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Data Driven Discovery of Physics for Reservoir Surveillance with Application to PTA

Dr. Sathish Sankaran

Xecta Digital Labs

xecta

https://www.linkedin.com/in/sathishsankaran/

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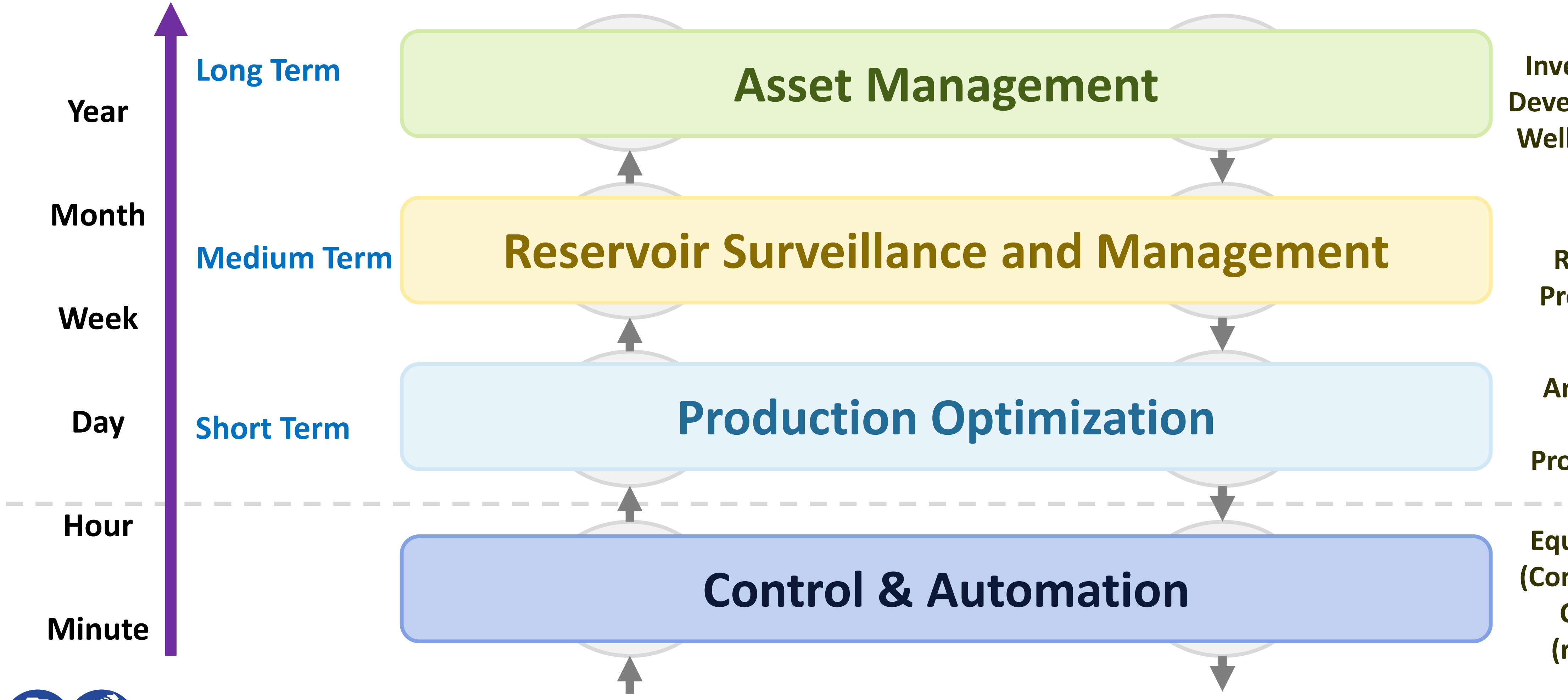
Multi Level Control Hierarchy



Typical Decisions

Investment options
Development strategy
Well location, design

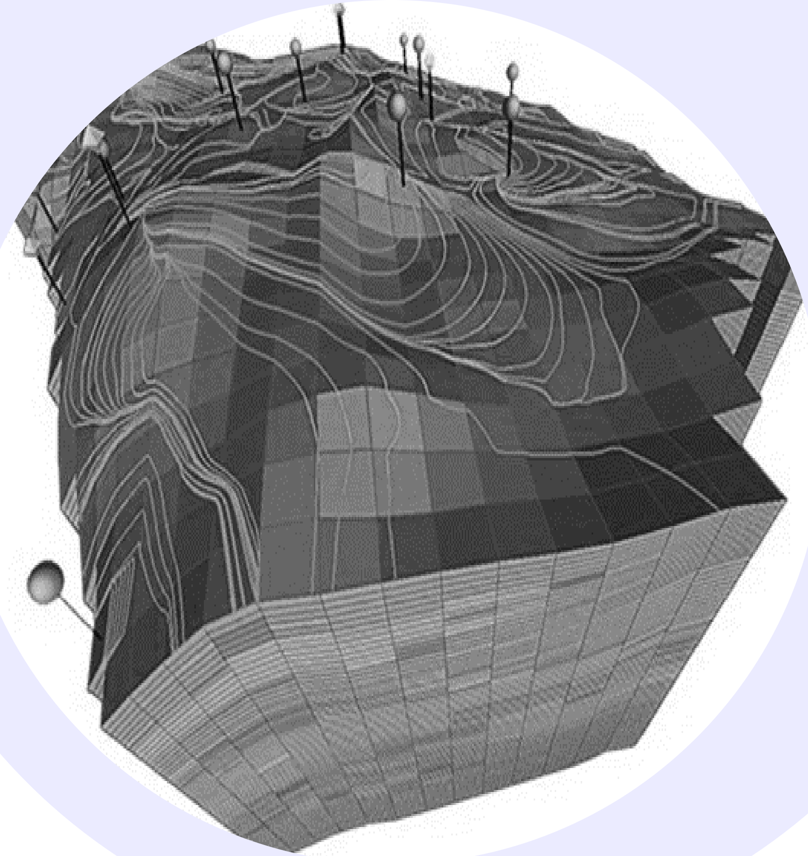
Workovers
Recompletions
Prod / Inj Targets

