A non-linear transport model for determining porous shale rock characteristics

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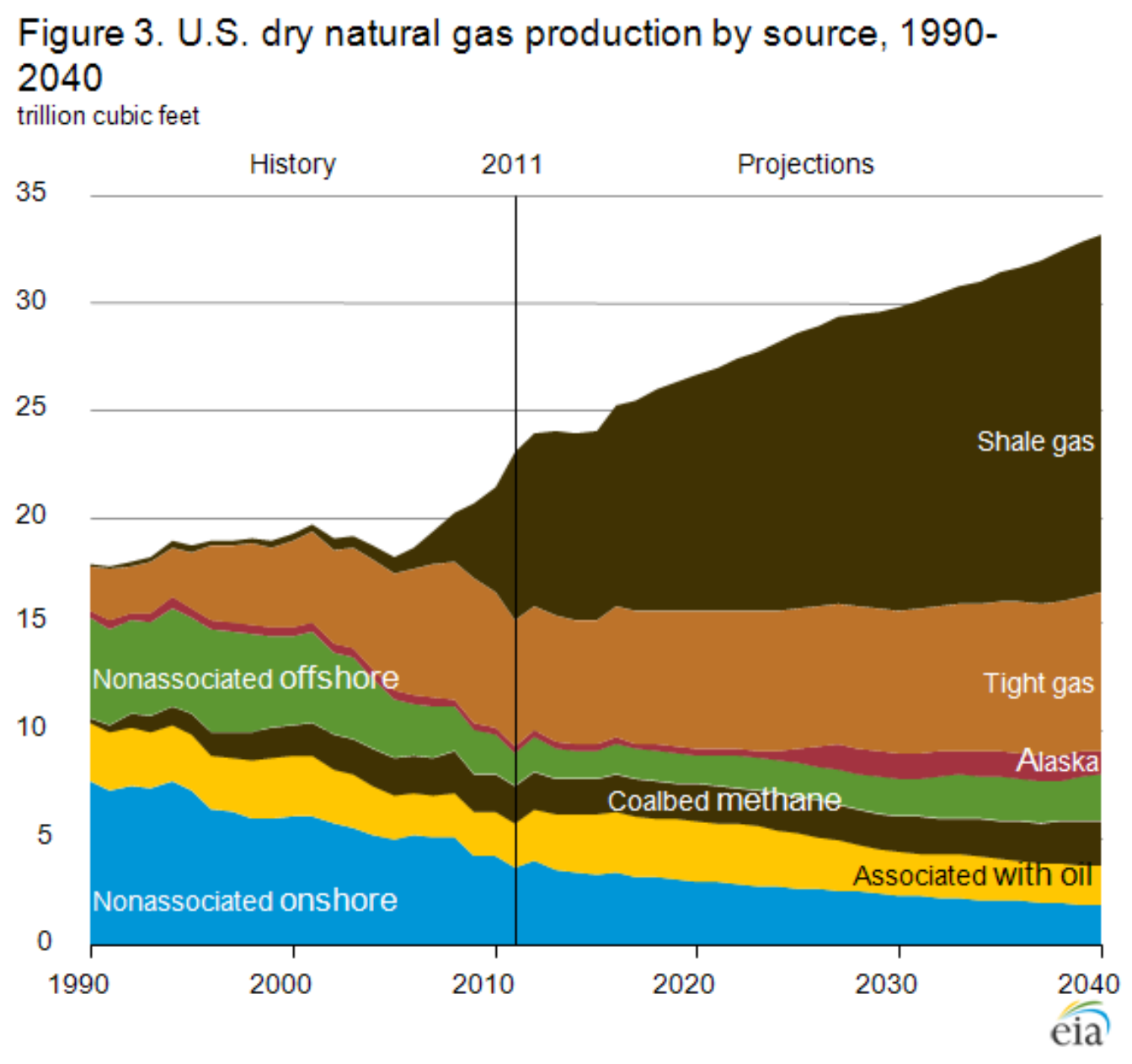
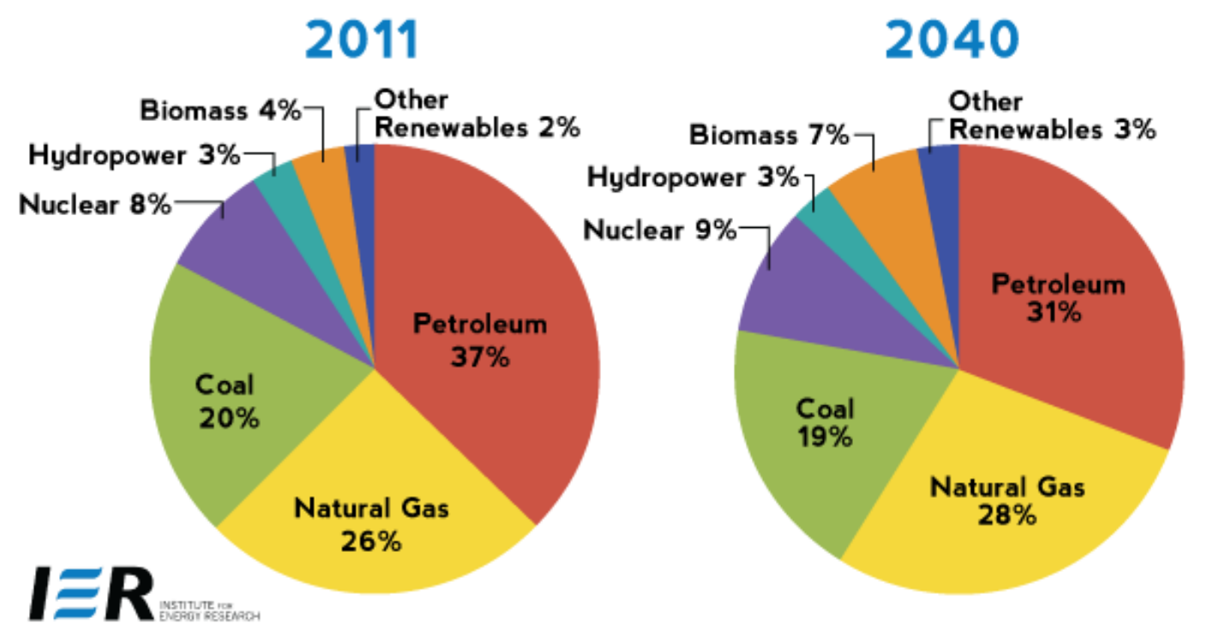
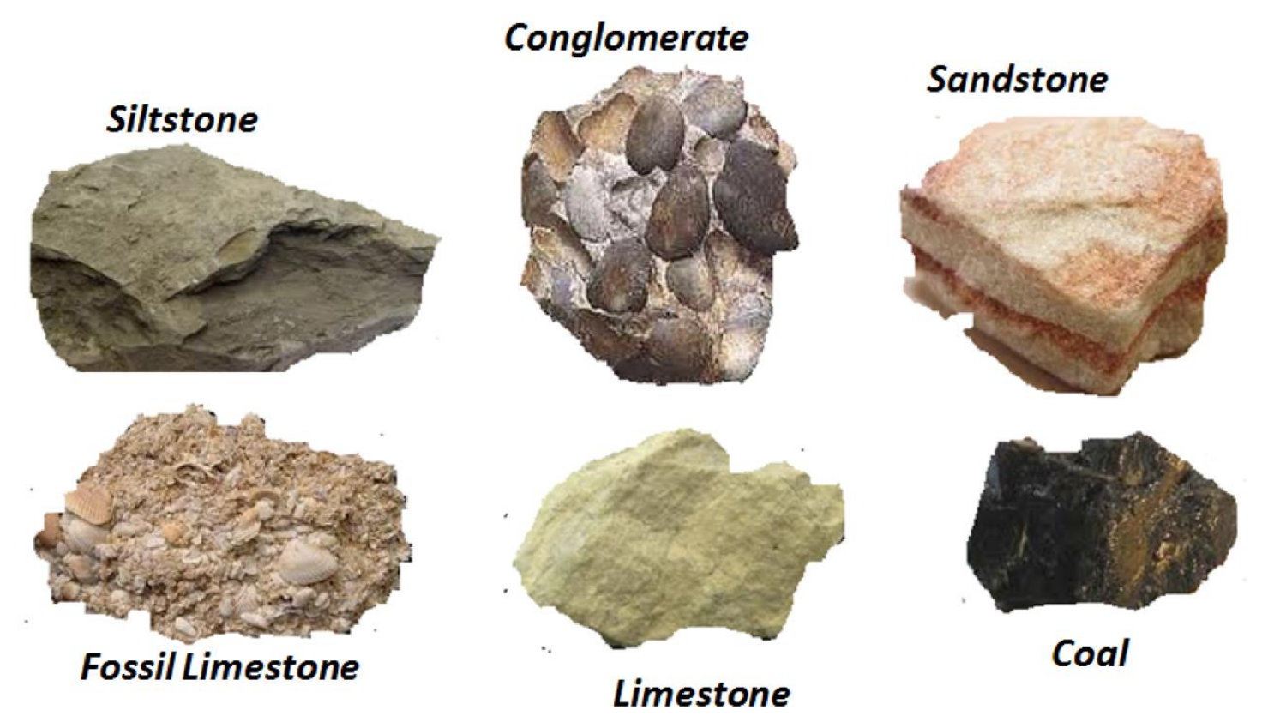




