Analyzing slippage coefficients and intrinsic permeabilities of dissimilar Indian coals considering their pore-size distributions: implications to CO2 storage in coal seams

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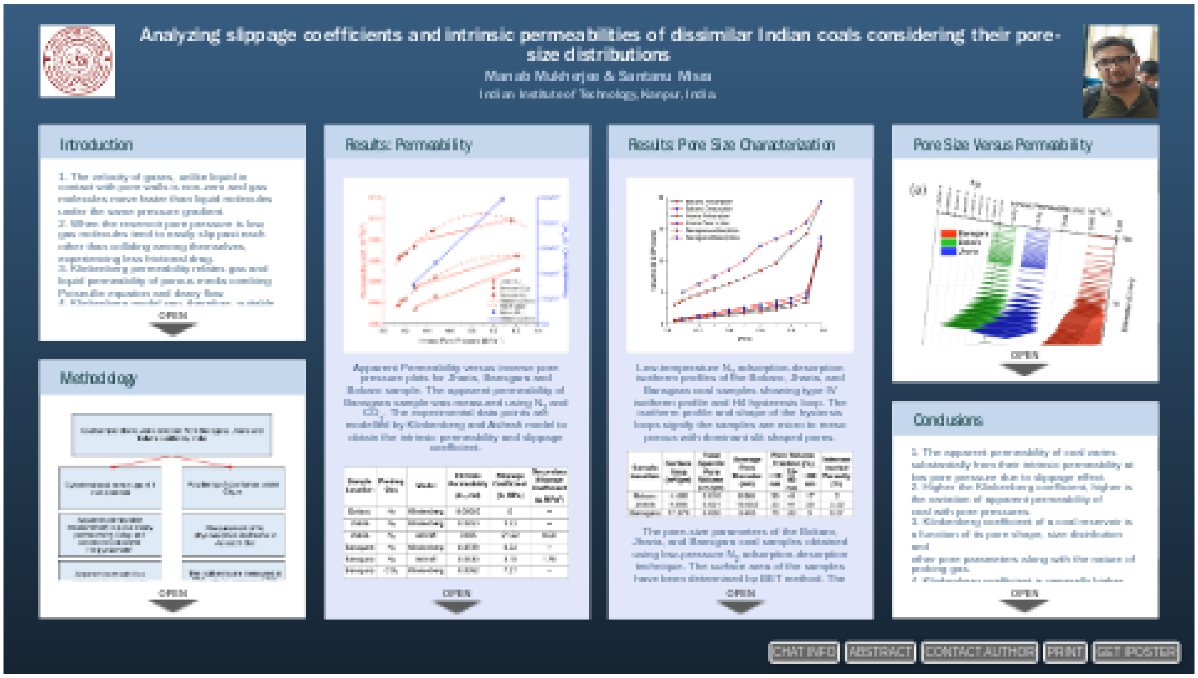
Abstract

Gas transport in dominantly microporous rocks such as coal, shale is significantly controlled by Klinkenberg or slippage effect at low reservoir pressures. Pore size fractions of the concerned reservoir rock control the degree of Klingenberg effect. This study tries to assess the differences in Klinkenberg effect in dissimilar coals owing to their difference in pore-size distributions. We report apparent permeabilities of three Gondowana coal samples from the Bokaro, Jharia, and Bansgara coalfields at room temperature and constant isostatic stress (6.2 MPa). The linear plots of apparent permeability versus inverse pore pressure were modelled using the Klinkenberg equation, and non-linear plots by the Ashrafi equation to determine the slippage coefficient and intrinsic permeabilities. Ashrafi model reports lower values of slippage corrected permeability compared to the Klinkenberg model. The slippage coefficient and intrinsic permeability obtained from N2 and CO2 is different for the Bansgara sample. The trends between transport parameters and pore-size parameters were examined. The slippage coefficient decreased with interconnected porosity and total specific pore volume. Intrinsic permeabilities showed an opposite trend to that of the slippage coefficient. The Bansgara sample having larger volumetric proportion of micropores in the pore volume gamut with open ended interconnected pore network resulted in the lowest slippage coefficient and highest intrinsic permeabiliity. Reporting the slippage coefficients and intrinsic permeabilities with corresponding pore size distributions of coal samples from different global basins will lead to statistically significant empirical relationships between pore size parameters and slippage coefficients.

Analyzing slippage coefficients and intrinsic permeabilities of dissimilar Indian coals considering their pore-size distributions



