A perspective on Thermal Conductivity of Geofluids and Potential Geothermal Reservoirs

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INTRODUCTION

- A key component of the geothermal puzzle is an improved understanding of the thermal properties of igneous, metamorphic and sedimentary rocks and their potential for heat exchange, fluid flow and heat capacity at different scales.
- It has been shown that heat capacity and thermal conductivity are functions of temperature pressure and saturation, but these physics remain poorly understood for subsurface formations.
- Core and pore scale imaging and experiments will provide data on nano- and micro-scale flow and thermal diffusivity and will be scaled to core, well and reservoir scale using a variety of upscaling and machine learning methods.
- Once understood, an optimal heat recovery process must be designed which takes into consideration the aforementioned science.
- Work do date demonstrates that unless the pore level heat transfer (conduction and convection) is not well understood, we will always rely on empirical correlations to predict thermal behavior.

PUBLISHED CORRELATIONS

Heat Transfer Equation:

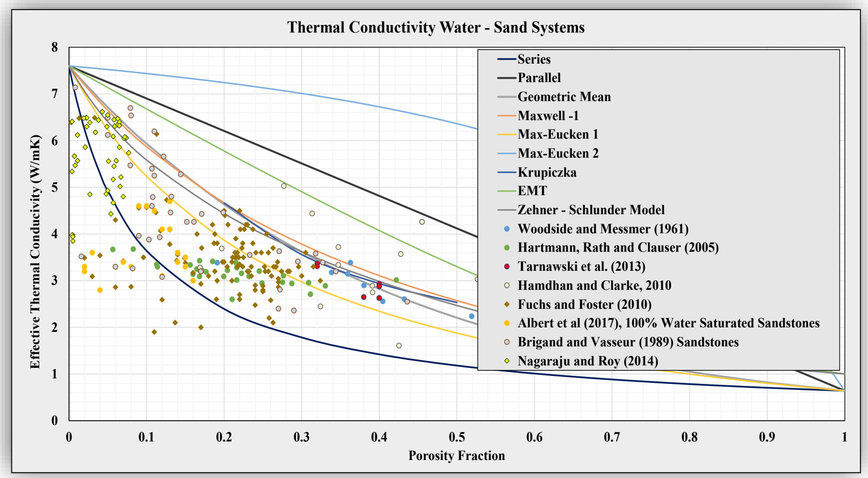
$$(\rho c C_p)_m \frac{\partial(T)}{\partial t} + (\rho C_p)_f \mathbb{v} \cdot \nabla T = \nabla \cdot (k_m \nabla T) + q_m^m$$

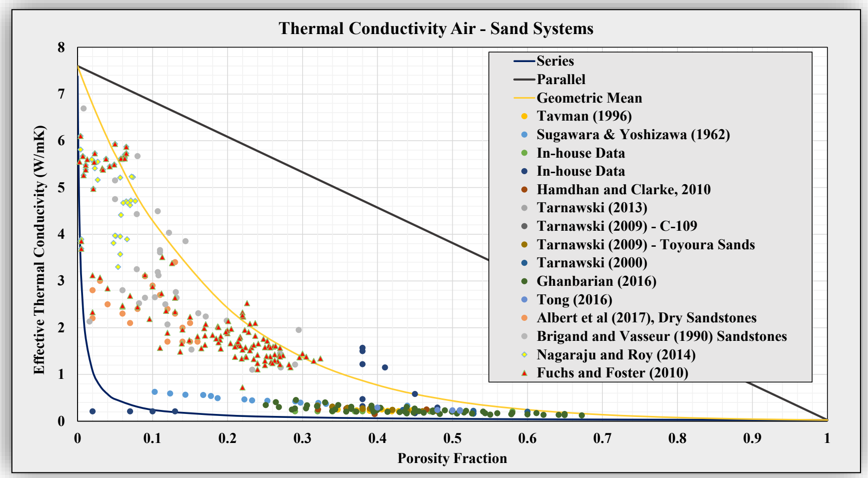
$$(\rho C_p)_m = (1-\varphi)(\rho C_p)_s + (\varphi)(\rho c)_f$$

$$k_m = (1-\varphi)k_s + (\varphi)k_f$$

$$q_m^m = (1-\varphi)q_s^m + (\varphi)q_f^m$$

Based on this the effective thermal conductivity should fit the ***"parallel model".***
Literature, however, proposes numerous correlations.