Objectives

- To develop a transport model for gas flow in tight porous media.
- Application to determine rock properties
- Application to sensitivity analysis to determine critical model parameters



Model Realism

The transport model is obtained as a partial differential equation for the pressure field, from consideration of mass conservation and momentum conservation. Physical realism is incorporated in to the model by including important effects due to:

- Different flow regimes that exist in the pores
- Adsorption and desorption of gas from the rock material
- Forchchiemer's correction due to high speed
- Pressure dependent correlations
- Nanoscale of pores which is characteristic of shale rocks

Computational Method

The numerical solver was developed using an implicit finite volume method with a flux limiter. Currently, the solver is applied to 1D flows.

References

[1] Ali, I., "A Numerical Study of Shale Gas Flow in Tight Porous Media through Nonlinear Transport Models". PhD Dissertation, KFUPM, March 2016.
[2] Ali I., Chanane B., & Malik N. A., "Compressibility Coefficients in nonlinear transport models in unconventional gas reservoirs". In Proc. AMMCS-CAIMS Congress, Waterloo, Ontario, Canada, 7-12 June, 2015.
[3] Ali I. & Malik, N. A. "A realistic transport model for shale gas in porous media for determining rock properties". Submitted to Fuel, 2016.
[4] Ali I. & Malik N. A., "Shale gas flow in tight rocks using a nonlinear transport model with fully pressure dependent model parameters". Proc. 6th Int. Conf. Porous Media, Hawaii, 3-8 July, 2016
[5] Pong, K.C., Ho C.M., Liu J.Q., & Tai Y.C., "Non-linear pressure distribution in uniform micro-channels. Applications of microfabrications to fluid mechanics". ASMEFED 197, 51-56, 1994.
[6] Civan, F., Rai, C. S., & Sondergeld C. H., "Shale-gas permeability and diffusivity inferred by improved formulation of relevant retention and transport mechanism". Transp. Porous Med. 68, 925-944, 2011.
[7] Beskok, I. & Karniadakis G.E., "A model for flows in channels pipes, and ducts at micro and nano scales". Thermophy. Eng. 3(1), 43-77, 1999.

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The Gas Transport Model: an advection-diffusion equation for the pressure field

$$\frac{\partial p}{\partial t}+U(p,p_x)\frac{\partial p}{\partial x}=D(p)\frac{\partial^2 p}{\partial x^2}$$

$$D(p)=\frac{FK_a}{\mu\xi_t}$$

$$U(p,p_x)=-\xi_3(p)D(p)\frac{\partial p}{\partial x}$$

$$F=\left[1+\frac{\rho}{\mu}K_a\beta\,|u|\right]^{-1}$$

$$\xi_f(p)=\frac{1}{p}\frac{d(f(p))}{dp}$$

This is a transport model for the pressure field *p(x,t)*. It contains many (about 20) parameters, *f(p),* and the same number of compressibility coefficients, ξ_f.