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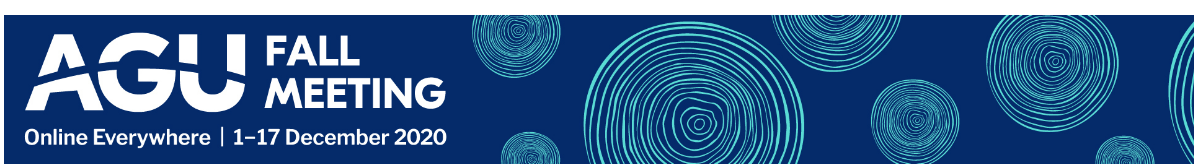
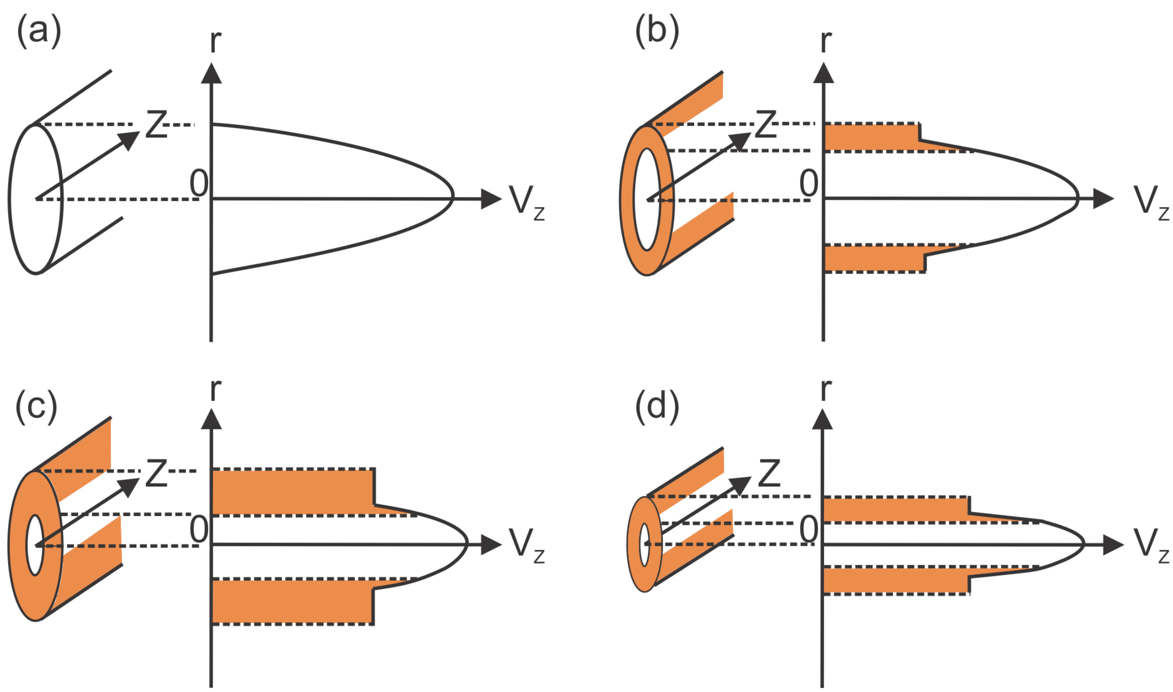


INTRODUCTION

1. The velocity of gases, unlike liquid in contact with pore walls is non-zero and gas molecules move faster than liquid molecules under the same pressure gradient.
2. When the reservoir pore pressure is low, gas molecules tend to easily slip past each other than colliding among themselves, experiencing less frictional drag.
3. Klinkenberg permeability relates gas and liquid permeability of porous media combing Poiseullie equation and darcy flow.
4. Klinkenberg model can, therefore, suitable to predict the apparent permeability of the depleted low pressure reservoirs.

