Developing a Novel Ultrafine Coal Dewatering Process (04-VaT-P1-32: Coal Beneficiation)

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University Coalition for Fossil Energy Research

2020 Virtual Annual Technical Review Meeting Host: National Energy Technology Laboratory

10/05/2021





Outline

- Background and motivation
- Project goal, proposed approach, and advantages
- Methods
- Results
 - Solvent recovery by filtration
 - Solvent recovery by drying
- Conclusions

Background

Dewatering fine coal is important for both coal beneficiation and the environment

> 70-90 million tons of fine coal tailings discarded each year in the US



- Dewatering by mechanical means has reached its limit
- Dewatering by thermal drying is energy-intensive
 - One of the most energy-intensive processes in industry due to the high enthalpy cost of phase change (Mujumdar and Wu, 2007)

HHS Technology

□ Hydrophobic-Hydrophilic Separation (HHS)



	Boiling	Heat of Vaporization	
Liquid	Point ¹ (°C)	kJ/mole ²	kJ/kg
Water (H ₂ O)	100.0	40.7	2,257
Butane (C_4H_{10})	-0.5	22.4	386
Pentane (C_5H_{12})	36.1	25.8	358
Hexane (C_6H_{14})	68.7	28.9	336
Heptane (C ₇ H ₁₆)	98.4	31.7	317





Solvent Recovery

Results Obtained with a Sub-bituminous Coal

Particle Size	Moisture	Ash	Heat Value
(mm)	(%wt)	(%wt)	(Btu/lb)
0.350	3.20	9.92	10,827
0.600	3.20	9.82	11,019
1.180	2.87	8.4	11,216
6.300	2.30	6.27	11,529



Solvent recovery is essential for the economic operation of HHS

- Low solvent loss (<~1400 ppm solvent in coal product or 0.56 gallon/ton coal)
- Low equipment/capital cost
- Low operation cost

Goal and Approach

- **Goal:** to develop an efficient solvent recovery system for the HHS process
- Approach in-situ recovery combining filtration and drying
 - recover the bulk of solvents by pressure filtration
 - recover the small amount of residual solvents by *in-situ* evaporation



stage 1: liquid-solid separation

stage 2: evaporative recovery

Key advantages

- Only a small fraction of solvents is removed through phase change
 → energy efficient
- A single device is used in separation and drying → low equipment cost

Methods – Physical Modeling

Solvent vaporization and removal by a carrier gas



Underlying physics

- Thermal transport
- Liquid solvent evaporation
- Transport of multi-component gas mixtures

Pore-scale model



Gas transport model

Dusty gas model:
$$\sum_{\substack{j=1\\j\neq i}}^{n} \frac{x_{j}J_{i}-x_{i}J_{j}}{\rho_{t}D_{ij}} + \frac{J_{i}}{\rho_{t}D_{ik}} = -\frac{1}{p}\frac{dp_{i}}{dz} - \frac{x_{i}k_{p}}{\mu}\frac{dp}{dz} \quad (i = 1, 2, ..., n)$$
$$J_{1} = \rho_{1}u_{1} = -\left(\left(\frac{x_{1}D_{2k}D_{1k}+D_{12}D_{1k}}{x_{2}D_{1k}+x_{1}D_{2k}+D_{12}} + \frac{k_{p}\rho_{1}R_{g}T}{\mu}\right)\frac{d\rho_{1}}{dz} + \left(\frac{x_{1}D_{2k}D_{1k}}{x_{2}D_{1k}+x_{1}D_{2k}+D_{12}} + \frac{k_{p}\rho_{1}R_{g}T}{\mu}\right)\frac{d\rho_{2}}{dz}\right)$$
$$J_{2} = \rho_{2}u_{2} = -\left(\left(\frac{x_{2}D_{2k}D_{1k}}{x_{2}D_{1k}+x_{1}D_{2k}+D_{12}} + \frac{k_{p}\rho_{2}R_{g}T}{\mu}\right)\frac{d\rho_{1}}{dz} + \left(\frac{x_{2}D_{2k}D_{1k}+D_{12}D_{2k}}{x_{2}D_{1k}+x_{1}D_{2k}+D_{12}} + \frac{k_{p}\rho_{2}R_{g}T}{\mu}\right)\frac{d\rho_{2}}{dz}\right)$$

Effective permeability (with slippage effect): $k_p = \frac{r_0^2}{8}(1 + 4\text{Kn}(\frac{2}{\sigma_v} - 1))$

Knudsen diffusion: $D_{ik} = \frac{2r_0}{3} \sqrt{\frac{8k_BT}{\pi m_i}}$ (i = 1,2)

Mutual diffusion: $D_{12} = (D_{x_1 \to 1})^{x_1} (D_{x_1 \to 0})^{(1-x_1)}, D_{x_i \to 1} = \frac{2}{3} \frac{\sqrt{m_i k_B T / \pi}}{M_i \sigma_i \rho_i}$ (i = 1, 2)

Viscosity for mixture gas: $\mu = \frac{\mu_1}{1 + \frac{x_2 \cdot 1.385 \mu_1}{x_1 \cdot D_{12} \rho_1}} + \frac{\mu_2}{1 + \frac{x_1 \cdot 1.385 \mu_2}{x_2 \cdot D_{12} \rho_2}}$

Model Development

Evaporation and radial mass transfer

Limit of evaporation Kinetics(evaporation << diffusion):

Schrage equation
$$\dot{m_k} = \frac{2\hat{\sigma}}{2-\hat{\sigma}} \left(\frac{M_2}{2\pi R_g}\right)^{0.5} \left(\frac{p_{sat}}{\sqrt{T_i}} - \frac{p_2}{\sqrt{T_v}}\right)$$

