Design and optimization of groundwater-filled and grouted borehole heat exchangers, from correlations to practice

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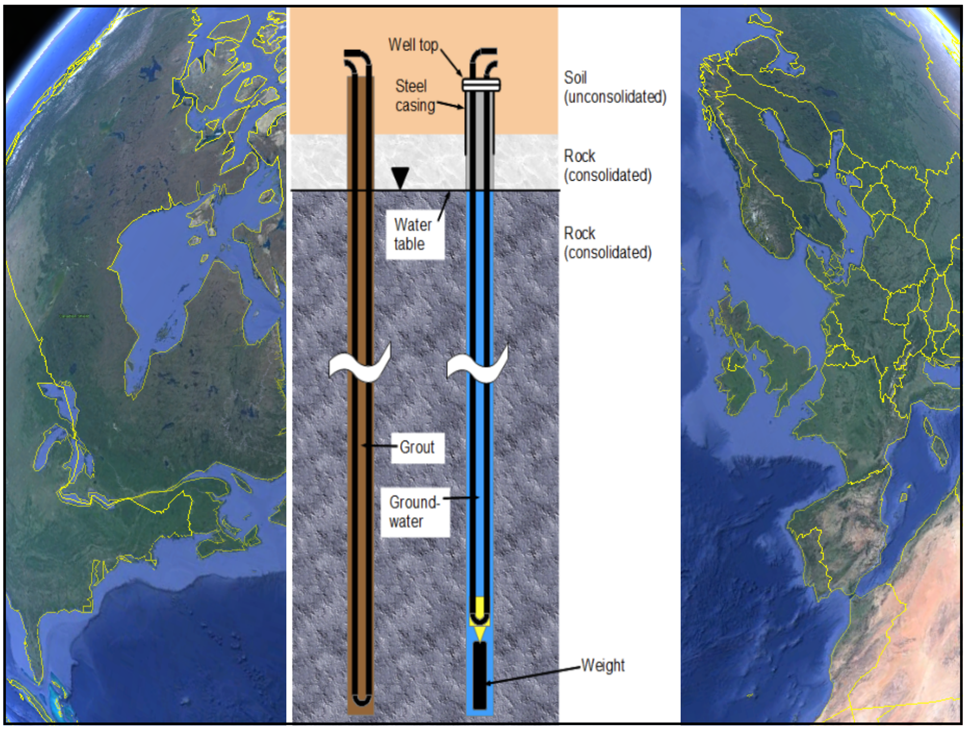
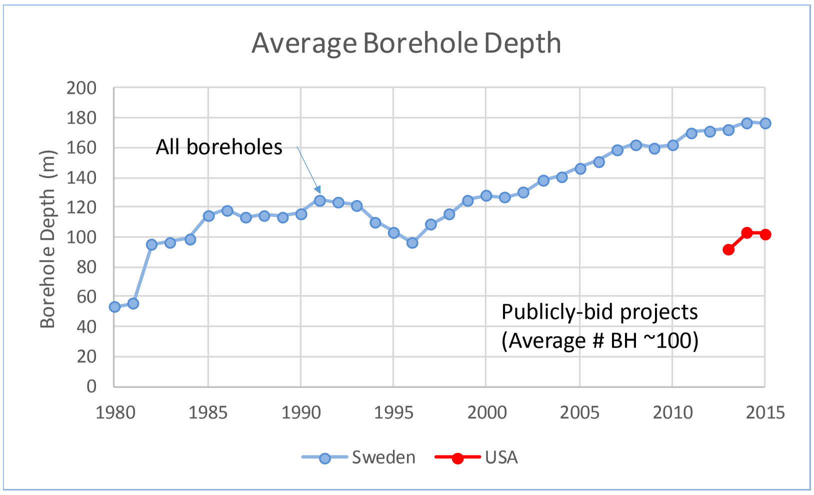


North America

- Grouted
- No casing
- Shallower
- Borehole resistance approximately constant.