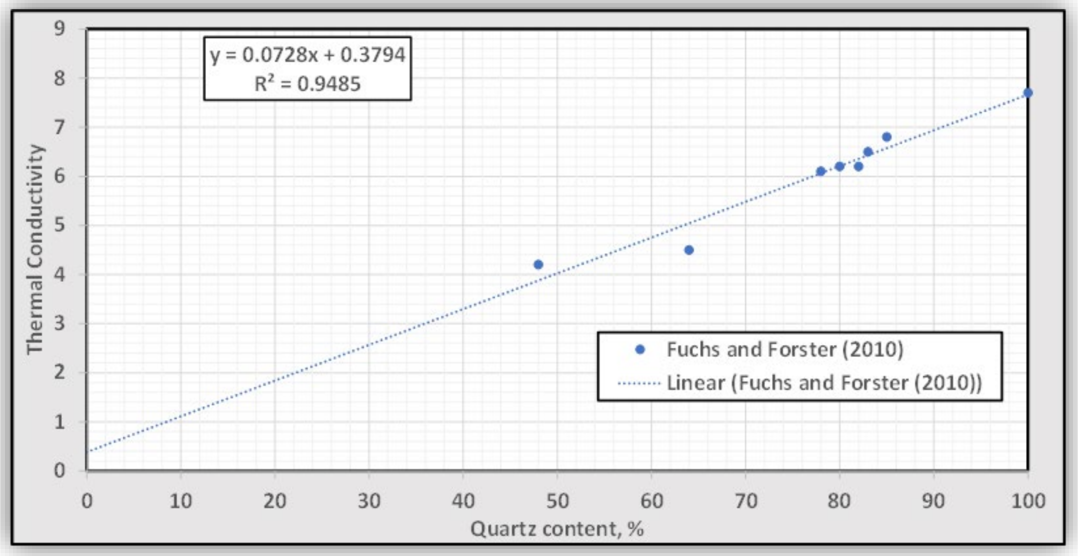




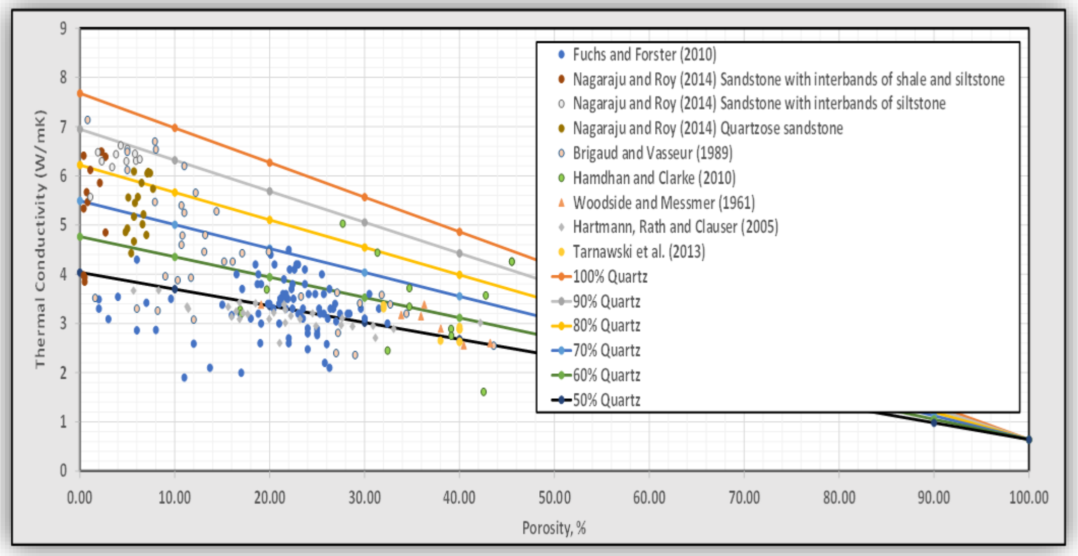
- Some of these correlations are plotted for reference purposes.
- There is absolutely no rational in the choice of the correlation.
- These are for single phase system at ambient conditions.

The thermal conductivity of the pure solid is a "mystery". Here it is assumed to be quartz.

MINERALOGY EFFECTS



The value of the solid thermal conductivity is a strong function of mineralogy and in high quartz content it can be linear with quartz fraction.