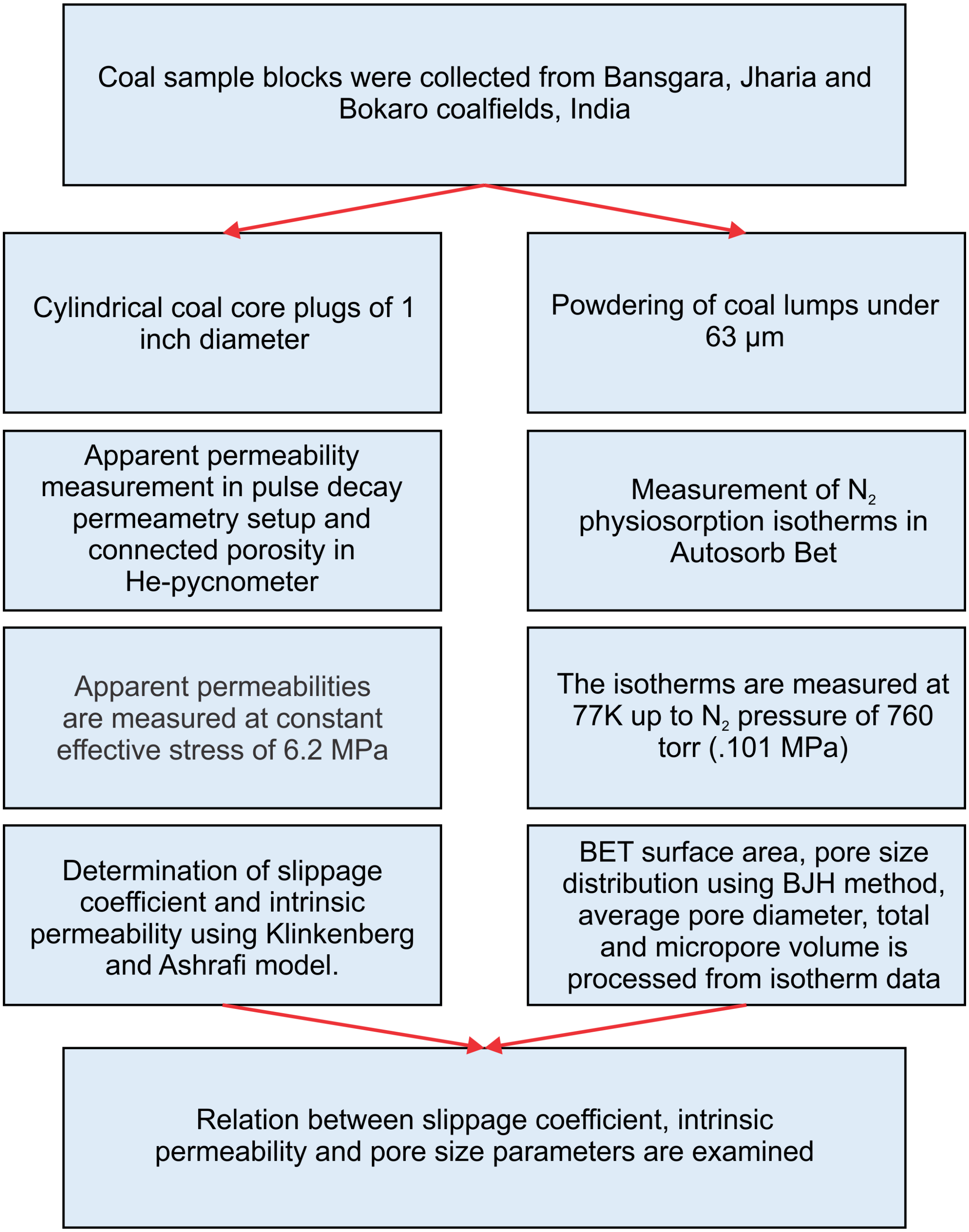


Velocity profile of fluid through capilary tubes. Orange shaded area represents the zone of slippage. Modified from Bravo, 2007 (http://10.1063/1.2786613).

Objectives

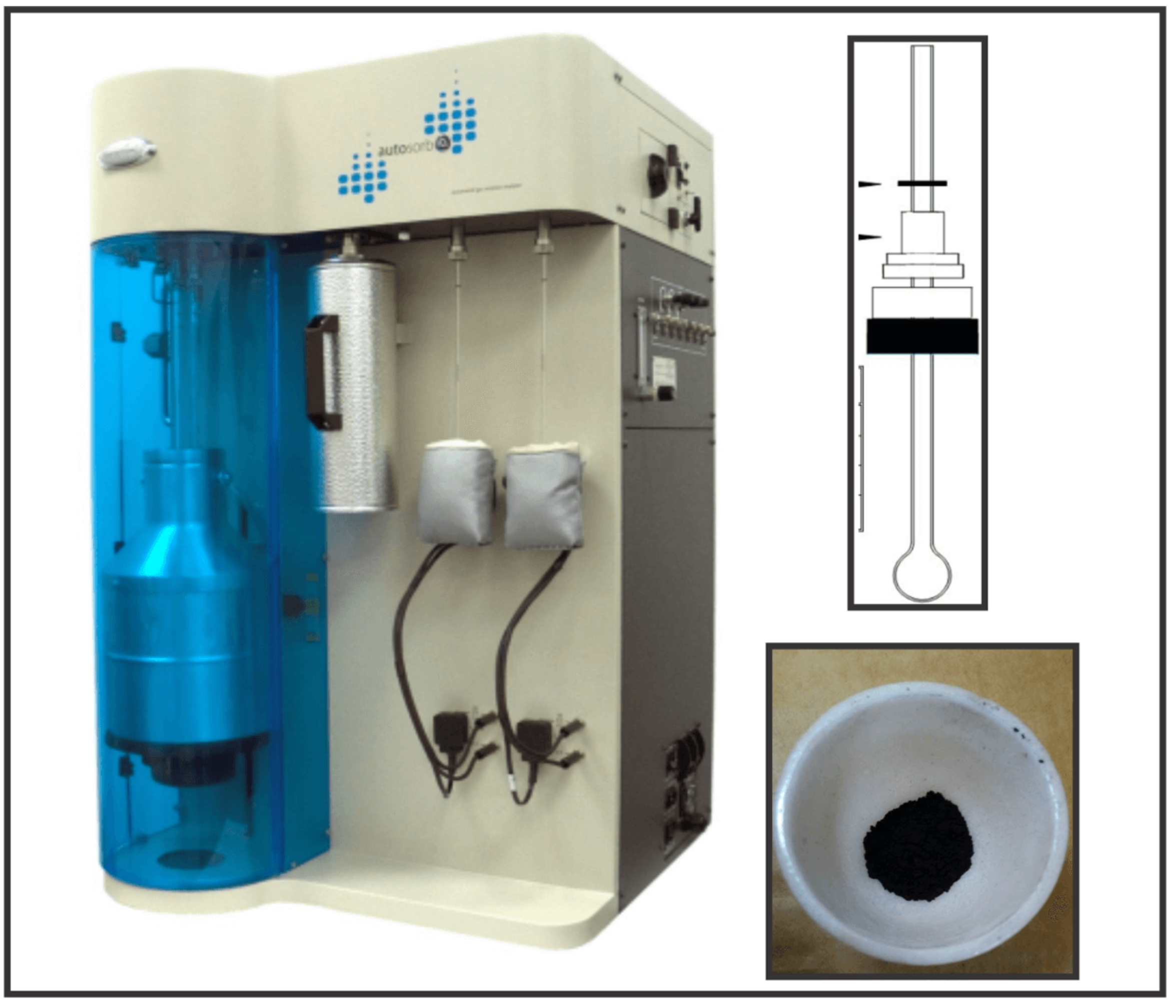
1. Apparent permeability variation of Bokaro, Jharia and Bansgara coal samples from India, using N_2 and CO_2 as probing gas.
2. Determination of BET surface area, BJH mesopore volume, average geometric pore diameter, micropore volume of the Bokaro, Jharia and Bansgara samples.
3. Determination of Klinkenberg coefficient and intrinsic permeability of the samples.
4. Evaluate the relationship between Klinkenberg coefficient and corresponding pore size parameters.