Scandinavia

- Ground-water filled
- Cased from surface to bedrock.
- “Usually” short distance to bedrock.
- Deeper
- Borehole resistance varies with annulus temperature and heat extraction rate.

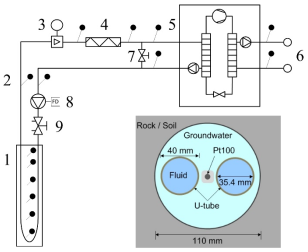


Swedish data: From SGU, via Signhild Gehlin of Svenskt Geonergicentrum
USA data: From analysis of commercial project databases, Ryan Carda of GeoPro, Inc., South Dakota

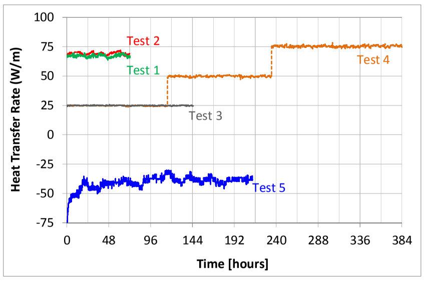
Background – GW-filled boreholes

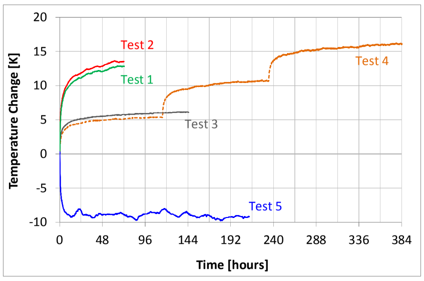
- Lund University - Claesson & Hellström (1988) showed effects of natural convection in boreholes.
- Lund – Kjellsson & Hellström (1997) – laboratory measurements
- Luleå Univ. Technology – Gehlin, et al. (2003) – thermosiphon effect
- Luleå – Gustafsson, et al. (2008-2010) – natural convection in boreholes – simulation and experiment
- Still no way to quantify effects for design purposes.

Experimental facility at Chalmers

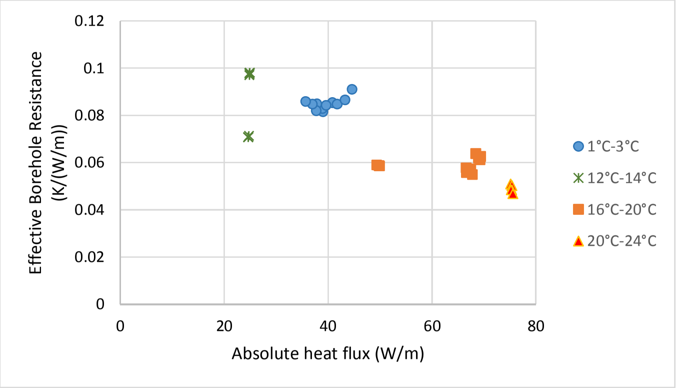


Series of injection and extraction TRTs over 27 months.

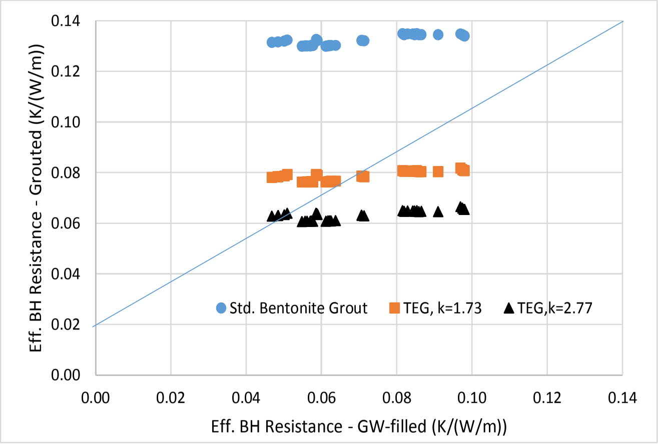




Results



Comparison to Grouted Boreholes



Correlations

For the resistance across the annulus:

$$Nu_{ann} = 0.14\left(Ra^{*}_{ann}\right)^{0.25} \qquad 4.0\text{E}7 > Ra^{*}_{ann} > 1.3\text{E}6$$