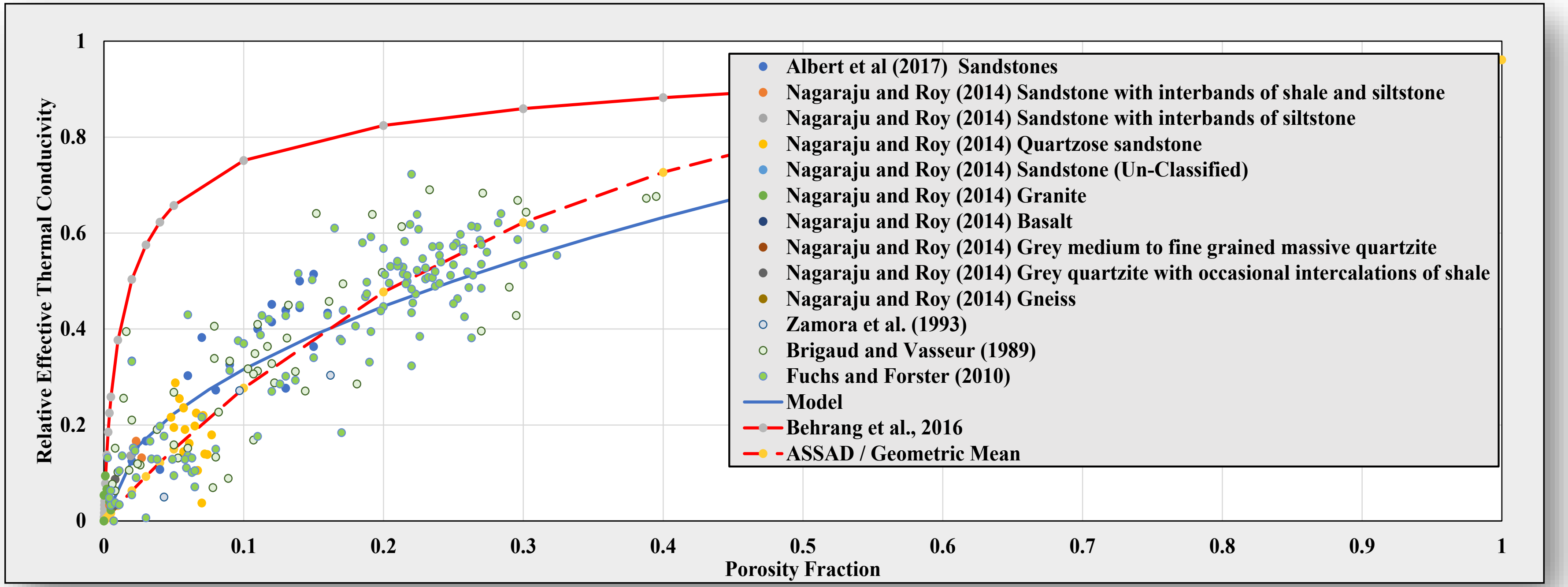


If the parallel model is true one can extrapolate for the solid thermal conductivity.

We can also develop compositional models based on the thermal conductivities of the minerals, via X-Ray diffraction.

- But then why should the choice of fluids affect the thermal conductivity selection model?
- Also, as porosity increases, we transition from a consolidated medium to a packing to a slurry, to a suspension.
- Should the same correlations apply for all porosities?
- Some correlations explicitly claim validity for narrow porosity ranges. Why?

Is There a Correlation Between Dry and Saturated Core Sample Effective Thermal Conductivities?