Artificial Lift Opt
Well routing
Prod management

Equipment control
(Compressor, pump)
Choke control
(rate, pressure)

Reference: Adapted from Sankaran et al (2009)

Reservoir Surveillance



Definition:

Collect information to understand **reservoir performance** with fewest assumptions and enable robust response to changing subsurface, surface or economic conditions

Automate
Interpretable
Sustainability

Rates, Pressures
Data Volumes

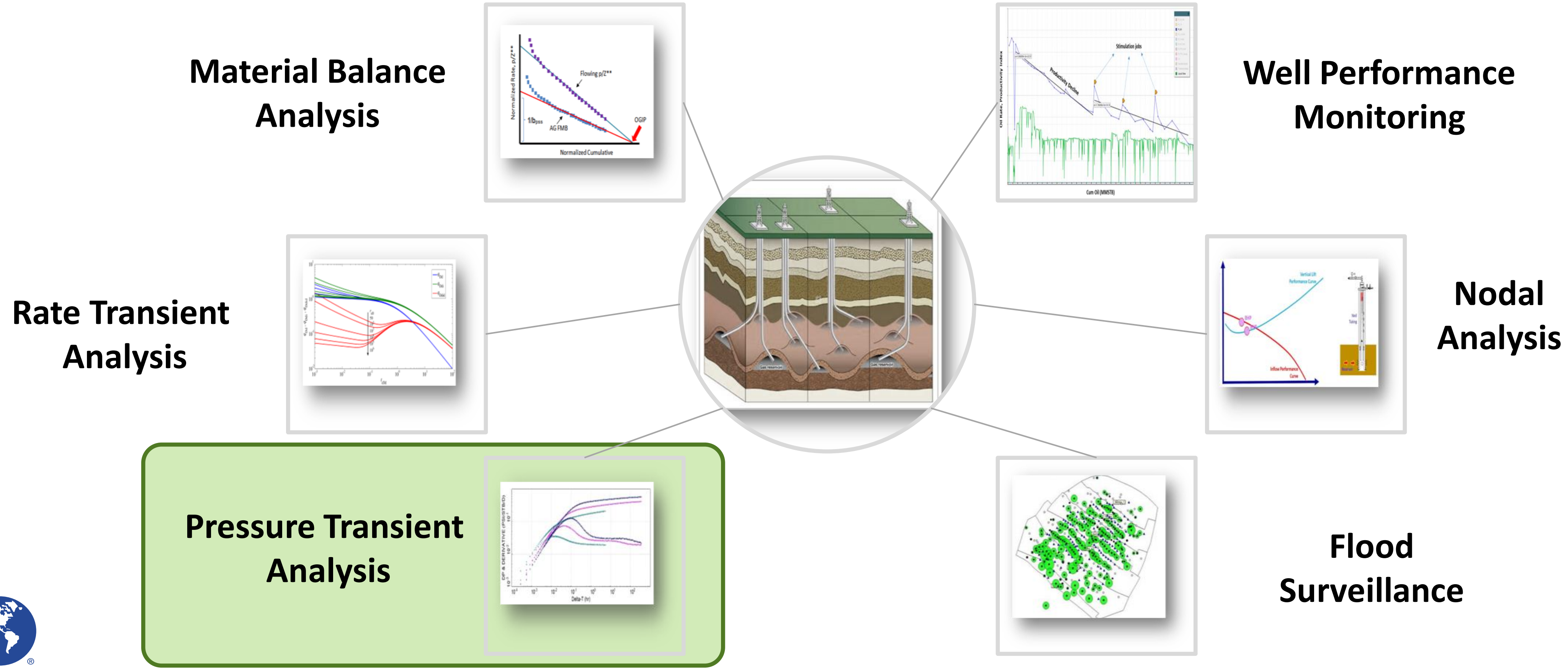
Reservoir Performance → *f*(Wells, Controls, Properties)

Models
Full physics
Data-driven
Hybrid

Fluid/Rock parameters
Unknown
Uncertain
Complex
Time Varying

Reservoir Surveillance

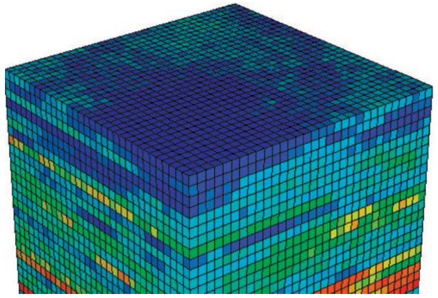
- **Objectives**:
  – Early understanding of reservoir / well performance
  – Identify under-performing elements (reservoir, well etc.) for remediation