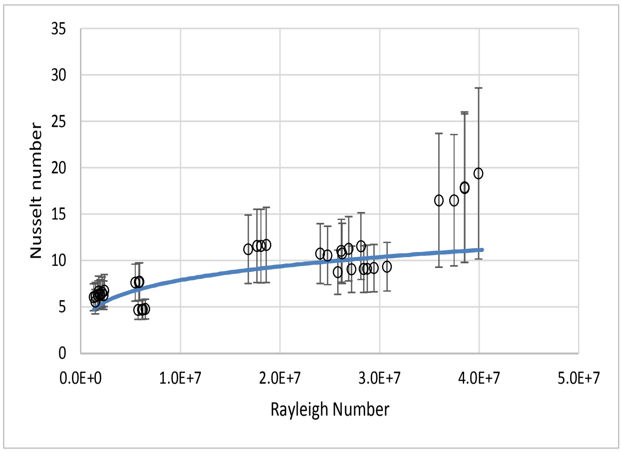
For resistance at the outer pipe wall:

$$Nu_{po} = 0.30\left(Ra^{*}_{po}\right)^{0.25} \qquad 4.1\text{E}7 > Ra^{*}_{po} > 1.8\text{E}6$$

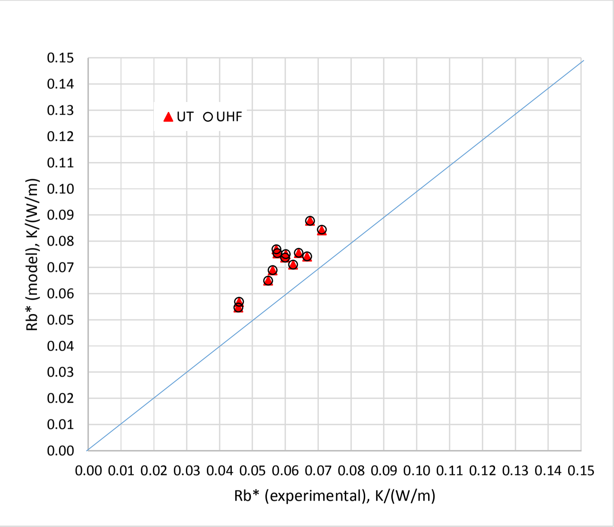
For resistance at the borehole wall:

$$Nu_{BHW} = 0.20\left(Ra^{*}_{BHW}\right)^{0.25} \qquad 2.9\text{E}7 > Ra^{*}_{BHW} > 5.4\text{E}5$$