METHODOLOGY



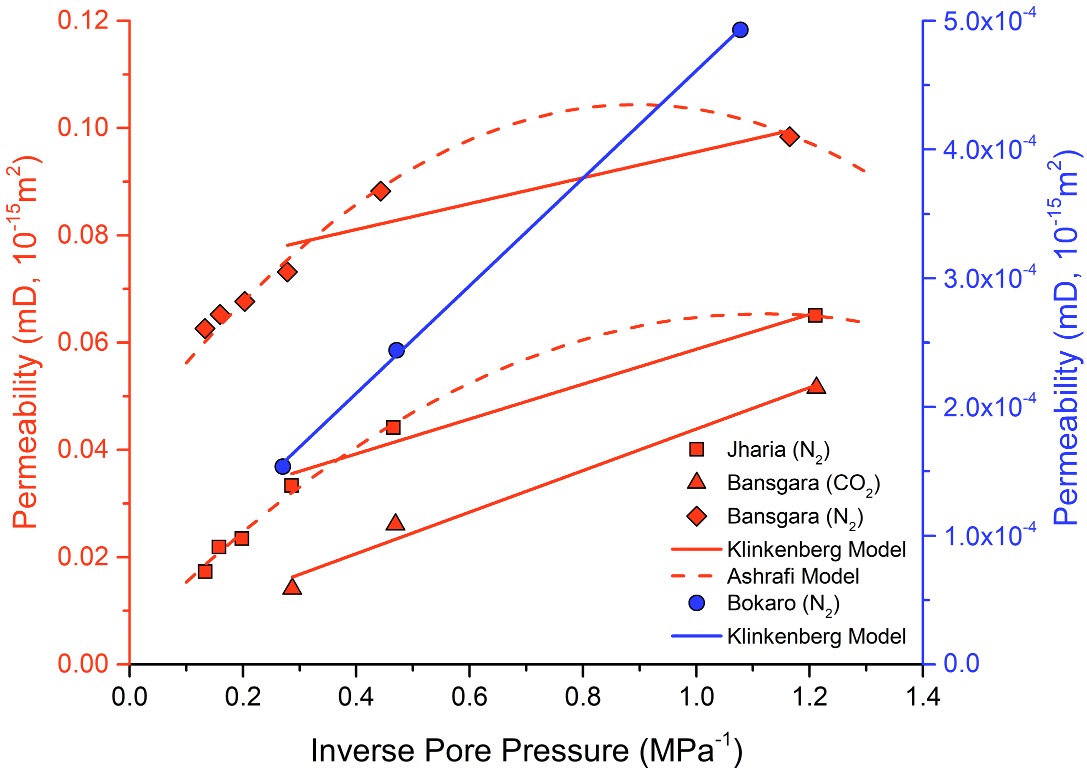
Schematic illustration of the workflow

Pulse decay permeameter for gas permeability measurement. Coal cores used for measurement is in the inset.



N_2 physiosorption instrument Autosorb BET with its sample cell assembly and coal powders user for measurement.

