UQ Centre for Natural Gas

Stress-dependent Gas-Water Two-phase Flow in Coal Cleats

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Introduction

Cleat characteristics, such as aperture and roughness, are critical for assessing coal seam gas well productivity. They affect both absolute permeability and relative permeability of coals. Significant challenges exist on the selection of coal relative permeability curve and understanding of its changes with the cleat characteristics. This work presents the effects of horizontal stress on the cleat deformation and two-phase transport phenomena in coal cleat network. A discrete fracture network was first built to reproduce the realistic cleat network pattern[1]. An improved experimental approach was developed to measure the cleat compressibility C_f directly using high precision non-contact video extensometer, which was then validated by triaxial permeability experiments as well as comparing with the data available in the literature. Given a horizontal stress, the obtained C_f was adopted to analyze the aperture variation in face and butt cleats. The direct simulations based on the lattice Boltzmann method are conducted on cleat-system realizations with varying apertures, to evaluate the liquid distribution, relative permeability and capillary pressure at varied saturation. The relationship between horizontal stress, cleat aperture and relative permeability was established, and the correlation was further fitted by the van Genuchten-based relative permeability model. The tortuosity index is found to be well linearly correlated to the cleat aperture. The developed framework facilitates the evaluation of cleat compressibility and builds the relationship between cleat aperture and coal relative permeability, which is useful in assessing the coal petrophysical properties at core scale.

