temp difference ΔT
- different conductivity, k
- different area, A

- In steady state, W for each layer is the same



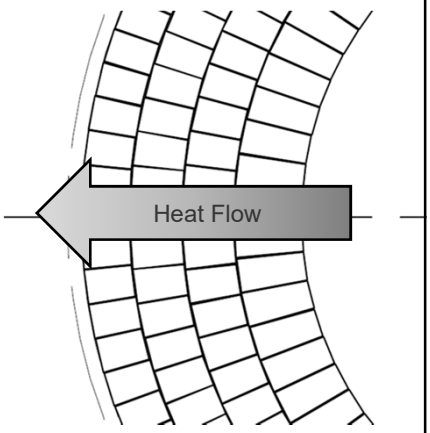
How models work –2- Flow through Lining

$W_1 = W_2 = W_{3.....}$

So

$k_1 A_1 \Delta T_1/\Delta x_1 = k_2 A_2 \Delta T_2/\Delta x_2$

Some re-arranging allows a solution to the equations to be found if k is known

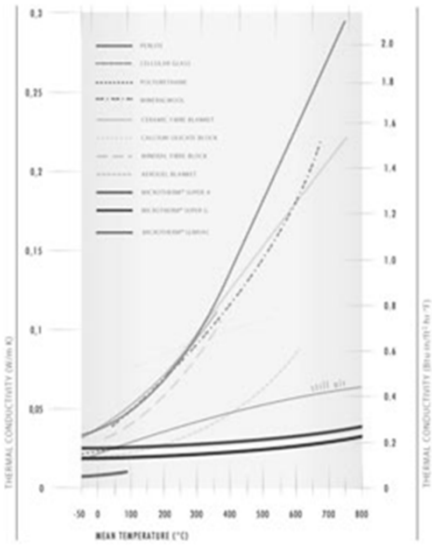


How models work –2- Flow through Lining

Thermal Conductivity and temperature

Thermal conductivity of a material is NOT a constant

- Use value for conductivity at mean temperature of layer
- How do we know mean temperature of layer if we don't know conductivity?



How Models work - 3 - Cold face Heat flow

Heat lost from surface by

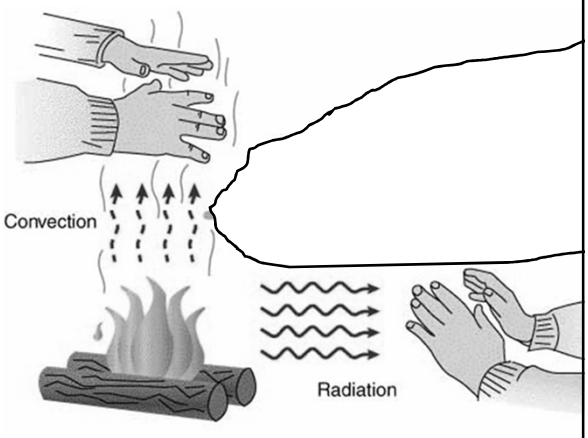
Radiation

Convection

Natural

Forced

(Conduction)