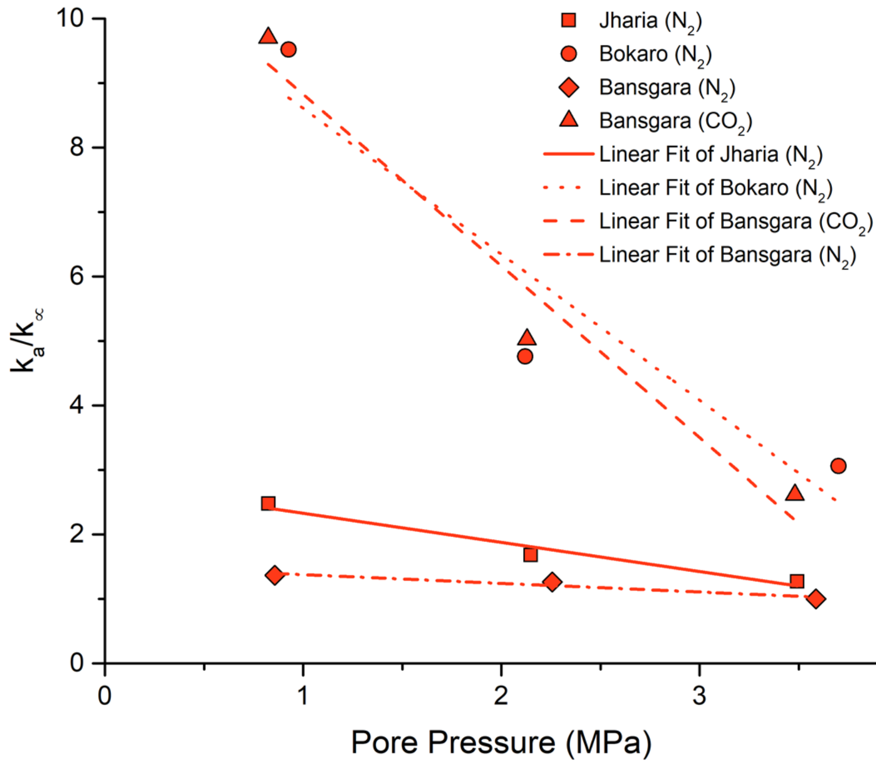
RESULTS: PERMEABILITY



Apparent Permeability versus inverse pore pressure plots for Jharia, Bansgara and Bokaro sample. The apparent permeability of Bansgara sample was measured using N_2 and CO_2. The experimental data points are modelled by Klinkenberg and Ashrafi model to obtain the intrinsic permeability and slippage coefficient.

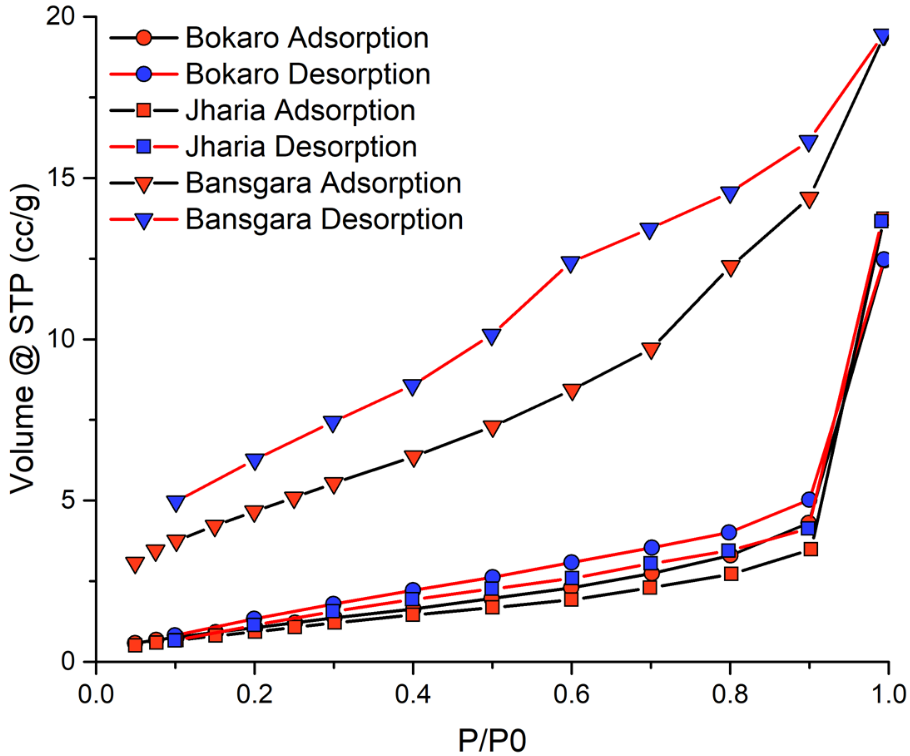
Sample Location	**Probing Gas**	**Model**	**Intrinsic Permeability (k_∞, md)**	**Slippage Coefficient (*b*, MPa)**	**Secondary Slippage Coefficient (a, MPa²)**
Bokaro	N_2	Klinkenberg	0.00005	8	--
Jharia	N_2	Klinkenberg	0.0263	1.23	--
Jharia	N_2	Ashrafi	0.005	21.62	9.68
Bansgara	N_2	Klinkenberg	0.0729	0.33	--
Bansgara	N_2	Ashrafi	0.0433	3.15	1.76
Bansgara	CO_2	Klinkenberg	0.0052	7.27	--

The model parameters obtained from fitting the apparent permeability versus inverse pore pressure plots of the Bokaro, Jharia, and Bansgara coal samples with Klinkenberg and Ashrafi model. The secondary slippage factor is only applicable to the Ashrafi model and not to the Klinkenberg model.



The variation of apparent is to intrinsic permeability ratio for the three samples with pore pressure. The ratio follows a linear trend with pore pressure. The Bansgara samples have been examined using both N_2 and CO_2 as probing gasses. Higher slope of the linear trend indicate that apparent permeability is significantly modified by slippage effect.