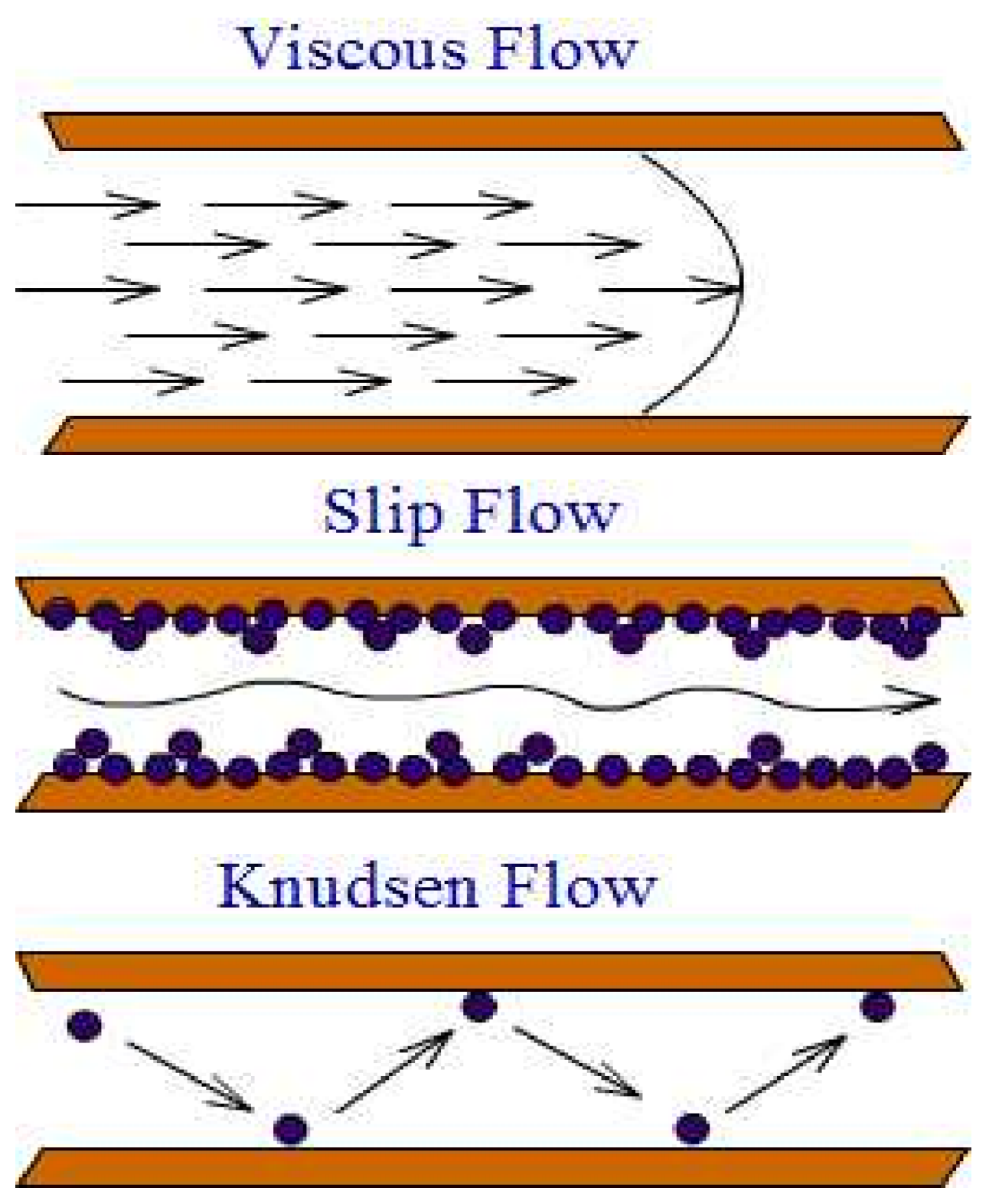
The porosity, and the permeability are the two most important rock characteristics and they play a central role in the model.

The apparent velocity $U(p,p_x)$ and the apparent diffusivity *D(p)* are complicated functions of $\xi_f(p)$; so they are also functions of the pressure and the pressure gradient, making this a highly nonlinear system.