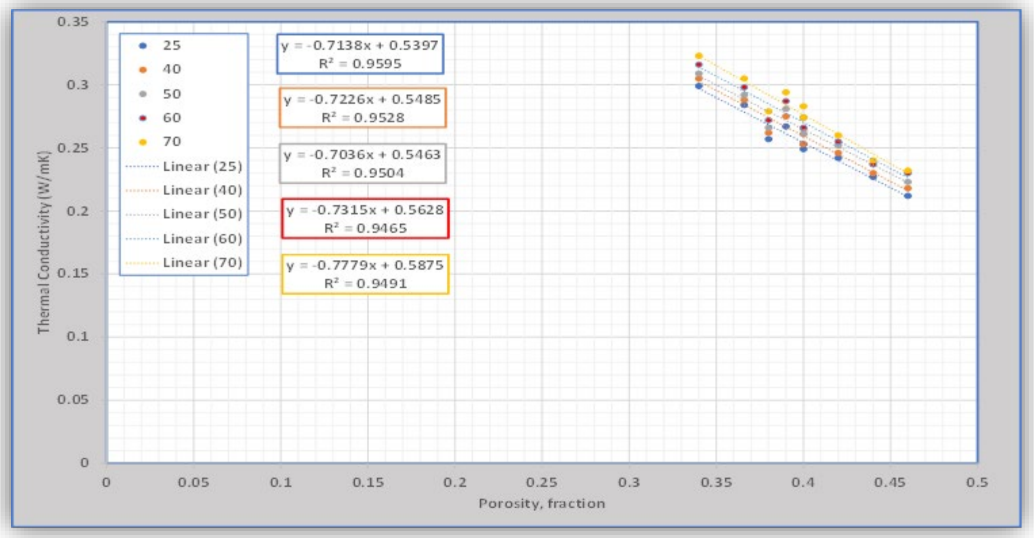


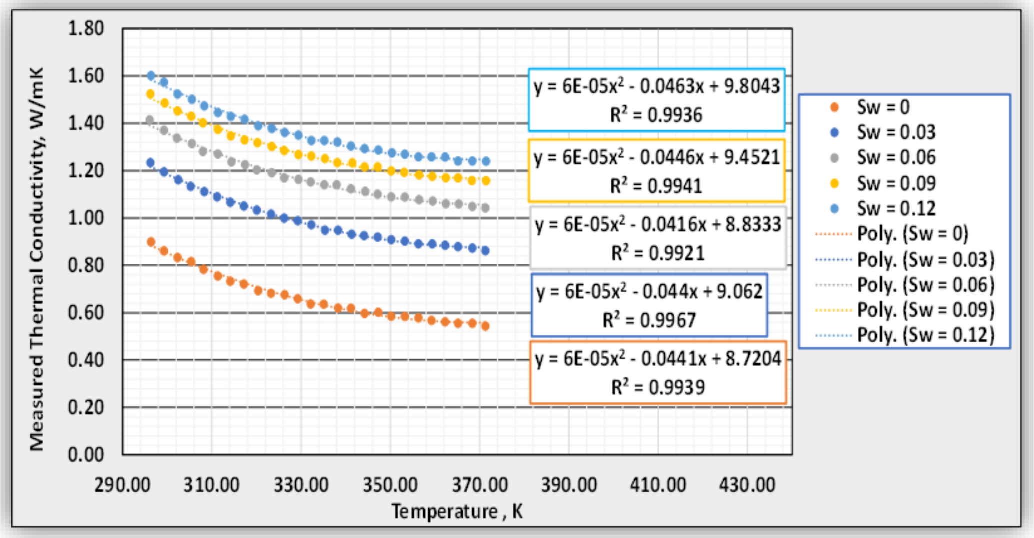
- Above, the relative effective thermal conductivity correlates well with the square root of porosity.
- There is no reason for this to happen.
- Of course, there is considerable scattering of the data which implies that the experimental error bars may be high.

SATURATION & TEMPERATURE EFFECTS

The effects of saturation and temperature are also complex.

$$Ke\,(S_r, T) = \frac{a_1 + a_2 S_r + a_3 S_r^2 + a_4 S_r^3 + a_5 T}{1 + a_6 S_r + a_7 S_r^2 + a_8 T + a_9 T^2 + a_{10} T^3}$$





- The Nikolaev et al. correlation can be used to match several different experimental data sets. It has 10 coefficients that need to be determined for EACH sample under testing.
- Generic coefficients for some data groups can be used as starting points.
- So experimental measurements are a must, but they are highly contested in the literature.

A SINGLE GENERALIZED CORRELATION

Combining measurable parameters with a mathematical correlation makes predicting thermal conductivity easier.

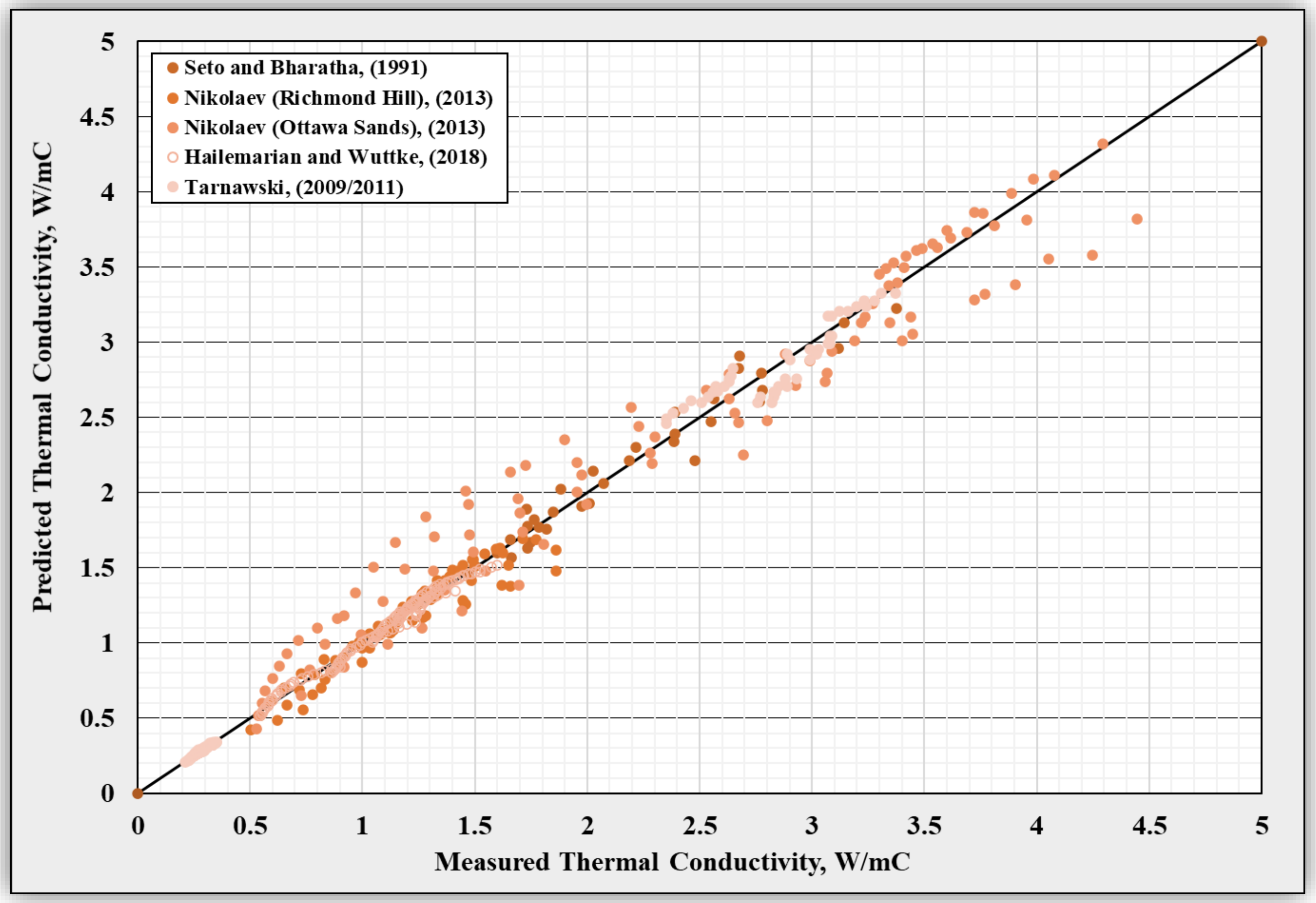
$$k\,(\varphi, S_w, T) = (a + bT - c\varphi)(dS_w^2 + eSw + f)$$