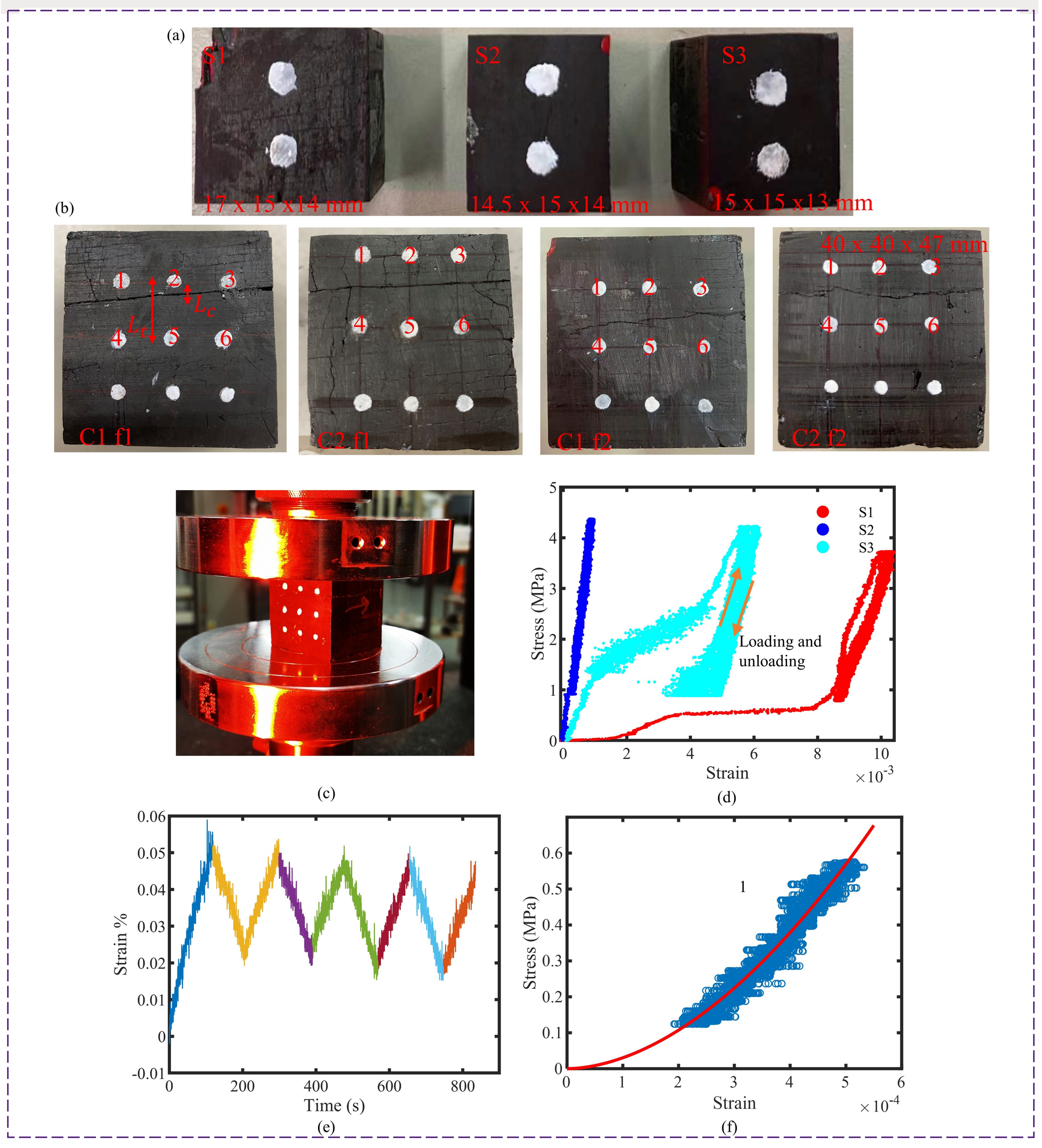

Figure 1: (a) Coal matrix; (b) Cleated coal. (c) Experimental setup for mechanically measuring the cleat compressibility through relevant movement of white dots. (d)-(f) typical loading curves.

Method

The coal samples are taken from Goonyella Middle Seam in Bowen Basin (Australia) and cut to the desired dimensions using the diamond wire saw. Three small coal cubic samples, named S1, S2 and S3 as shown in Fig. 1(a), were prepared for measuring the elastic modulus of the coal matrix. This is to assess the intact coal properties without the effect of cleats, which will be used later to interpret C_f. To assess the cleat impacts, two new cleated coal samples of 40 mm cubes, named C1 and C2, were machined, as illustrated in Fig. 1(b).

The uniaxial compression tests were carried out on Instron machine 5900R-5584. The principle of advanced video extensometer (AVE) is to detect the variation of gauge length between marked points (see Fig. 1(c)) using the high-resolution digital camera. For the coal matrix, the gauge length refers to the distance between two white points, as shown in Fig. 1(a), while the gauge length for cleated samples is the distance between white point 1 and 4, point 2 and 5 as well as point 3 and 6, illustrated in Fig. 1(b), to measure the deformation near the visible cleats.

The loading/unloading rate was set up to be 450 N/min in the direction perpendicular to the face cleats, and four loading and unloading cycles were applied between 200 N and 950 N. The variation of gauge length was measured from AVE simultaneously and recorded along with the applied axial force, to determine the elastic modulus for both intact and cleated coals. The obtained cleat compressibility is used to simulate the aperture variation under increasing stress.

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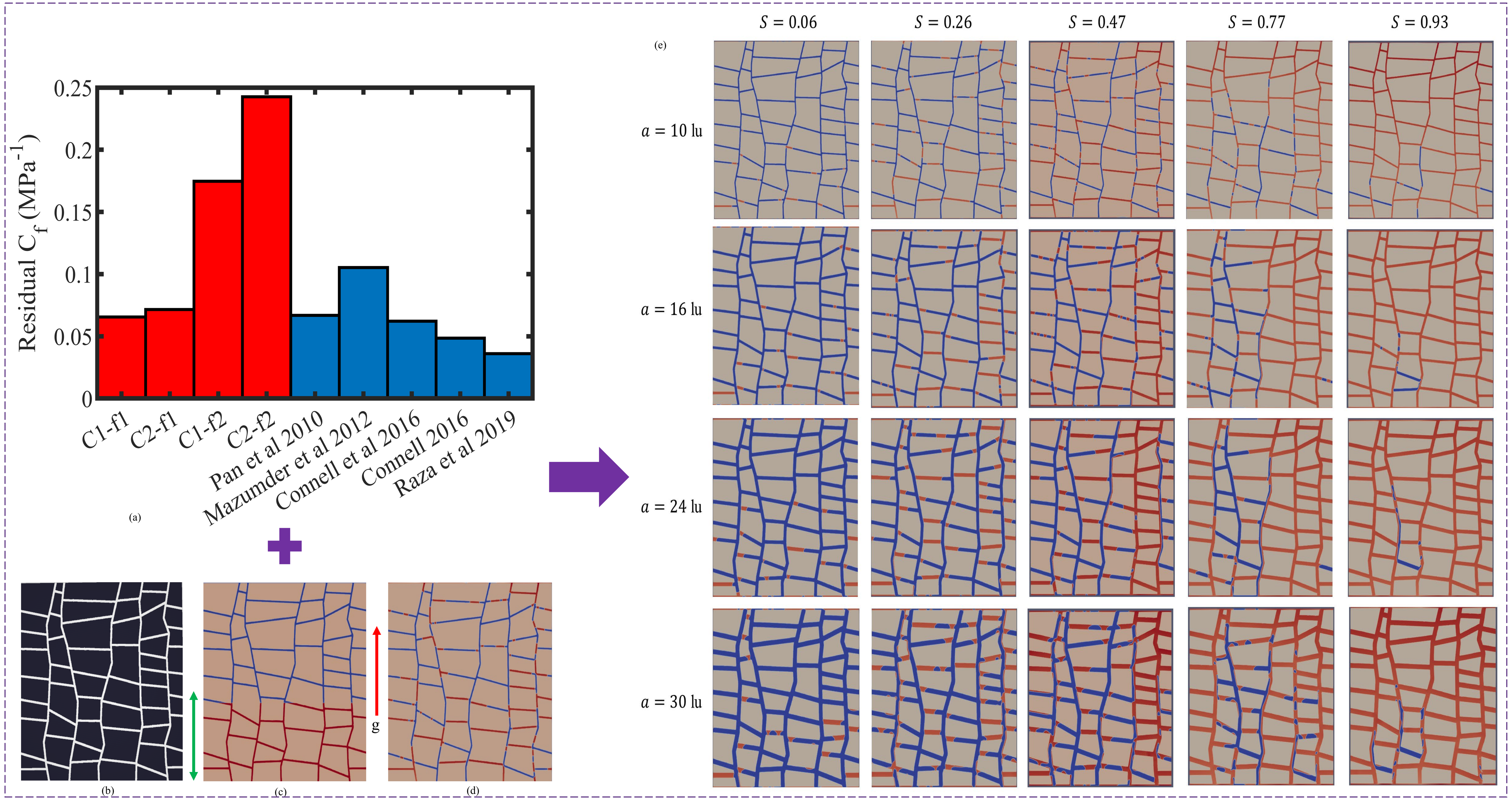