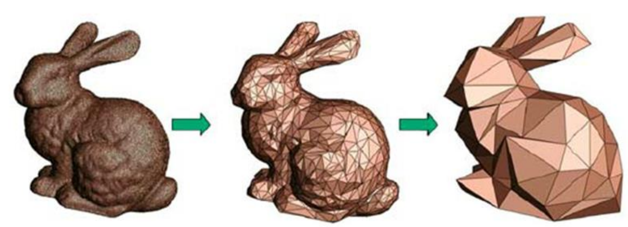
Hybrid Reservoir Modeling

Physics-constrained, data-driven modeling

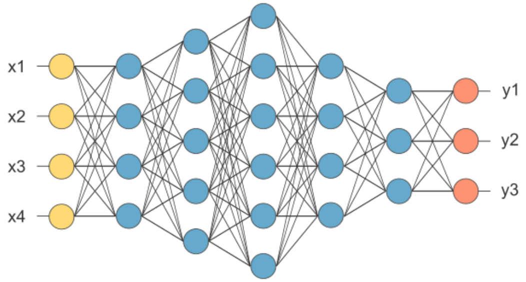
Full Physics



Hybrid Models



Data-Driven



Conventionals

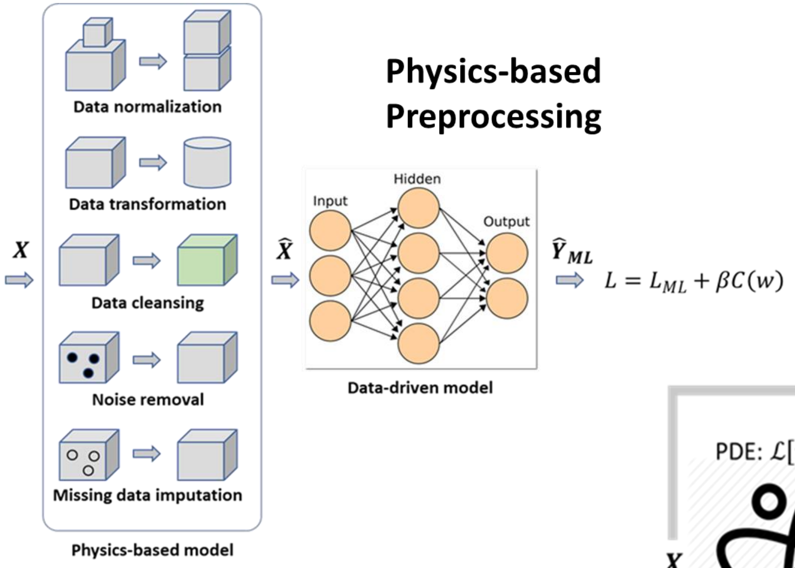
- **Automate shutin analysis (SPE 196122)**
- **Estimate average reservoir pressure (SPE 209300)**
- **Track varying well productivity index (SPE 196122, SPE 209300)**
- **Virtual meter for flow rates (SPE 209300)**
- Forecasting and flood optimization (SPE 203390, SPE 206238)

Unconventionals

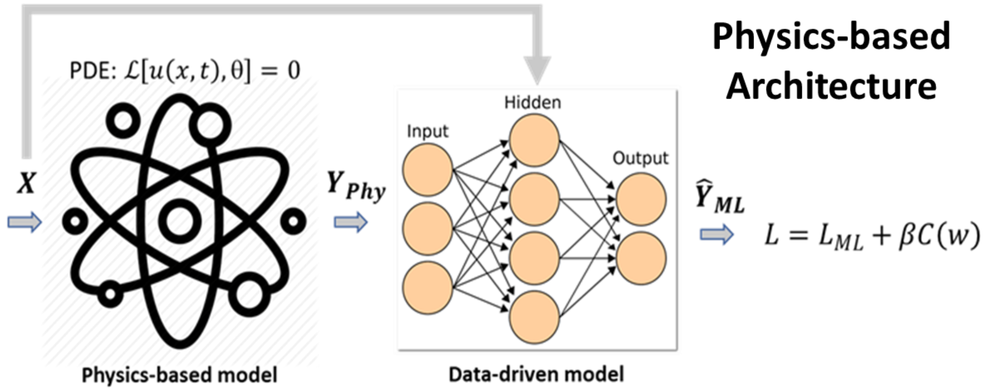
- Hybrid bottomhole pressure (URTeC 5261)
- Transient well performance (URTeC 5023)
- Reduced-physics forecasting (URTeC 5023, 3723189, 371899)
- Production optimization (IPTC 22493, URTeC)
- Parent-child interference (SPE 195813)