$$= aS_w^2 + bS_w^2T - cS_w^2\varphi + dS_wT - eS_w\varphi + fS_w + gT + h\varphi + i$$

- Basic laboratory procedures can be conducted to obtain these three parameters.
- The proposed correlation is purely empirical.
- The results have a linear relation with temperature and porosity and a second order relation with water saturation.

VALIDITY OF THE CORRELATION

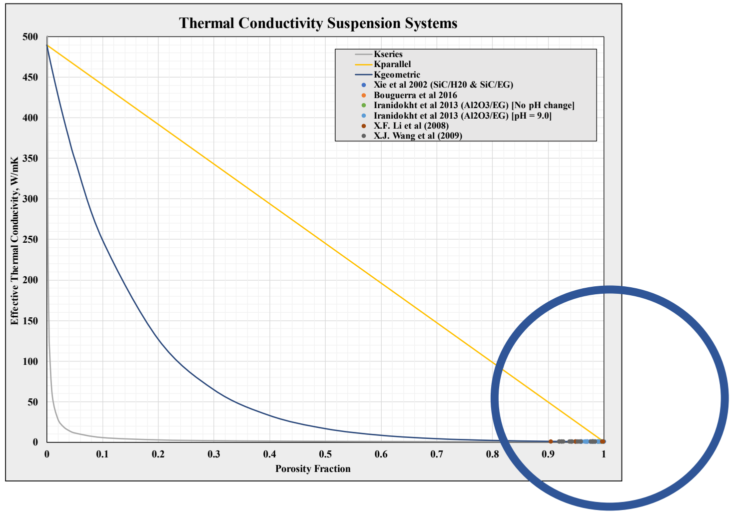
How accurate is the proposed generalized correlation?