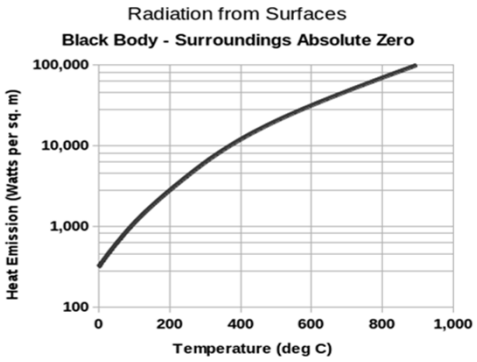
Radiation

Heat flow depends on
- Shell Temperature
- Ambient Temperature
- Emissivity, e

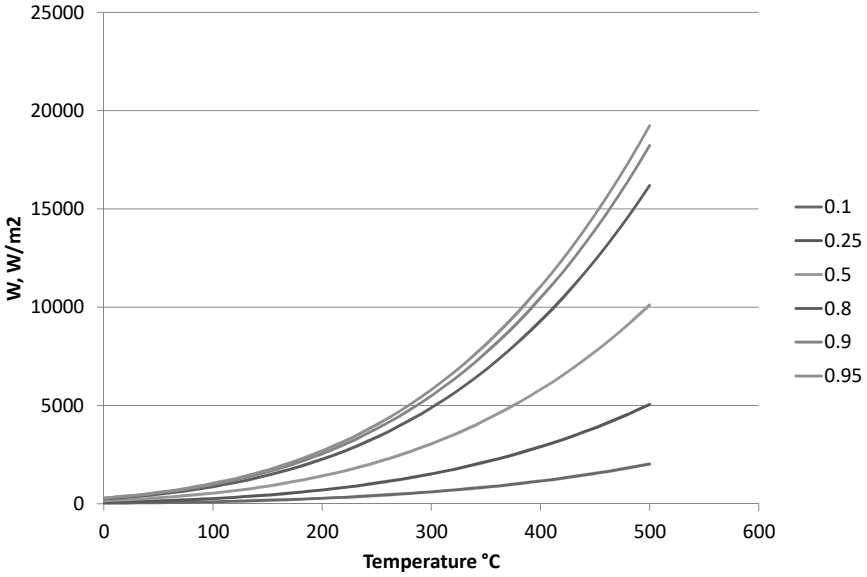
Steffan Boltzman Law

$$W = e \sigma A T^4$$

where σ is a constant



Radiation



Convection

More complicated
- Forced convection
  - Air blowers
  - Water cooling
- Natural Convection
  - Geometry
    - Plate
    - Cylinder
    - Sphere
  - Angle
    - Vertical
    - Underside
    - Topside

Just read a text book on heat transfer…….

Heat Transfer Coefficient

$W = h_c A \Delta T$

where

W = heat transferred per unit time (W)

A = heat transfer area of the surface (m^2)

h_c= convective heat transfer ($W/(m^2K)$)

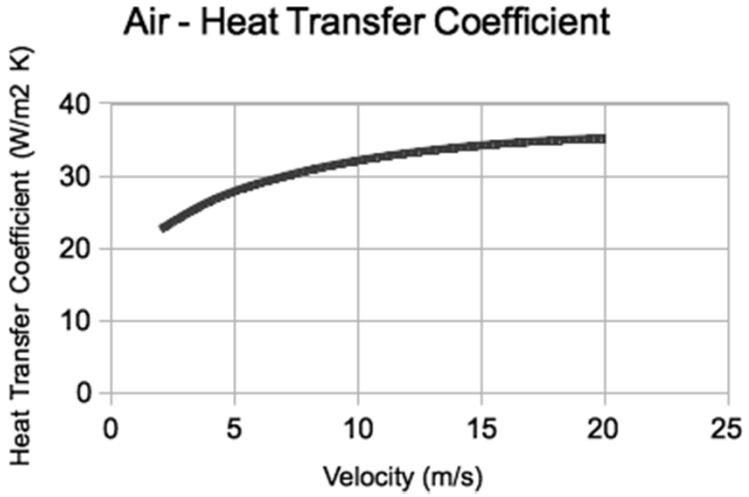
ΔT = *temperature difference between the surface and the bulk fluid*