Hybrid Reservoir Modeling

Physics-based Preprocessing

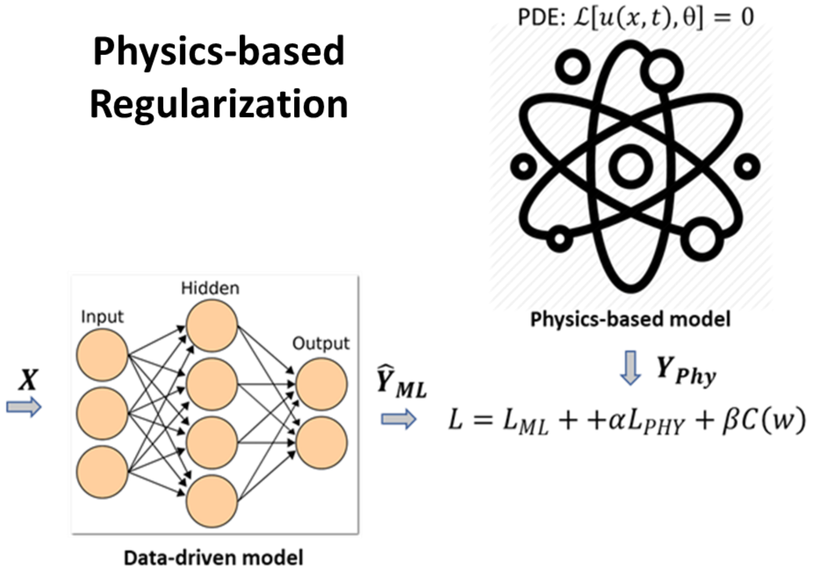


Physics-based Architecture



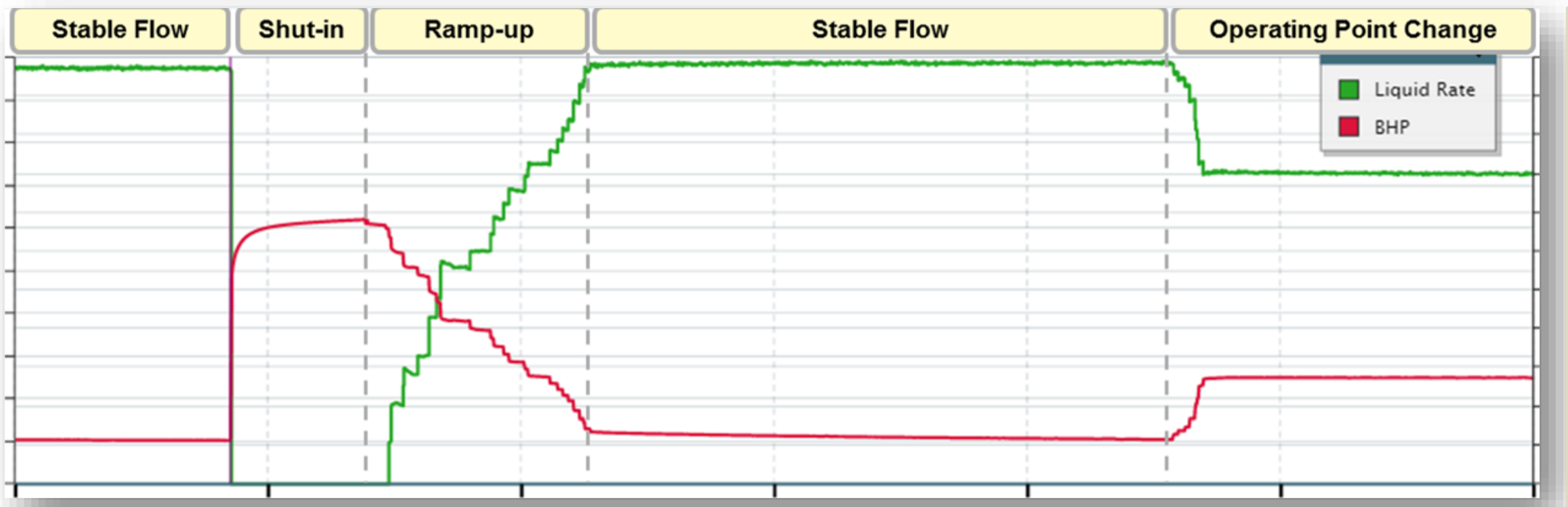
Reference: URTeC 5261

Physics-based Regularization



Tracking Well Performance

- Can we extract well diagnostics from routine production operations?