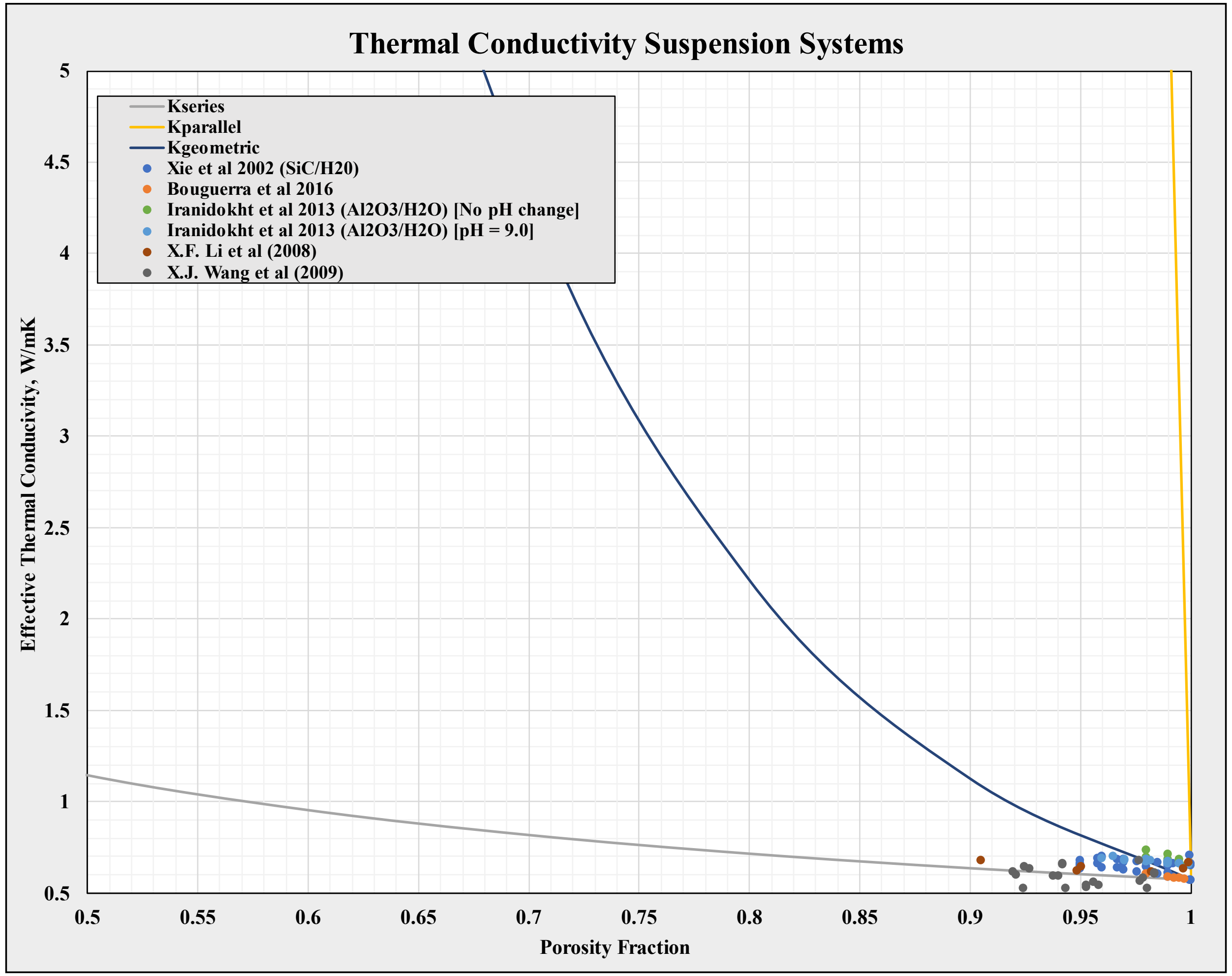


- Five independent experimental data sets ranging in both solid and fluid types, were used to check the validity of the proposed model.
- All data sets fit the model well with minimal scatter.
- This indicates that the correlation – although strictly empirical – is valid for predicting thermal conductivity of porous systems.
- An advantage of this proposed model is its high degree of versatility amongst porous systems.

Almost like ML but not quite

SUSPENSIONS & THE MODELS





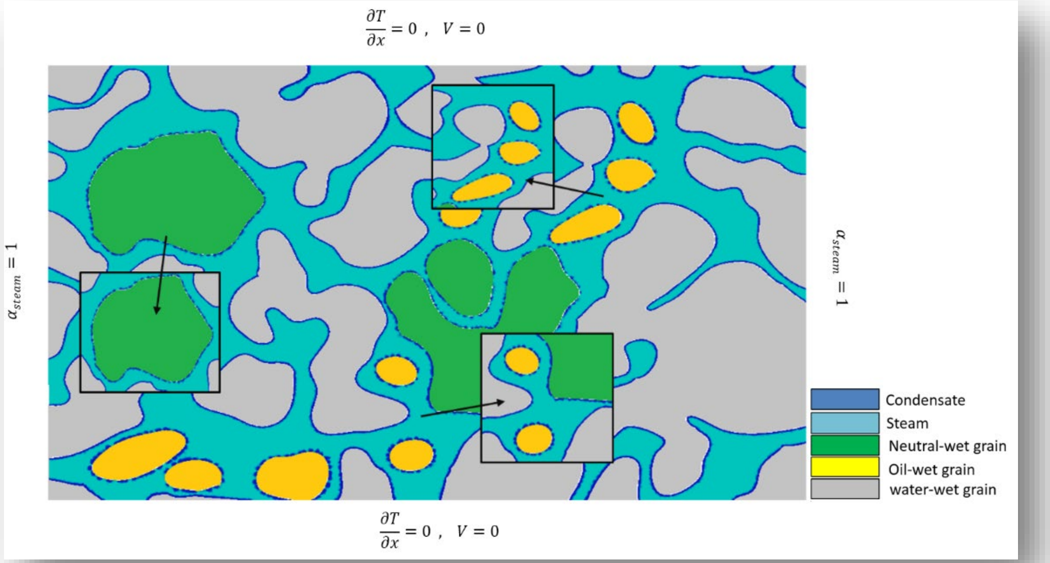
- Experimental data sets from the literature were plotted against the 3 most frequently used models (Series, Parallel, Geometric Mean).

- The series and the geometric models proved to be better estimations, whereas the parallel model overestimated the thermal conductivity.