This is a simplified 1D version of the 3D transport model. See [1--4] for details.

p(x,t) – pressure field; U -- apparent velocity; D -- apparent diffusivity;
Ka – apparent permeability; β *– turbulence factor;* μ *– viscosity;* ρ *– density;*
ξ_3 *and* ξ_f *- compressibility coefficients.*

4-Flow regime, High velocity, Pressure dependent parameters



Nano scale pore radius means that various flow regimes must be accounted for:

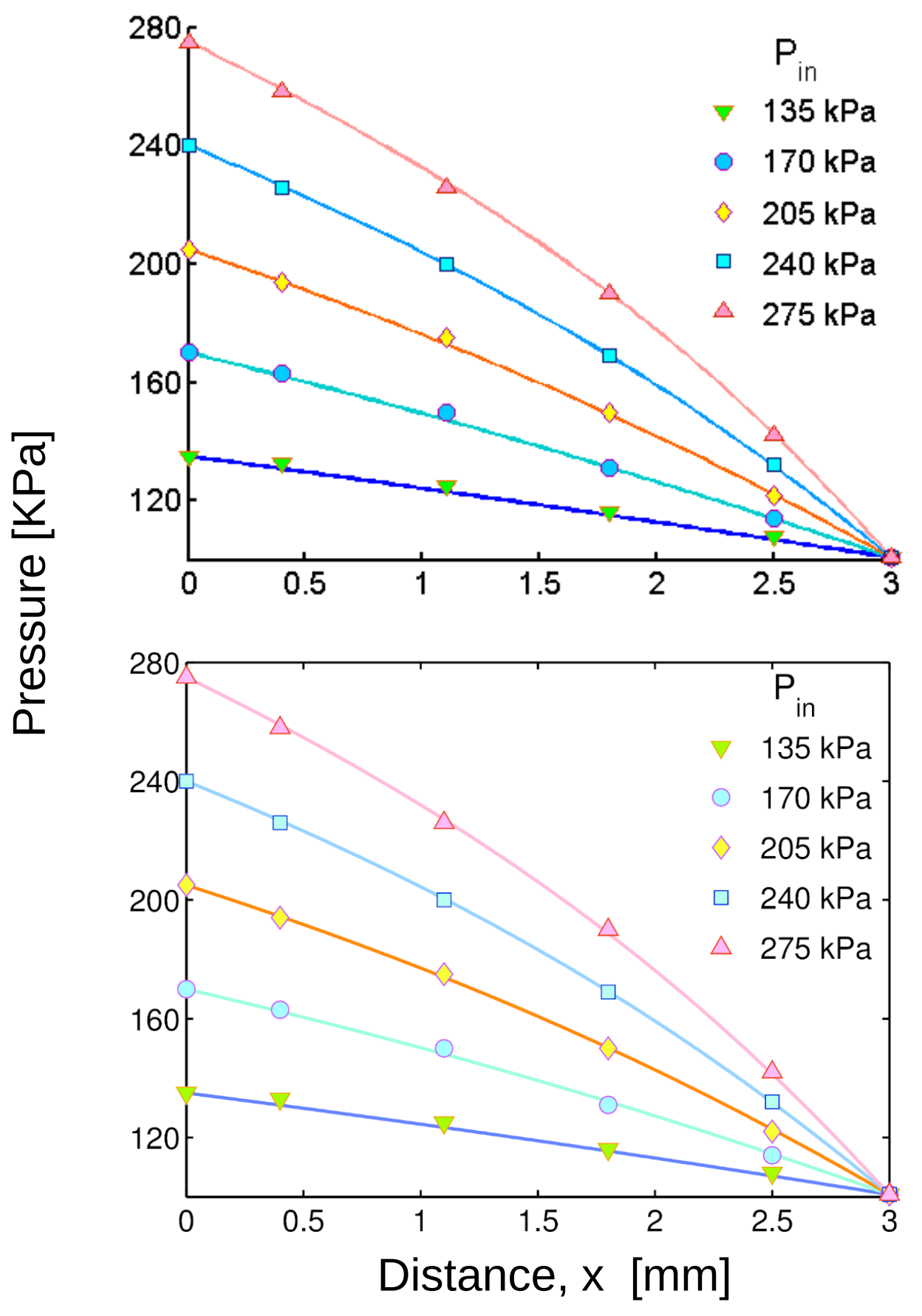
- Knudsen diffusion
- Slip flow
- Transition flow
- Continuum flow
- Adsorption and desorption from rock material

These are characterized by the Knudsen number *Kn* = mean free path/pore radius

The Forchchiemer's correction for high velocity is included.

All model parameters and their associated compressibility coefficients are functions of the pressure, *f= f(p),* $\xi_f = \xi_f(p)$.