Figure 2: (a) Comparison with other reported cleat compressibility. (b) Generated square cleat network with the side length of 10 mm. (c) Initial configuration in the lattice Boltzmann simulation. (d) Final liquid distribution under gravity g. The height of liquid phase id modified to reflect varying saturation. (e) Snaps of liquid distribution with different aperture size at increasing saturation The suffix of f represents the face. The red, blue and brown colours represent the liquid, gas and coal matrix boundary, respectively.

The Shan-Chen lattice Boltzmann method with D2Q9 lattice is then employed to solve for gas-liquid flow in generated cleat networks with different apertures. The contact angle is set up to be 45 degree.

Results

Coal compressibility calculation

Fig. 1(d) summarizes the stress-strain curves for each tested specimen, and the elastic modulus of coal matrix E_m is derived and averaged from the slope of linear fitting for four unloading curves, with $E_m = 3254$ MPa. The cleated coal cubic samples are then under the compression experiments. The gauge length is selected between an obvious fracture, as shown in Fig. 1(b). Three measurements are conducted for each sample, between white point 1 and 4, point 2 and 5 as well as point 3 and 6. The variation of gauge length under vertical load is captured by the AVE. A typical strain variation as a function of time for the sample C1-f1 is plotted in Fig. 1(e), with the exponential fitting of the first part, as seen in Fig. 1(f). The elastic modulus at each strain point can be derived from the first derivative of the fitted exponential equation. Given the elastic modulus of coal matrix E_m in MPa, the cleat elastic modulus E_{cleat} is then computed as

$$\frac{\sigma}{E_{\text{cleat}}} \cdot L_c + \frac{\sigma}{E_m} \cdot (L_t - L_c) = \Delta L_t$$

The cleat compressibility C_f is therefore given as

$$C_f = \frac{1}{K} = \frac{3(1-2\upsilon)}{E_c}$$

where K and υ denote the bulk modulus and Poisson's ratio, respectively. Fig. 2 (a) summarizes the calculated cleat compressibility in comparison with values reported by other researchers.