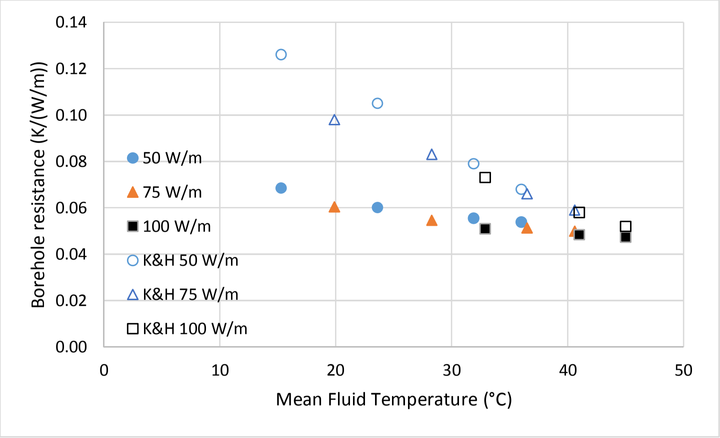
Annulus correlation



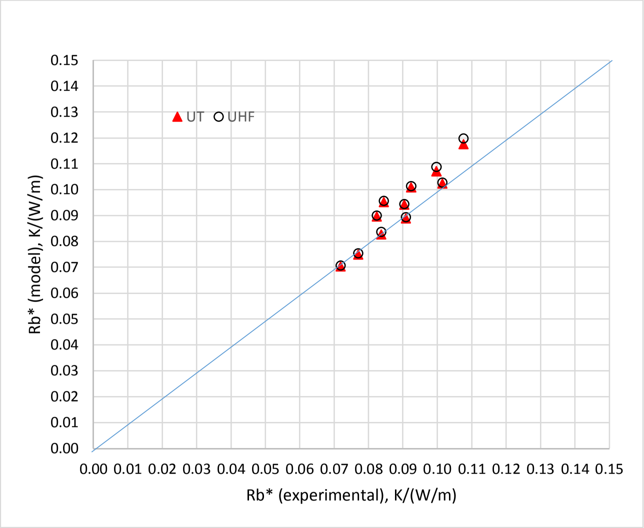
Other Boreholes at Chalmers



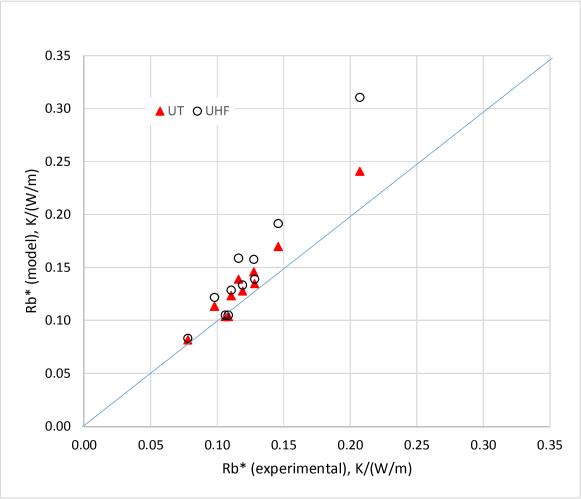
Laboratory measurements
(3m high test borehole)