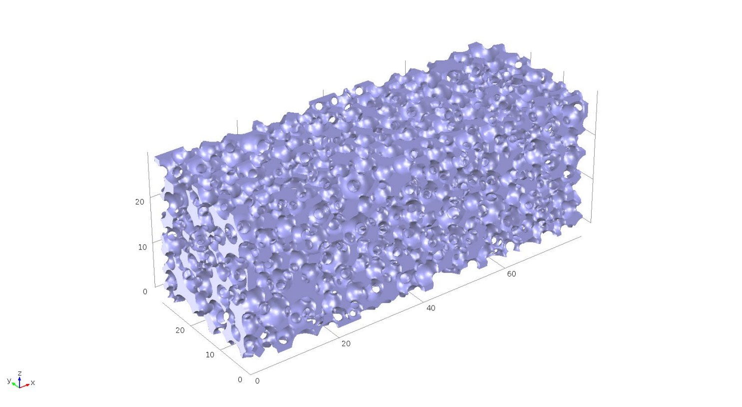
PORE LEVEL MODELLING

Macroscopic modelling is not able to explain what are the possible contributors in the discrepancies in effective thermal conductivity predictions.

The answer lies with pore level modelling.



- In pore level models we can specify the mineralogy, wettability and thermal conductivity of each pore and each grain.
- We can also build artificial media of specified geometries.
- What is not clear is whether a 2-D model can properly predict low porosity systems where both fluid and solid must be continuous.
- In suspensions, this might not be a problem.



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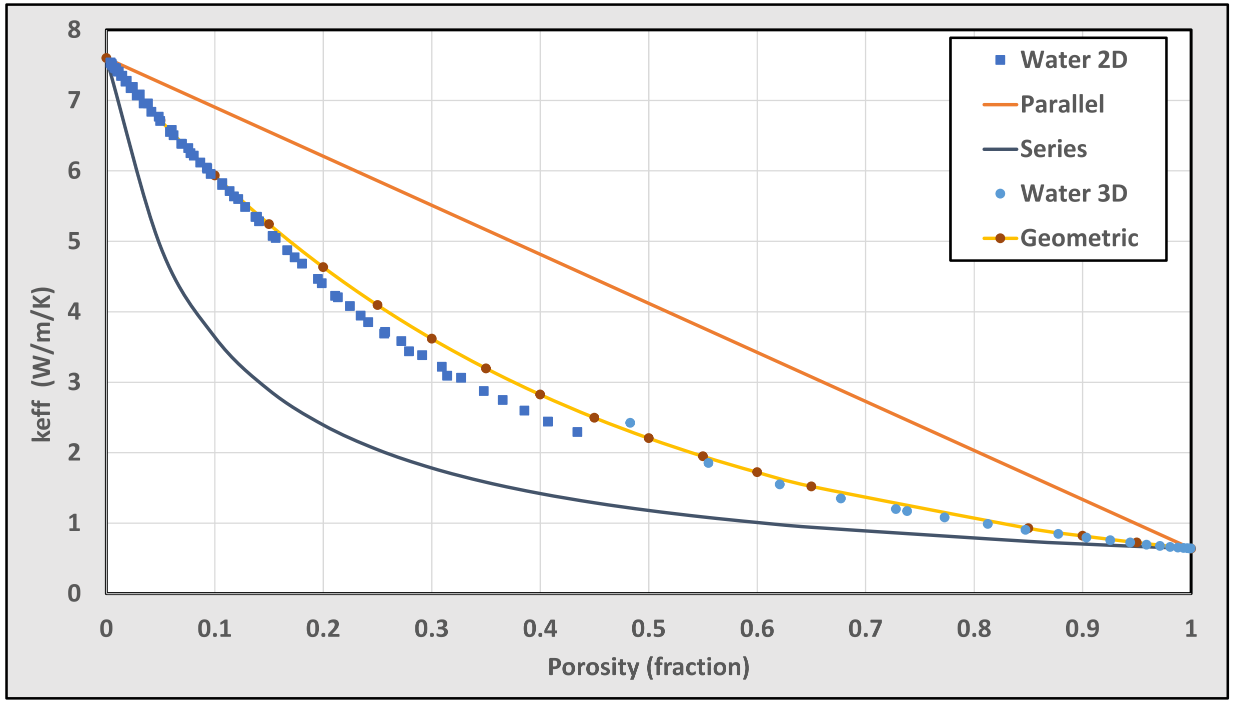
PORE LEVEL MODELLING

- Preliminary modelling shows that for water saturated media the parallel model does not work (contrary to earlier work from our group).
- The geometric mean model seems to work better.
- Computational Multiphysics models are used.



- Please note there are 2-D and 3-D models in the graph, and they do not perfectly align.
- There are several issues of how the solid grains touch, how the fluid wets the grains.
- Also meshing has become a major pain in properly generating realistic representations of grain-to-grain contacts.