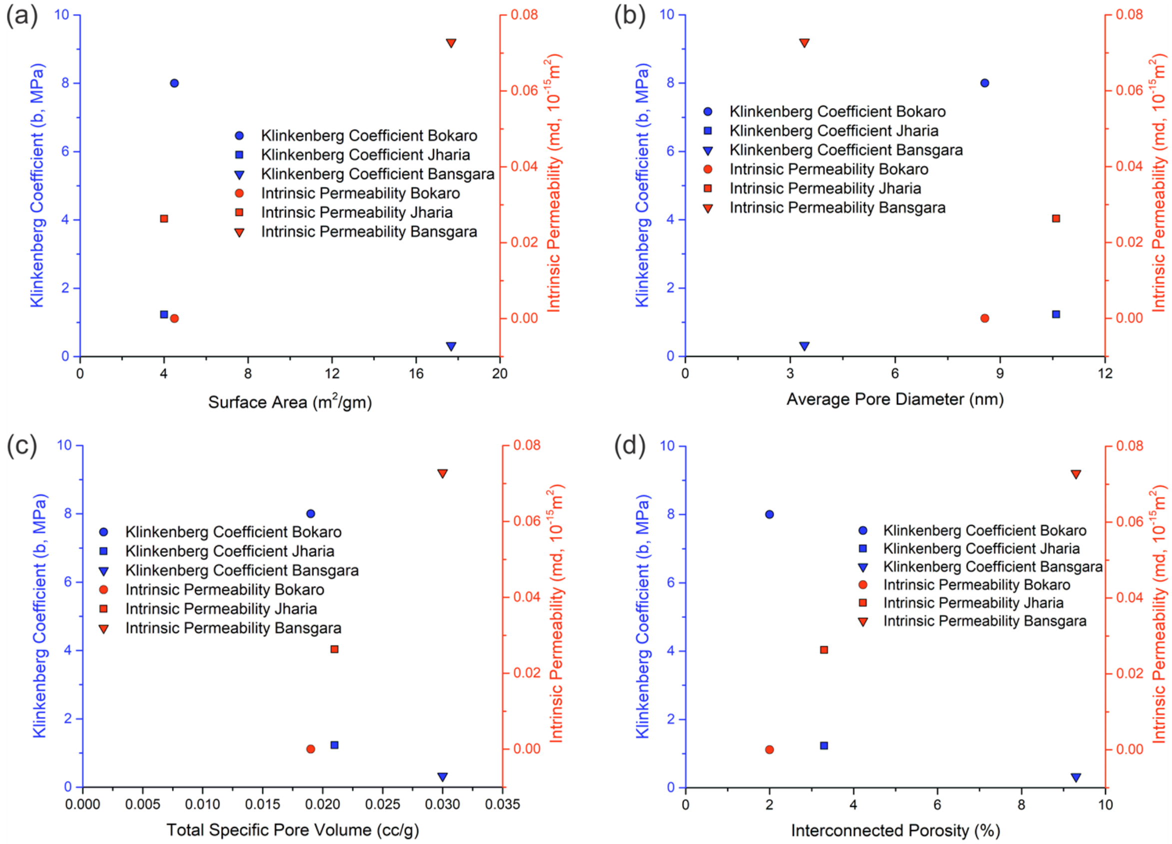
RESULTS: PORE SIZE CHARACTERIZATION



Low-temperature N_2 adsorption-desorption isotherm profiles of the Bokaro, Jharia, and Bansgara coal samples showing type IV isotherm profile and H4 hysteresis loop. The isotherm profile and shape of the hystersis loops signify the samples are micro to meso porous with dominant slit shaped pores.