Shut-in

Well test start/stop

Artificial lift start/stop

Well restart

Stable flow

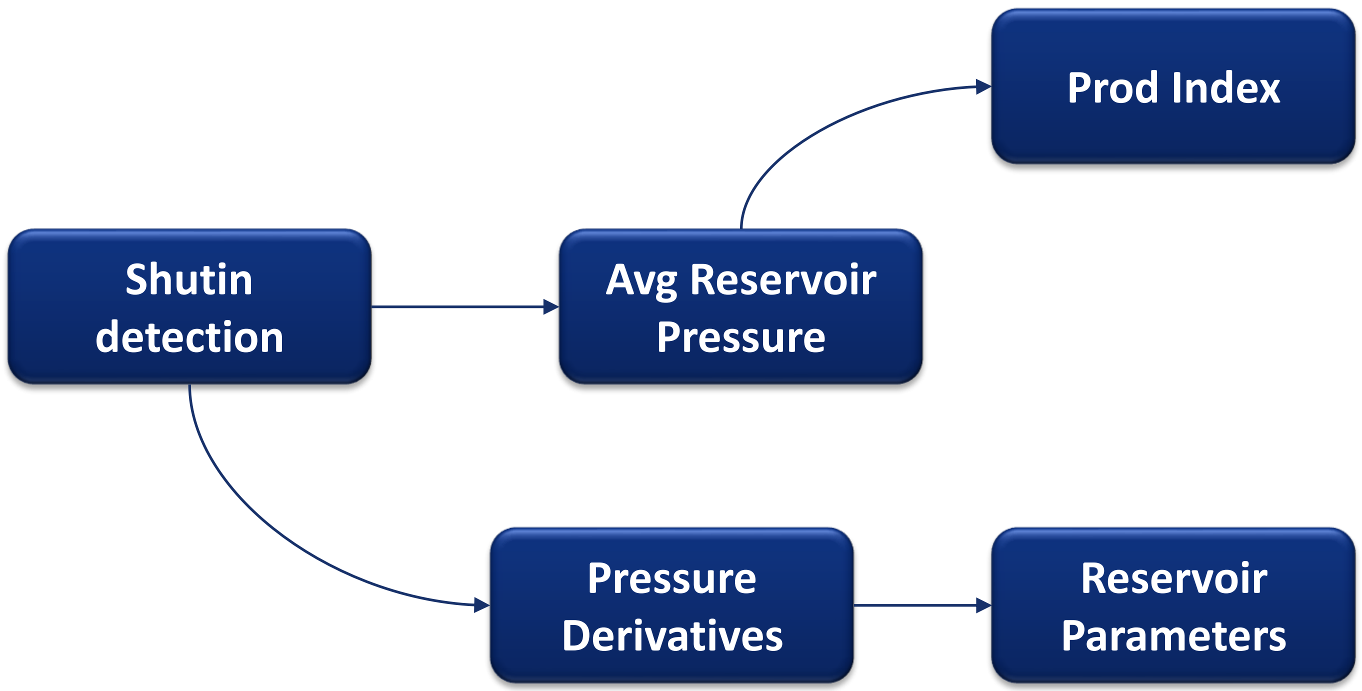
Choke change

Setpoint change

Flowline alignment

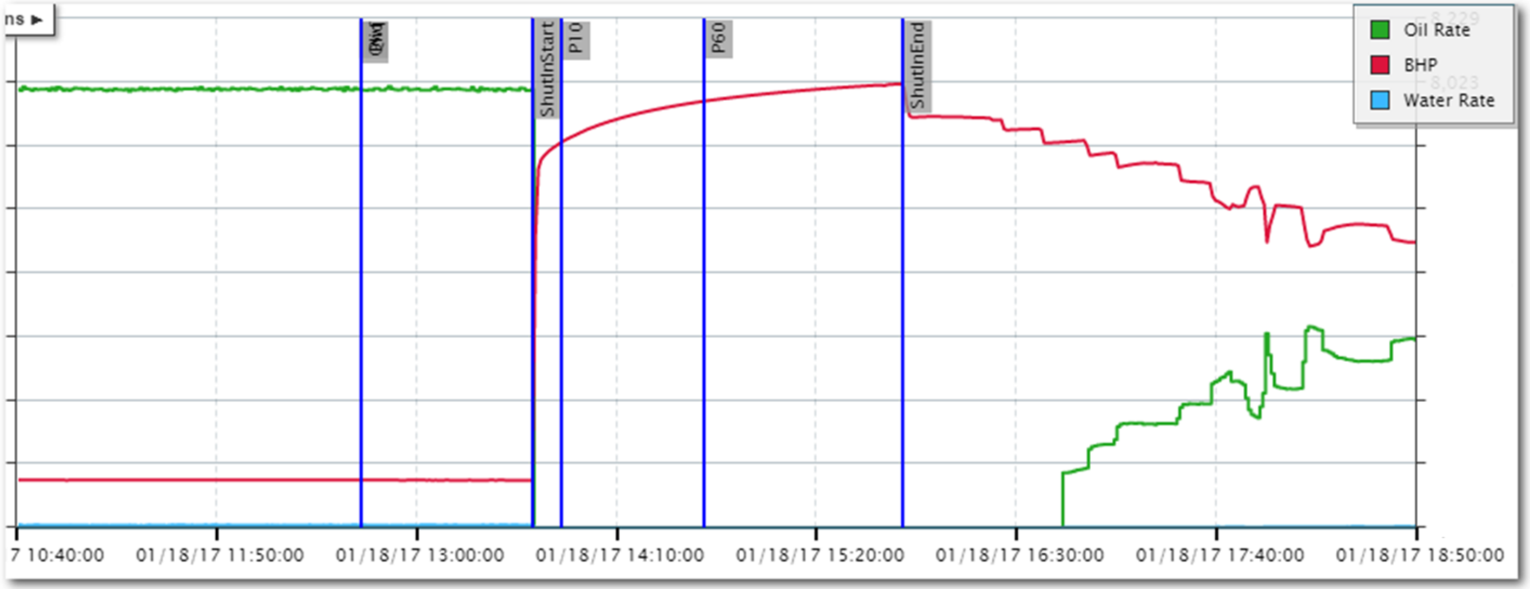
Pressure Transient Analysis

- Can we extract well diagnostics from routine production operations?
  - Estimate shutin pressure, average reservoir pressure, productivity index, pressure derivatives and other reservoir parameters



Pressure Transient Analysis

- **Productivity Index from Shutin**
  - Quantify impact and analyze planned and unplanned shut-ins for well performance