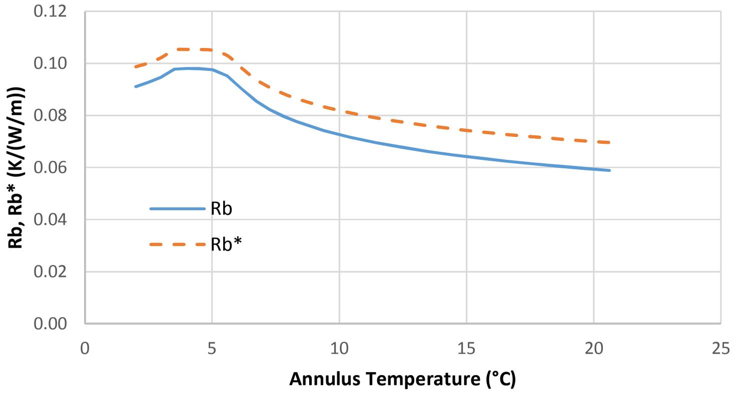
Norwegian Boreholes



Swedish Boreholes

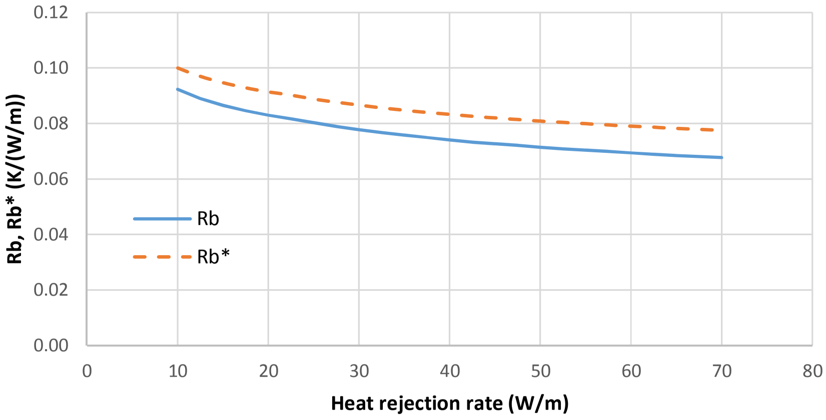


Application: Sensitivity to Annulus Temperature



Heat rejection rate kept at 35 W/m

Application: Sensitivity to Heat Rejection Rate



Annulus temperature kept at 8.9°C

Conclusions – GW-filled Boreholes

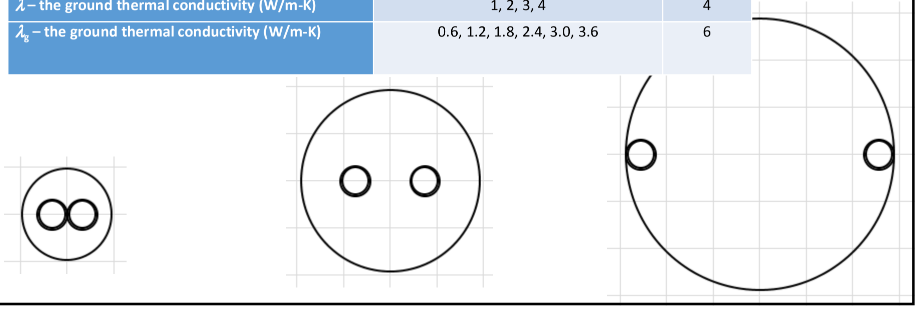
- Correlations for natural convection in boreholes with single U-tubes give reasonable performance.
  - Gives “conservative” prediction of resistance for design purposes.
  - Implemented in GLHEPRO.
  - Effect of height on scaling?
- Average uncertainty, annulus Nusselt #: ±29%
  - Better controlled experiments: nice, but expensive.
- Correlations for double U-tubes, co-axial heat exchangers are needed.

Grouted Boreholes

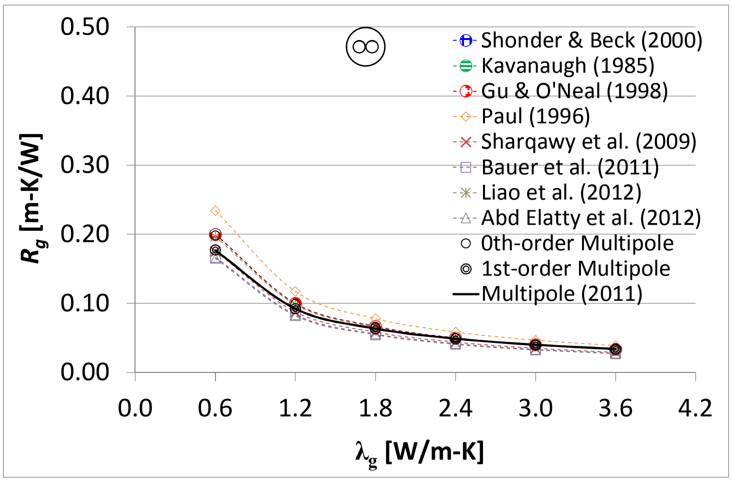
- Many simplified methods for predicting borehole thermal resistance. (Few for internal thermal resistance.)
- Multipole algorithm – Lund University (1987); later refinement Claesson and Hellström (2011)
  - 2-dimensional conduction heat transfer calculation
  - Variable-order: 10th order gives accuracy to 8 significant digits
  - Verified against detailed numerical models
  - Difficult to implement
  - Hence, simpler methods are desirable

Parametric Study: 216 Cases

Parameter	Levels	Number of levels
θ_2 – The ratio of the borehole radius to outer pipe radius. Since pipe outer diameter is always fixed at 32 mm, borehole diameters are 96 mm, 192 mm, and 288 mm.	3, 6, 9	3
Shank spacing configuration; corresponds to Paul's (1996) A, B, C configurations	Close, Moderate, Wide For θ_2 = 3, θ_1 = 0.333, 0.555, 0.667 For θ_2 = 6, θ_1 = 0.167, 0.389, 0.833 For θ_2 = 9, θ_1 = 0.111,0.370,0.889	3
λ – the ground thermal conductivity (W/m-K)	1, 2, 3, 4	4
λ_g – the ground thermal conductivity (W/m-K)	0.6, 1.2, 1.8, 2.4, 3.0, 3.6	6