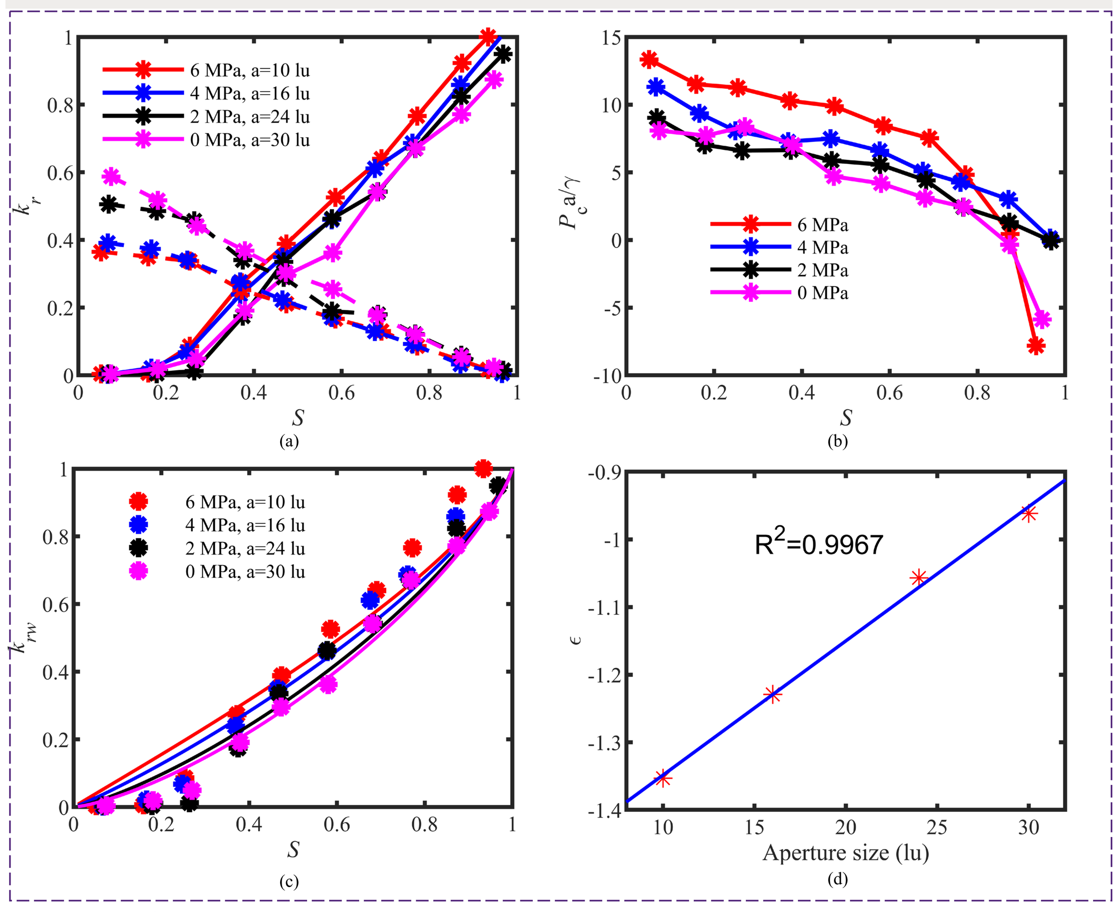

Figure 3: (a) relative permeability and (b) capillary pressure curves under increasing stress. (c) liquid relative permeability fitted using van Genuchten model. (d) linear fitting between ϵ and aperture size.

Acknowledgements

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Relative permeability of coal

The relative permeability and capillary curves for the cleat network under a range of horizontal stresses from 0 to 6 MPa are plotted in Fig. 3(a) and (b), respectively. There are many available models to describe the relative permeability, e.g., Brooks-Corey and van Genuchten-based models. The Brooks model defines the relationship between relative permeability and saturation through a single pore-distribution parameter, which is incompetent in some cases. The van Genuchten equation is another widely recognized approach and can be analytically embedded in the Mualem's relative permeability model:

$$k_{rw} = S^{\epsilon}(1-(1-S^{1/m})^m)^2$$

where m is the van Genuchten parameter related to the pore-size distribution, ϵ represents the link between pore space and flow path tortuosity and can be negative, zero or positive.

With the aperture change, the microscale flow behaves differently, as shown in Fig. 2(e), revealing that ϵ is highly dependent on the aperture. The fitted results are shown in Fig. 3 (c) and obtained ϵ are further found to be linearly correlated to aperture size with the slope, intercept and R^2 of 0.01984, -1.547 and 0.9967, respectively, as demonstrated in Fig. 3(d). Using the proposed correlation between the aperture and tortuosity index ϵ, the relative permeability curves can now be estimated for a given cleat network.

Conclusions

- We develop a robust framework to study the stress-dependent two-phase flow in coal cleat systems via a combination of experimental and numerical approaches.
- The directly measured cleat compressibility is found to be consistent with available literature values. This independent measurement is advantageous in terms of accuracy and time-cost, in contrast to the traditional way of fitting permeability values across different confining pressure.
- The multiphase lattice Boltzmann method is adopted to model gas-liquid flow in cleat networks with varying apertures. It is observed that the relative permeability and capillary pressure curves shift leftward and upward with decreasing cleat aperture.
- Through the fitting using the van Genuchten-based relative permeability model, the linear correlation is identified between the tortuosity index and the cleat aperture.

References

1 Jing, Y., Armstrong, R. T., Ramandi, H. L., & Mostaghimi, P. (2016). Coal cleat reconstruction using micro-computed tomography imaging. *Fuel, 181*, 286–299. https://doi.org/10.1016/j.fuel.2016.04.127

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