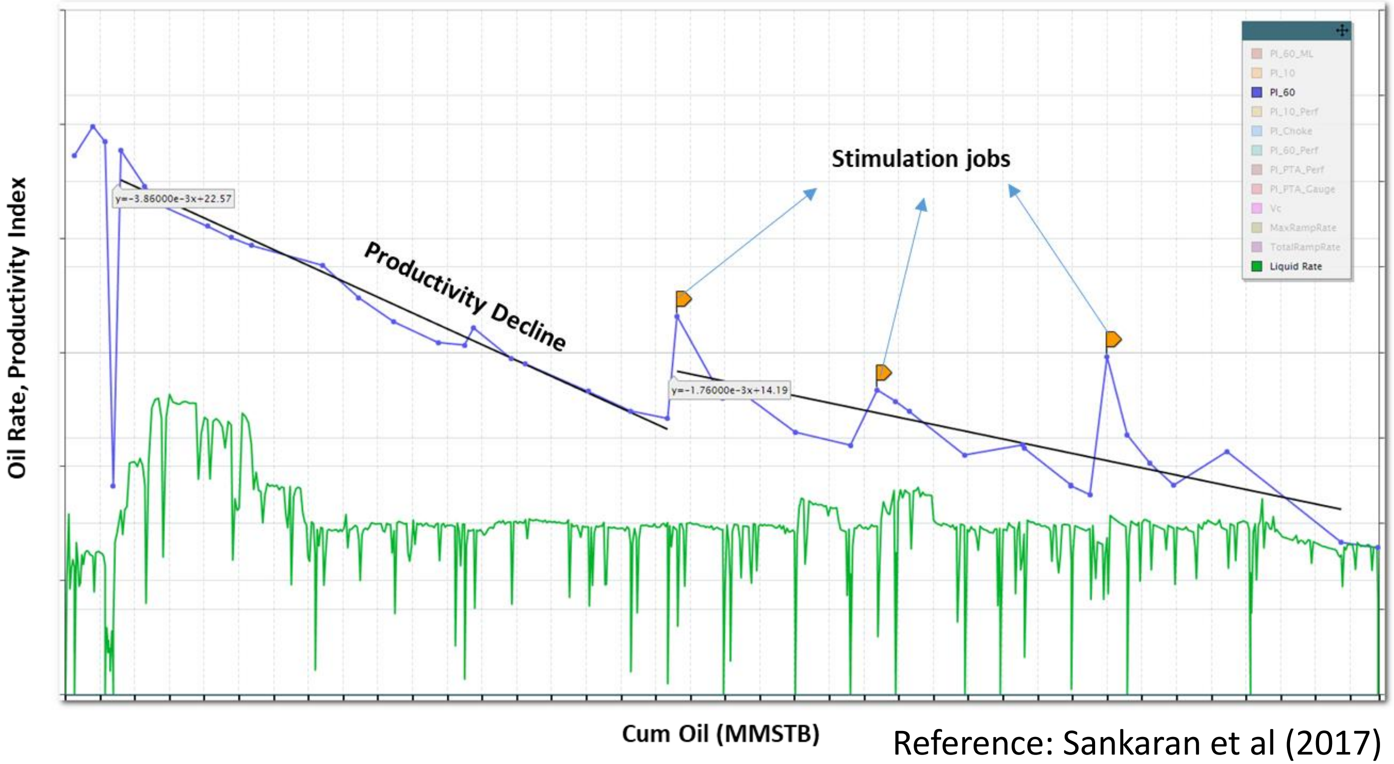
Reference: Sankaran et al (2017)

$$PI_x = \frac{q}{P_x - P_{wf}}$$

$$x = \left\{ \begin{array}{c} 1\ hr \\ 48\ hr \\ Shutin\ end \\ Avg\ reservoir \\ etc. \end{array} \right\}$$

Pressure Transient Analysis

- **Productivity Index from Shutin**
  - Quantify impact and analyze planned and unplanned shut-ins for well performance
  - Estimate shutin pressure, average reservoir pressure, productivity index, pressure derivatives and other reservoir parameters