Sample Results (λ=3)



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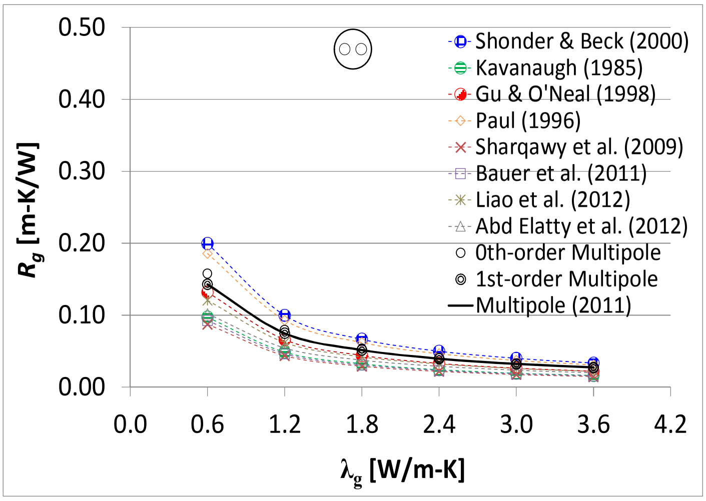
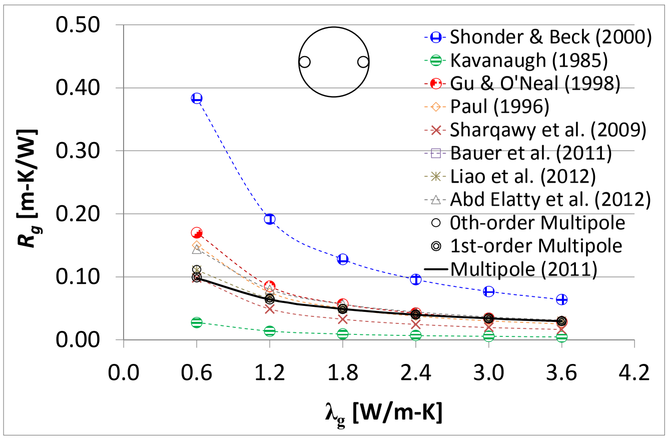
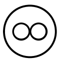
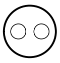
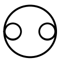


Sample Results (λ=3)



Best methods

Grout Thermal Conductivity (λ_g)			
Low (0.6 – 1.2 W/m-K)	– Sharqawy et al. (2009) – ***First-order Multipole***	– ***First-order Multipole***	– *First-order Multipole*
Medium (1.2 – 2.4 W/m-K)	– Shonder & Beck (2000) – Kavanaugh. (1985) – Gu & O'Neal (1998) – Liao et al. (2012) – Zeroth-order Multipole – ***First-order Multipole***	– Zeroth-order Multipole – ***First-order Multipole***	– Liao et al. (2012) – ***First-order Multipole***
High (2.4 – 3.6 W/m-K)	– *Shonder & Beck (2000)* – *Kavanaugh (1985)* – *Gu & O'Neal (1998)* – *Liao et al. (2012)* – *Zeroth-order Multipole* – *First-order Multipole*	– *Zeroth-order Multipole* – ***First-order Multipole***	– *Liao et al. (2012)* – ***First-order Multipole***

- Methods here have mean absolute percentage error lower than 3% and maximum absolute percentage error less than 10%.
- Italics indicate maximum absolute percentage error lower than 5 %.
- Italics + Bold indicate maximum absolute error smaller than 1 %.