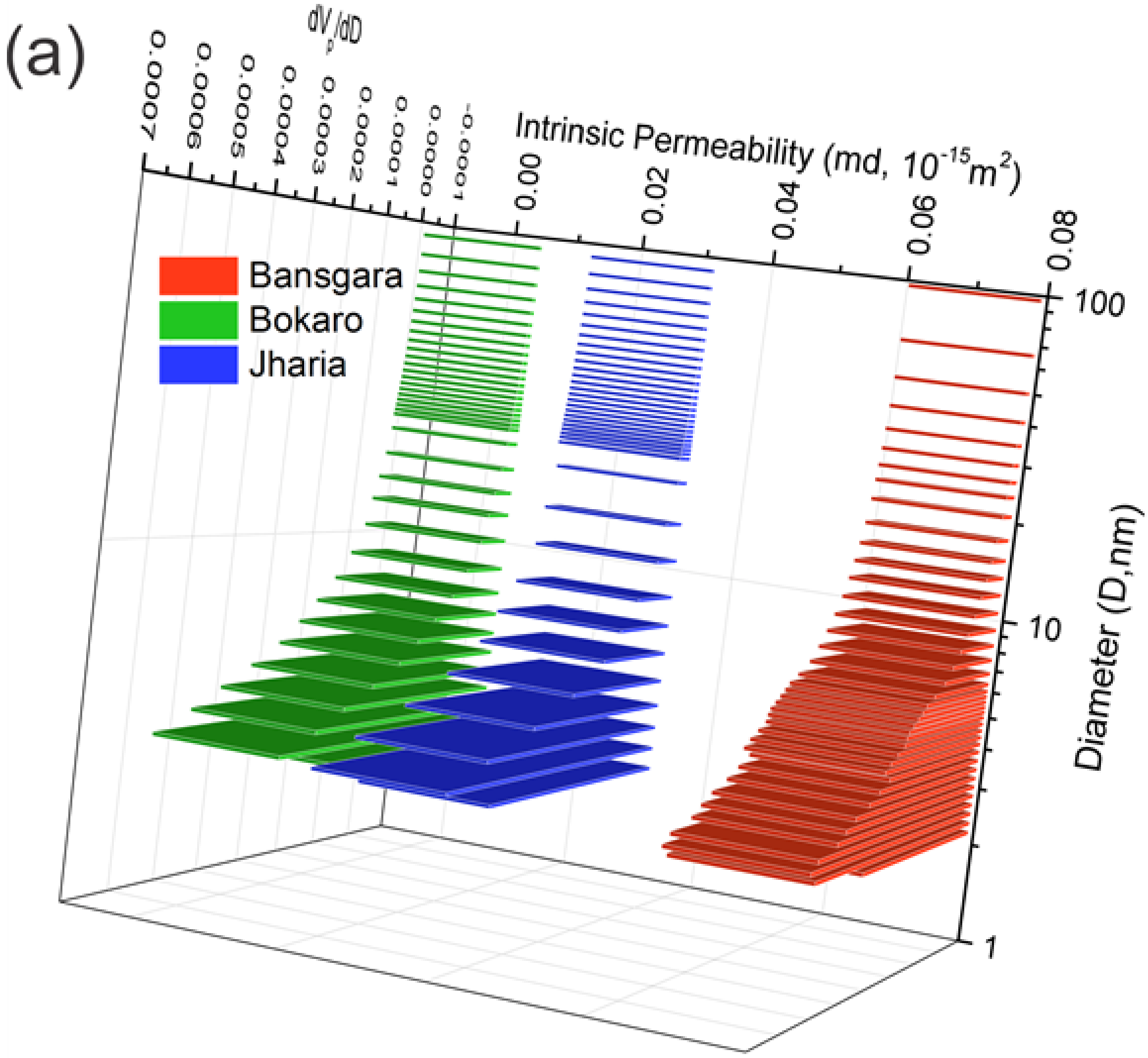
Sample Location	Surface Area (m^2/gm)	Total Specific Pore Volume (cc/gm)	Average Pore Diameter (nm)	Pore Volume Fraction (%)			Interconnected Porosity (%)
				<10 nm	10-50 nm	>50 nm	
Bokaro	4.495	0.019	8.564	39	44	17	2
Jharia	4.006	0.021	10.602	33	47	20	3.32
Bansgara	17.676	0.030	3.403	75	20	5	9.37

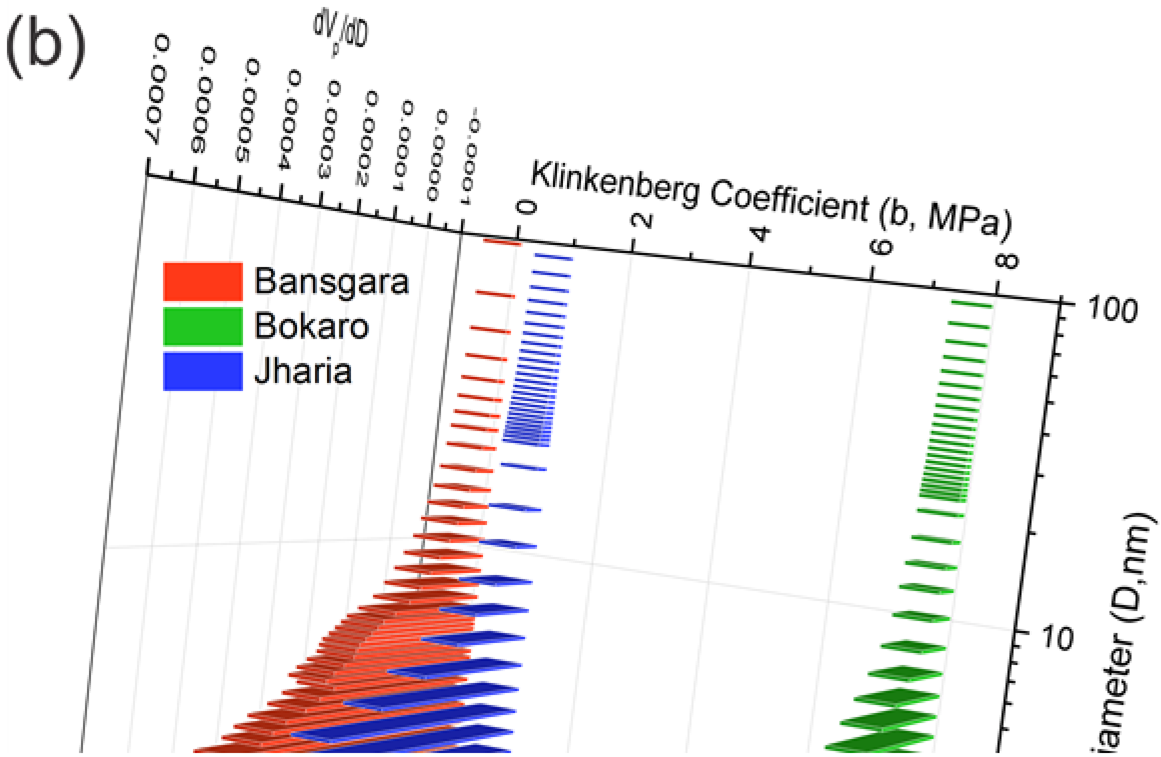
The pore-size parameters of the Bokaro, Jharia, and Bansgara coal samples obtained using low-pressure N_2 adsorption-desorption technique. The surface area of the samples have been determined by BET method. The pore volume fractions are determined using the data from desorption branch and adopting BJH method. The porosity of the samples has been measured separately using a Helium gas pycnometer.