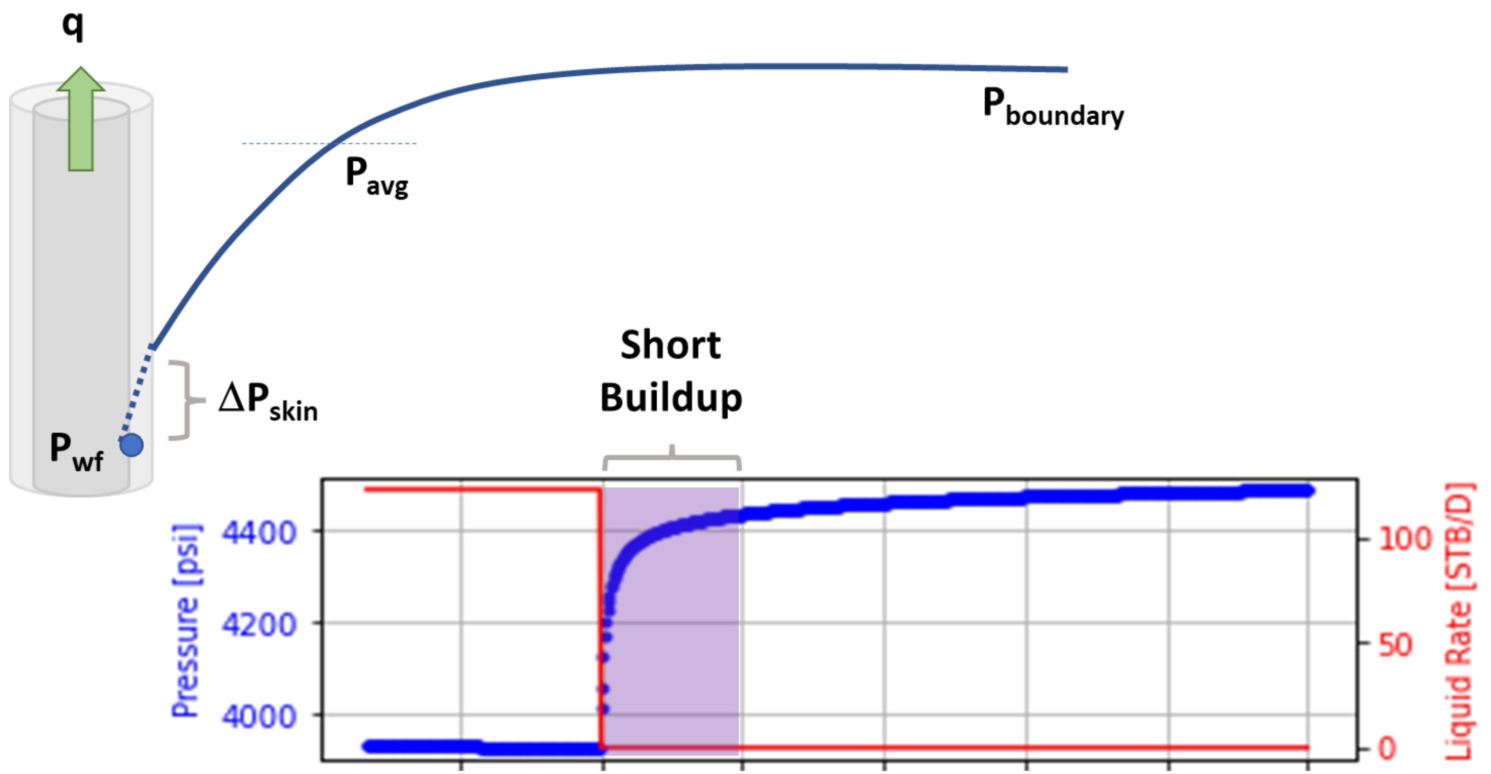


$$PI_{1hr} = \frac{q}{P_{1hr} - P_{wf}}$$

Reference: Sankaran et al (2017)

Pressure Transient Analysis

- **Average Reservoir Pressure**
  - Estimate from short pressure transient (buildup) data
  - Applications: IPR, OHIP estimation, material balance analysis, reservoir simulation, etc.



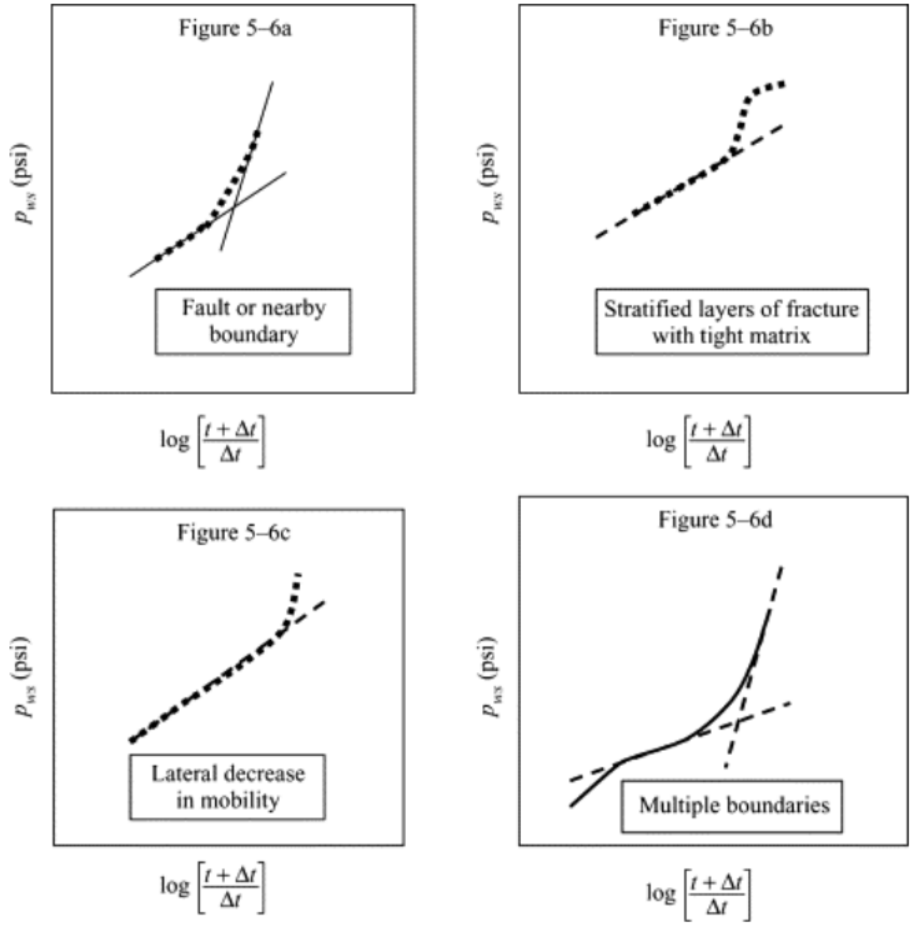
Pressure Transient Analysis

- **Average Reservoir Pressure**
  - Estimate from short pressure transient (buildup) data
  - Applications: IPR, OHIP estimation, material balance analysis, reservoir simulation, etc.