Results: A. Determining rock properties



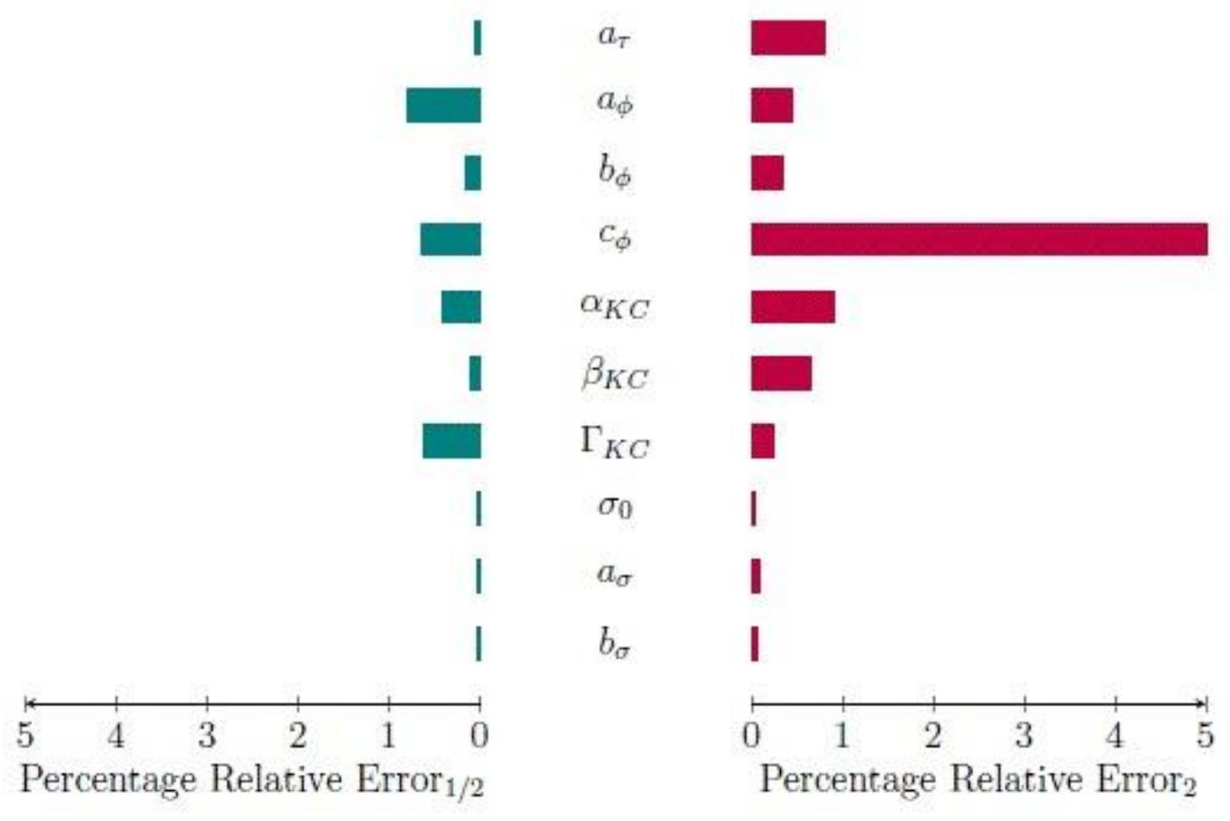
Experimental data (symbols) from pressure pulse tests in a shale rock core sample of length 3mm, from Pong [5], was matched from simulations (solid lines) using the new transport model developed here. The data is in the form of pressure measurements at various stations along the core sample, for different inflow pressures $\boldsymbol{P_{in}}$ as shown on the figures, left. The steady-state model was used in this case. The model parameters were adjusted until the error between simulations and data were minimized.