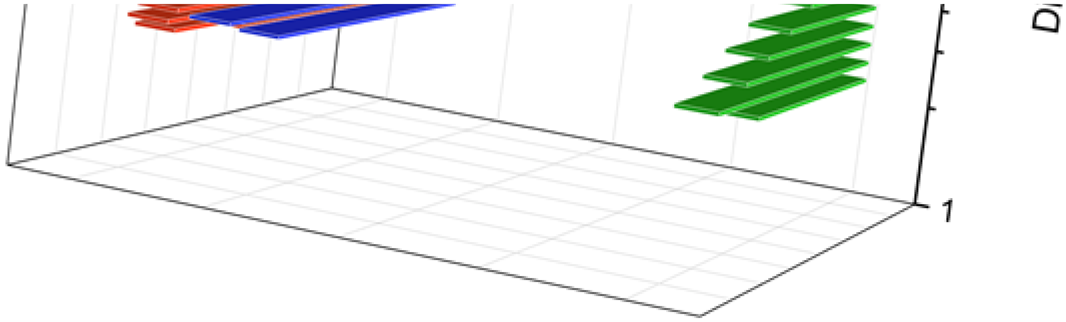


Cross plots of the intrinsic permeability and slippage coefficient of the Bokaro, Jharia, and Bansgara coal samples estimated from Klinkenberg model using N_2 as a probing gas with a) surface area b) average pore diameter c) total pore volume d) interconnected porosity. Interconnected porosity is determined in a gas pycnometer, while the other pore size variables are computed from low-temperature N_2 adsorption-desorption isotherms. Intrinsic permeability increases with total specific pore volume and intercoonected porosity. Slippage coefficient decreases with increase in total pore volume and interconnected porosity. Surface area, average pore diameter donot show any specific trend with either of slippage coefficient and intrinsic permeability.

PORE SIZE VERSUS PERMEABILITY







Pore-size distributions (relative abundance of a particular pore-size fraction) of the Bokaro, Jharia, and Bansgara coal samples with corresponding a) intrinsic permeability b) slippage coefficient. The intrinsic permeability and the slippage coefficients of the samples are estimated from the Klinkenberg model using N2 as a probing fluid. The pore size distribution of Jharia and Bokaro is almost similar. Bansgara sample contains a high volume of micropores and shows the highest intrinsic permeability and lowest slippage coefficient.

CONCLUSIONS

1. The apparent permeability of coal varies substantially from their intrinsic permeability at low pore pressure due to slippage effect.
2. Higher the Klinkenberg coefficient, higher is the variation of apparent permeability of coal with pore pressures.
3. Klinkenberg coefficient of a coal reservoir is a function of its pore shape, size distribution and other pore parameters along with the nature of probing gas.
4. Klinkenberg coefficient is generally higher for a adsorptive gas CO_2 as compared with a non adsorptive gas of N_2.
5. Klinkenberg coefficient is lowest for the Bansgara sample which possess the highest volumetric proportion of micropores.
6. Klinkenberg coefficient shows a negative trend with interconnected porosity and total pore volume while intrinsic permeability shows a positive trend with porosity and pore volume.

Acknowledgements

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ABSTRACT

Gas transport in dominantly microporous rocks such as coal, shale is significantly controlled by Klinkenberg or slippage effect at low reservoir pressures. Pore size fractions of the concerned reservoir rock control the degree of Klingenberg effect. This study tries to assess the differences in Klinkenberg effect in dissimilar coals owing to their difference in pore-size distributions. We report apparent permeabilities of three Gondowana coal samples from the Bokaro, Jharia, and Bansgara coalfields at room temperature and constant isostatic stress (6.2 MPa). The linear plots of apparent permeability versus inverse pore pressure were modelled using the Klinkenberg equation, and non-linear plots by the Ashrafi equation to determine the slippage coefficient and intrinsic permeabilities. Ashrafi model reports lower values of slippage corrected permeability compared to the Klinkenberg model. The slippage coefficient and intrinsic permeability obtained from N_2 and CO_2 is different for the Bansgara sample. The trends between transport parameters and pore-size parameters were examined. The slippage coefficient decreased with interconnected porosity and total specific pore volume. Intrinsic permeabilities showed an opposite trend to that of the slippage coefficient. The Bansgara sample having larger volumetric proportion of micropores in the pore volume gamut with open ended interconnected pore network resulted in the lowest slippage coefficient and highest intrinsic permeability. Reporting the slippage coefficients and intrinsic permeabilities with corresponding pore size distributions of coal samples from different global basins will lead to statistically significant empirical relationships between pore size parameters and slippage coefficients.