For still air over a horizontal cylinder…

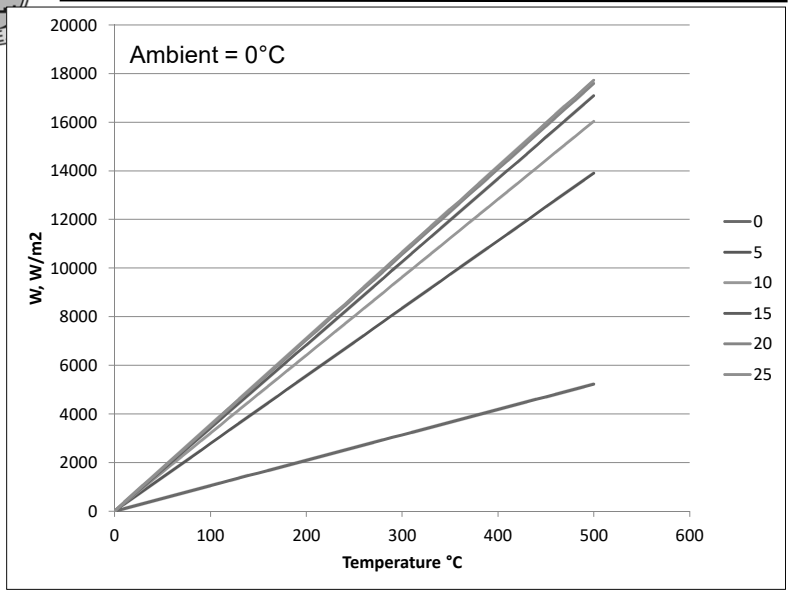
$h_c = 10.45 - v + 10\ v^{1/2}$

where v is air (wind) speed in m/s

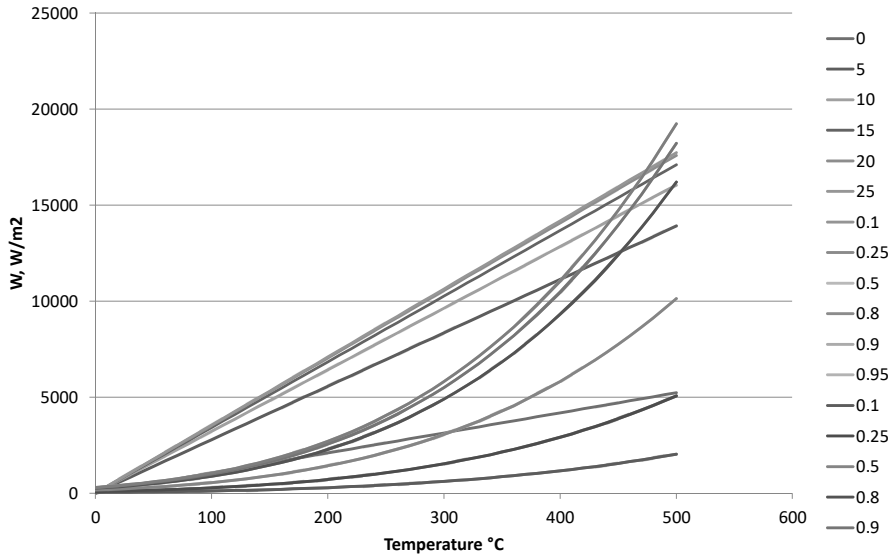
Heat Transfer Coefficient



Convective Heat Flow



Radiation AND Convection



Thermal Gradient Step-by Step

1 Collect Data IN SAME UNITS
- Hot Face (°C)
- Ambient (°C)
- Lining Thickness (m)
- Lining conductivity over range of temperatures (W/mK)
- Surface Emissivity (no unit)
- Wind Speed (m/s)

2 First Estimate of Shell Temp – Guess

3 Find Surface Heat Transfer per sq m from graph
- For Radiation
- For Convection
- Add together for Total

4 Calculate mean temp of lining

Thermal Gradient Step-by Step

5 Identify Conductivity of lining at mean temp

6 Calculate temp drop across lining from

$$W = k A \Delta T/\Delta x$$

W from step 3
K from step 5
ΔT is (Hot Face-Shell)
Δx is thickness (in m not mm)

7 New Shell Temp Estimate is Hot Face – ΔT
Calculate Shell Temp from Hot Face – DT
If this is larger than estimate, your estimate is too small, try again for a larger shell temp
If this is smaller than estimate. Your estimate is too small, try again for a smaller shell temp

8 Repeat from Step 3 until step size of change is small

Computers

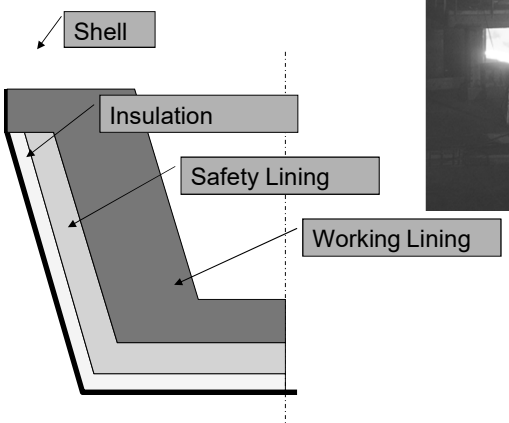
Designation: C680 – 10

Standard Practice for
Estimate of the Heat Gain or Loss and the Surface Temperatures of Insulated Flat, Cylindrical, and Spherical Systems by Use of Computer Programs[1]