 Limit of vapor transport (evaporation >> diffusion): Vapor diffusion *m*_t~*D*_s*M*₂(*ρ*_{sat} - *ρ*₂)/*r*₀
 Ratio: *m*_t/*m*_t ~ *2r*₀/*D*_s (*R*_g*T*/*D*_s)^{0.5} = 7.5 >> 1

Vapor diffusion is more rate-limiting than evaporation kinetics

Quasi-static condition at any cross section

$$\dot{m}_{evp} = \alpha(\rho_{sat} - \rho_2) \qquad \alpha = Sh \times D_s/2r_0$$



Conservation laws

$$\begin{aligned} \frac{\partial \rho_1}{\partial t} &= -\frac{\partial J_1}{\partial z} \\ \frac{\partial \rho_2}{\partial t} &= -\frac{\partial J_2}{\partial z} + 2\dot{m}_{evp}/r_0 \\ \rho_{liq}\frac{\partial h}{\partial t} &= -\dot{m}_{evp} \end{aligned}$$

□ Initial and boundary conditions

Initial conditions

$$\rho_{1}(t = 0) = \frac{p_{d}}{R_{g}T} - \rho_{sat} \qquad z = 0: \rho_{1} + \rho_{2} = \frac{p_{u}}{R_{g}T}$$

$$\rho_{2}(t = 0) = \rho_{sat} \qquad z = 0^{-}: J_{2} = 0$$

$$h(t = 0) = h_{0} \qquad z = L: \rho_{1} + \rho_{2} = \frac{p_{d}}{R_{g}T}$$

$$z = L: \frac{\partial \rho_2}{\partial z} = 0$$

boundary conditions

Method – Solid/Liquid Filtration

Stage 1: pressure filtration to remove bulk of solvents

- Pressurized room-temperature N₂ as the agent
- Solvent-coal slurries are pressure filtered





Stage 2: solvent vaporization and removal



evaporation and mass convection

operating temperature must be elevated for some solvents

Room-temperature N₂, heated N₂, and superheated steam as carrier gas

Stage 2: solvent vaporization and removal



3 Stage 2: solvent vaporization and removal



Stage 2: solvent vaporization and removal



Device fabrication, shake-down, and tuning accomplished in 11/2020



Coal: Met Warrior Clean Coal



D₅₀ = 13.1 μm; D₈₀ = 43.3 μm

Solvents: pentane and hexane

Solvent	Viscosity	Boiling point	Vapor pressure
	(mPa·s)	(°C)	(kPa)
Pentane	0.250	36.0	57.3
Hexane	0.310	69.0	16.0

Results – Solid/Liquid Filtration

Stage 1: pressure filtration for bulk solvent removal



filtration curves for 10-15% pentane-coal slurries at various pressure differences

- Nonlinear filtration kinetics due to cake formation and three phase flow in cakes
- Gas breakthrough occurs within 60 s even at the lowest pressure difference → compatible with HHS technologies

Results – Solid/Liquid Filtration

Stage 1: pressure filtration for bulk solvent removal



filtration curves for 10-15% hexane-coal slurries at various pressure differences

- Slurries with 10% mass loading are selected in subsequent studies
- Solvent: pentane and hexane

Results – Filtration Cake Properties

Analytical model for pressure filtration



Huang, Pan, and Yoon, *Minerals Eng.*, **115**, 88, 2018 19/25

Results – Room-Temperature N₂ Drying





- Pentane and hexane are removed to acceptable concentration (1400ppm) in 105 and 230 s
- Drying rate decreases during the late stage of solvent removal
- Drying time is far longer than desired (within 10 s for integration with HHS)

Results – Model Validation

Drying of pentane-loaded cakes by room-temperature N₂



- Cake properties taken from measurement and filtration model fitting
- Dropping drying rate accommodated by dividing residual solvents in filtration cakes into two populations
- Model revealed that gas at cake exit is not saturated with solvent vapor

Results – Drying by Heated N₂

Drying of solvent-loaded filtration cakes by heated N₂



- Heating N₂ to 100°C and 150°C reduces drying time, but not significant enough
- Increasing pressure difference reduces drying time, but still not enough
- Transport of vapor from solvent evaporation site to carrier gas streams in filtration cake limits the drying rate

Results – Drying by Superheated Steam

Drying of solvent-loaded filtration cakes by superheated steam

- Superheated steam greatly accelerates drying
- Increasing pressure greatly accelerates drying

Sub-10s drying time achieved!

- Superfast heating (and possibly perturbation of cake structure by water condensation and evaporation) responsible for fast drying
- Final water content in coal cake <5% \rightarrow acceptable for commercial coal handling

Results – Drying of Vacuum-Formed Cakes

Drying of filtration cakes formed by Vacuum filtration

- Vacuum filtration is sometimes preferred over pressure filtration due to lower equipment cost
- Vacuum-formed filtration cake is less compact

Summary

- An *in-situ* solvent recovery method for recovering solvents from solvent-ultrafine coal slurries is proposed
- Bench-scale tests confirmed the effectiveness of the proposed method
 - Pressure filtration can be accomplished in less 60 s at realistic coal loading (10-15%)
 - Using superheated steam as carrier gas, the solvents in the final filtration cake can be reduced below 1400 ppm in less than 10 s
- The project cleared the way for pilot-scale development of the proposed method

Fruitful collaboration with Dr. Evan Granite of NETL is gratefully acknowledged