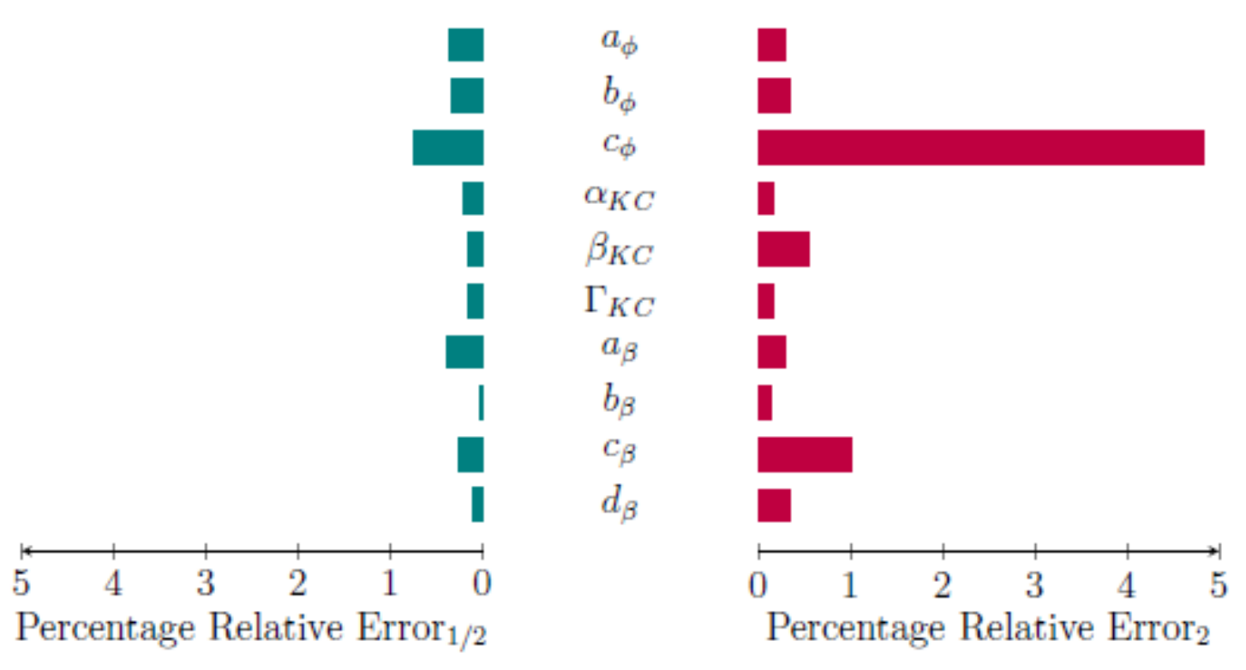
Fig. 1 (Top). Best fit model using steady-state transport model without turbulence correction, $\beta = 0$. The porosity is $\phi \approx 20\%$, and permeability is $K \approx 10^6\, nD$. These are very large, but comparable to Civan's model [6,7] results.

Fig. 2 (Bottom). Best fit model using steady-state transport model with turbulence correction, $\beta \neq 0$. The porosity is $\phi \approx 10\%$, and permeability is $K \approx 100\, nD$. These are much more realistic of shale rocks than from previous models, such as Civan's model [6,7].

This illustrates the importance of including high velocity correction term in the model.

Results: B. Sensitivity analysis of model parameters





To determine the most critical and most insensitive model parameters, a One-At-a-Time sensitivity analysis was carried out on all model parameters. In OAT, starting from a base set of model parameter values, each model parameter in turn is multiplied first by 2 and then by ½ and the simulations re-run. The change in error between simulation and data is displayed as a percentage for each parameter.

The simulations for the lowest P_{in} = 135 KPa were found to be insensitive to variations in model parameters. The results below are of the highest P_{in} = 275 KPa.

Fig. 3 (Top). OAT sensitivity analysis using steady-state transport model without turbulence correction, $\beta = 0$. Only C_ϕ shows critical sensitivity. (C_ϕ is a parameter that appears as a power in the correlation for the porosity.) All other parameters are weak to moderately sensitive.

Fig. 4 (Bottom). OAT sensitivity analysis using steady-state transport model with turbulence correction, $\beta \neq 0$. Again Only C_ϕ shows critical sensitivity. All other parameters are weak to moderately sensitive. Importantly, except for C_ϕ, there is no clear pattern compared to Fig. 3.

Conclusions

- A new nonlinear shale gas transport model has been developed incorporating greater realism than previous studies, yielding more realistic values for rock properties than previous models.
- For optimal generality in application, all model parameters must be kept in the model as pressure dependent quantities. (Previous models of often neglected some parameters or made them constants.)
- To determine rock properties accurately, high values of P_{in} should be used in experiments.