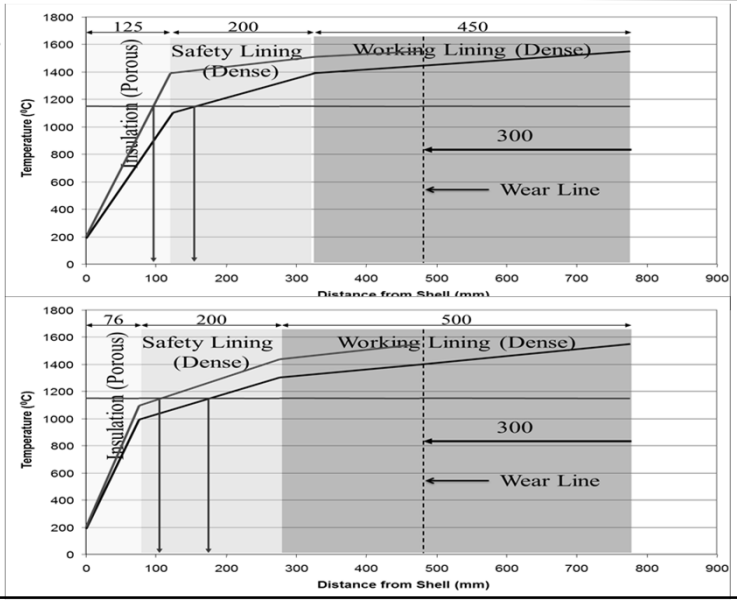
New and Worn Lining

- Lining is thinner when worn
  - More heat conducted
  - Shell temperature will be higher
  - Freeze line will be in different position

New and Worn Lining - Trough



New and Worn Lining - Trough



Limitations

Many Limitations to this method

- Wind speed is rarely constant
- Rain?
- Sunshine?
- Surface of shell
  - Dust
  - Rust
- Does lining ever reach steady state?

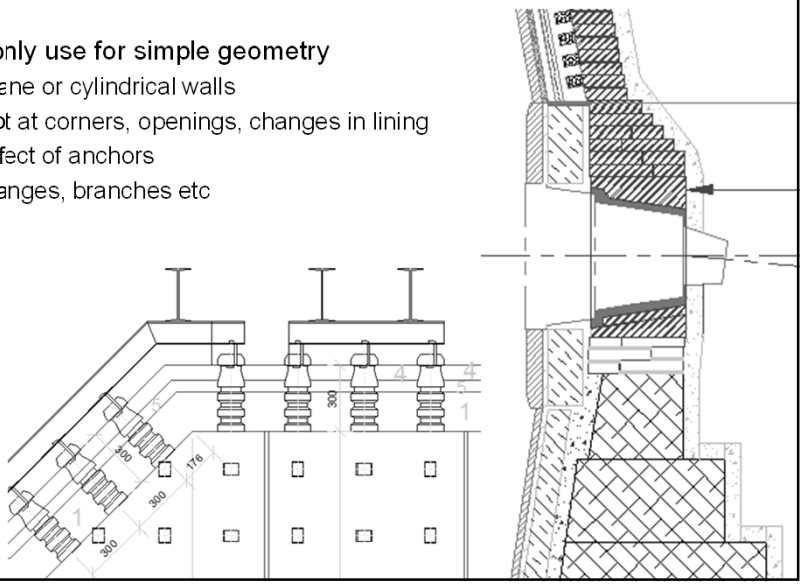
Advantages

- Quick
- Generally gives ‘worst case’ for lining design, esp for zero wind

Calibration?

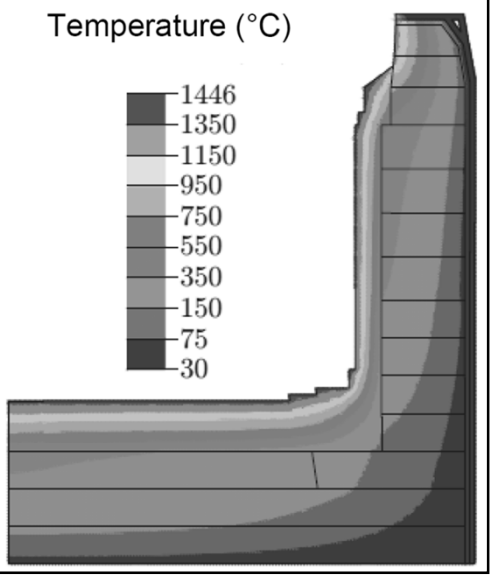
Limitations

- Can only use for simple geometry
  - Plane or cylindrical walls
  - Not at corners, openings, changes in lining
  - Effect of anchors
  - Flanges, branches etc



Finite Element Modelling FEM)

- Thermal Profile
- Expansion Movements
- Thermal Stress



Any Questions