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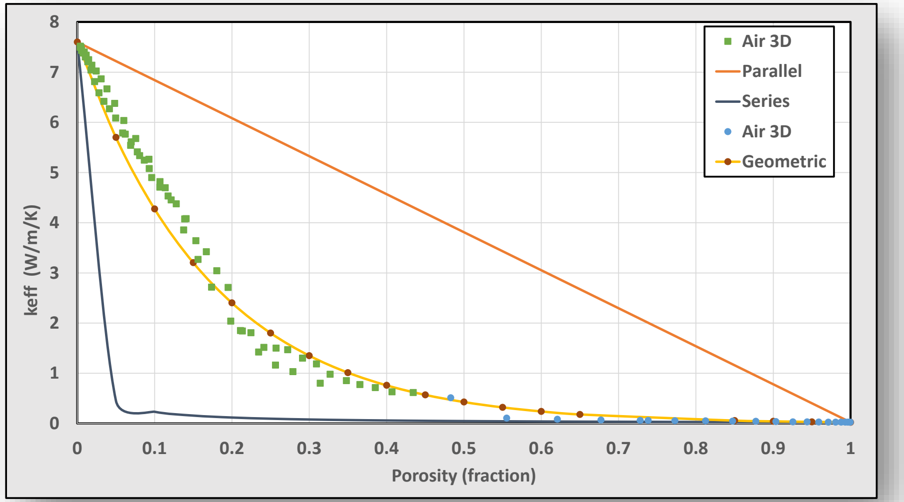
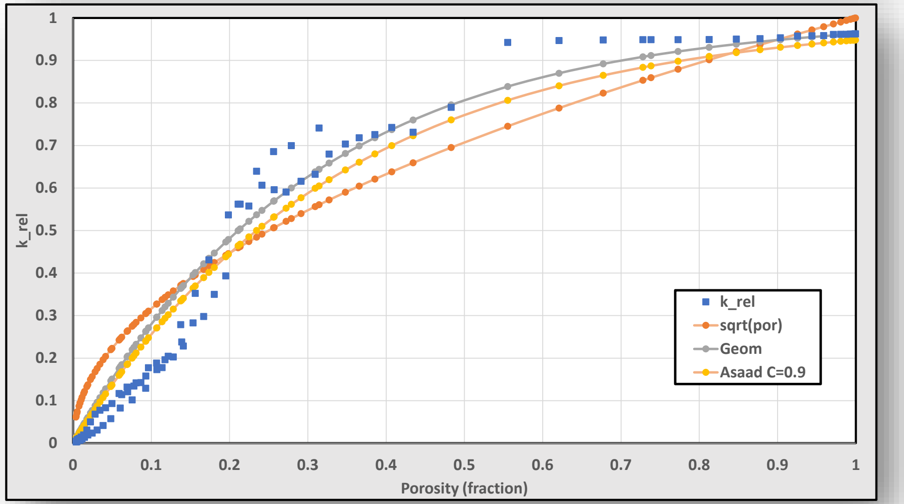
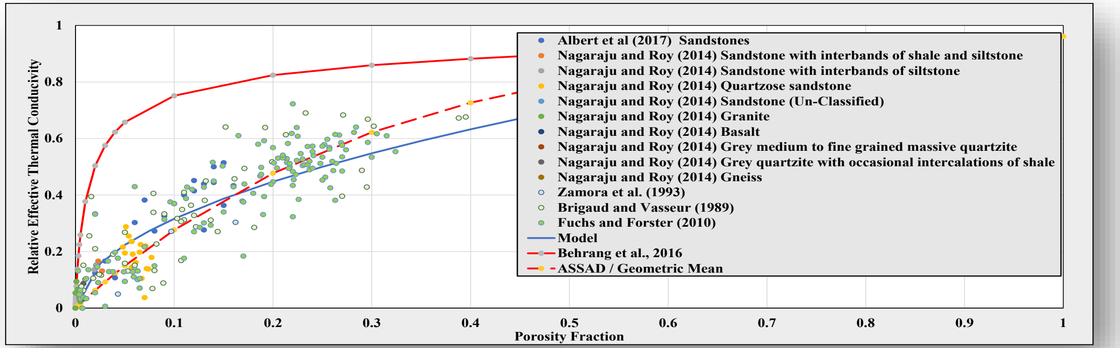
PORE LEVEL MODELLING

Looking at dry media, the models are at least consistent, and the geometric model predicts both water and air saturated media.



When we are looking for relative effective thermal conductivity, the models qualitatively match experimental data.





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CONCLUSIONS

- Prediction of effective thermal conductivity is a challenge.
- Empirical models do not expand beyond the data sets used for calibration.
- Mineralogy / chemical composition must be taken into account.
- Pore level approach favors the geometric models.
- Pore level approach implies geometry of grains and contacts is essential.
- Experimental work requires standardization.

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Thank You!