Implications for Design

- 1^{st}-order multipole expressions give excellent accuracy over entire range. (MAPE=0.2%, Max. APE=2%)
- Nothing else comes close.
- Easy to implement, e.g.:

$$R_b = \frac{1}{4\pi\lambda_g}\left[\beta + \ln\left(\frac{\theta_2}{2\theta_1(1-\theta_1^4)^\sigma}\right) - \frac{\theta_3^2\left(1-\frac{4\sigma\,\theta_1^4}{1-\theta_1^4}\right)^2}{\frac{1+\beta}{1-\beta} + \theta_3^2\left(1+\frac{16\sigma\,\theta_1^4}{(1-\theta_1^4)^2}\right)}\right]$$

$$\theta_1 = \frac{s}{2r_b}, \quad \theta_2 = \frac{r_b}{r_{po}}, \quad \theta_3 = \frac{r_{po}}{s} = \frac{1}{2\theta_1\theta_2}, \quad \sigma = \frac{\lambda_g - \lambda}{\lambda_g + \lambda}, \quad \beta = 2\pi\lambda_g R_p$$

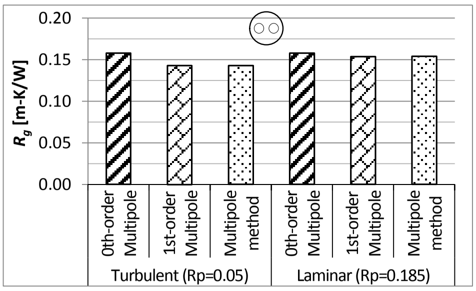
Implications for Design

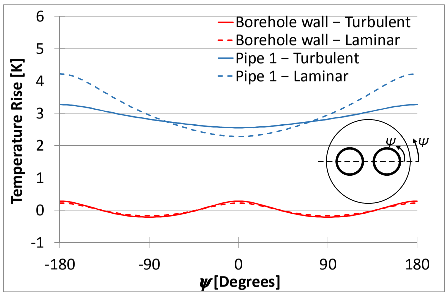
- Similar study for internal thermal resistance.
- MAPE=0.2%, Max. APE < 6%
- Still easy to implement.

$$R_a = \frac{1}{\pi\lambda_g}\left[\beta + \ln\left(\frac{(1+\theta_1^2)^\sigma}{\theta_3(1-\theta_1^2)^\sigma}\right) - \frac{\theta_3^2(1-\theta_1^4+4\sigma\,\theta_1^2)^2}{\left(\frac{1+\beta}{1-\beta}\right)(1-\theta_1^4)^2 - \theta_3^2(1-\theta_1^4)^2 + 8\sigma\,\theta_1^2\,\theta_3^2(1+\theta_1^4)\Big)}\right]$$

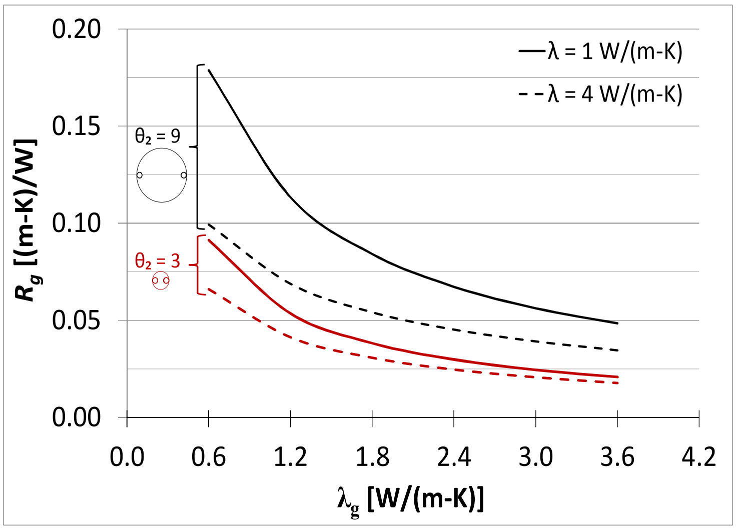
Grout Resistance

- Affected by:
  - Pipe resistance
  - Ground thermal conductivity





Sensitivity to Ground Conductivity



Questions?

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