Known Well Drainage Configuration	**Unknown Well Drainage Configuration**
Miller et al (1950)	Muskat (1937)
Mathews et al (MBH, 1954)	Mead (Hyperbola, 1981)
Horner (Horner time, 1967)	Kabir & Hasan (Rectangular hyperbola, 1983)
Ramey & Cobb	Kuchuk (Inverse time, 1999)
Dietz (1967)	Chacon (2004)
Odeh & Al-Hussainy (1971)	Crump & Hite (Modified Muskat, 2008)

Known Drainage Configuration

- **Average Reservoir Pressure**



Horner plot – Chaudhry (2004)

TABLE 3 — DETERMINATION OF AVERAGE PRESSURE

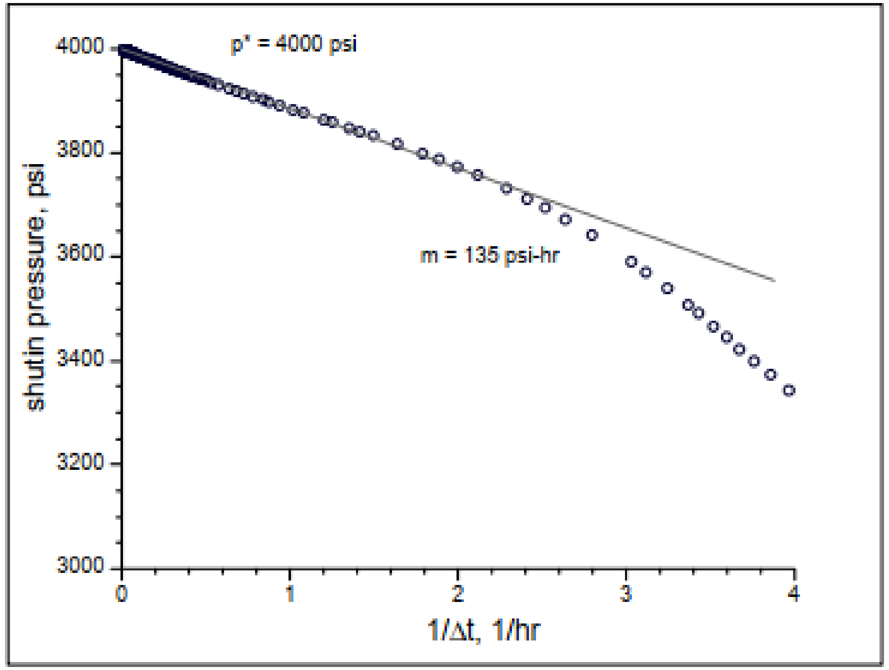
Well	p^* psia	$\frac{q\mu}{4\pi kh}$ atm	q at res. cond. $\frac{cc}{sec}$	$\frac{kh}{\mu}$ $\frac{darcy\text{-}cm}{cp}$	fv_j cc x 10^{-11}	C atm^{-1}	Total Production tank bbl
1	3877	1.594	86	4.29	1.76	2 x 10^{-4}	4430
2	3858	.1870	74	31.5	1.49	2 x 10^{-4}	5640
3	3932	3.051	63	1.643	1.28	2 x 10^{-4}	1930
4	3787	2.047	330	12.83	6.77	2 x 10^{-4}	10,800

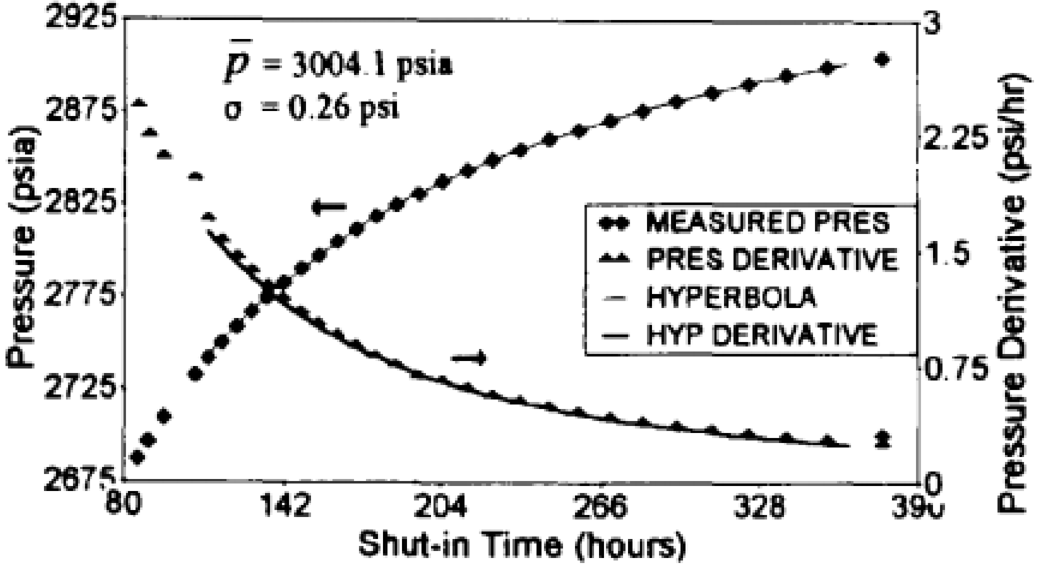
Well	t sec x 10^{-6}	$\frac{kt}{f\mu cA}$	Model	$\frac{p^*-\bar{p}}{q\mu/4\pi kh}$	$p^*-\bar{p}$ psi	$\bar{p}$ psia	v_j/v_t	Volumetric Avg. Press.
1	9.94	1.21	2:1	1.76	41	3836	.156	
2	14.77	15.6	2:1	4.27	12	3846	.132	
3	5.96	.383	4:1	.11	5	3927	.113	
4	6.17	.585	2:1	1.90	57	3730	.599	
								3784

MBH (1954)

Unknown Drainage Configuration

- **Average Reservoir Pressure**



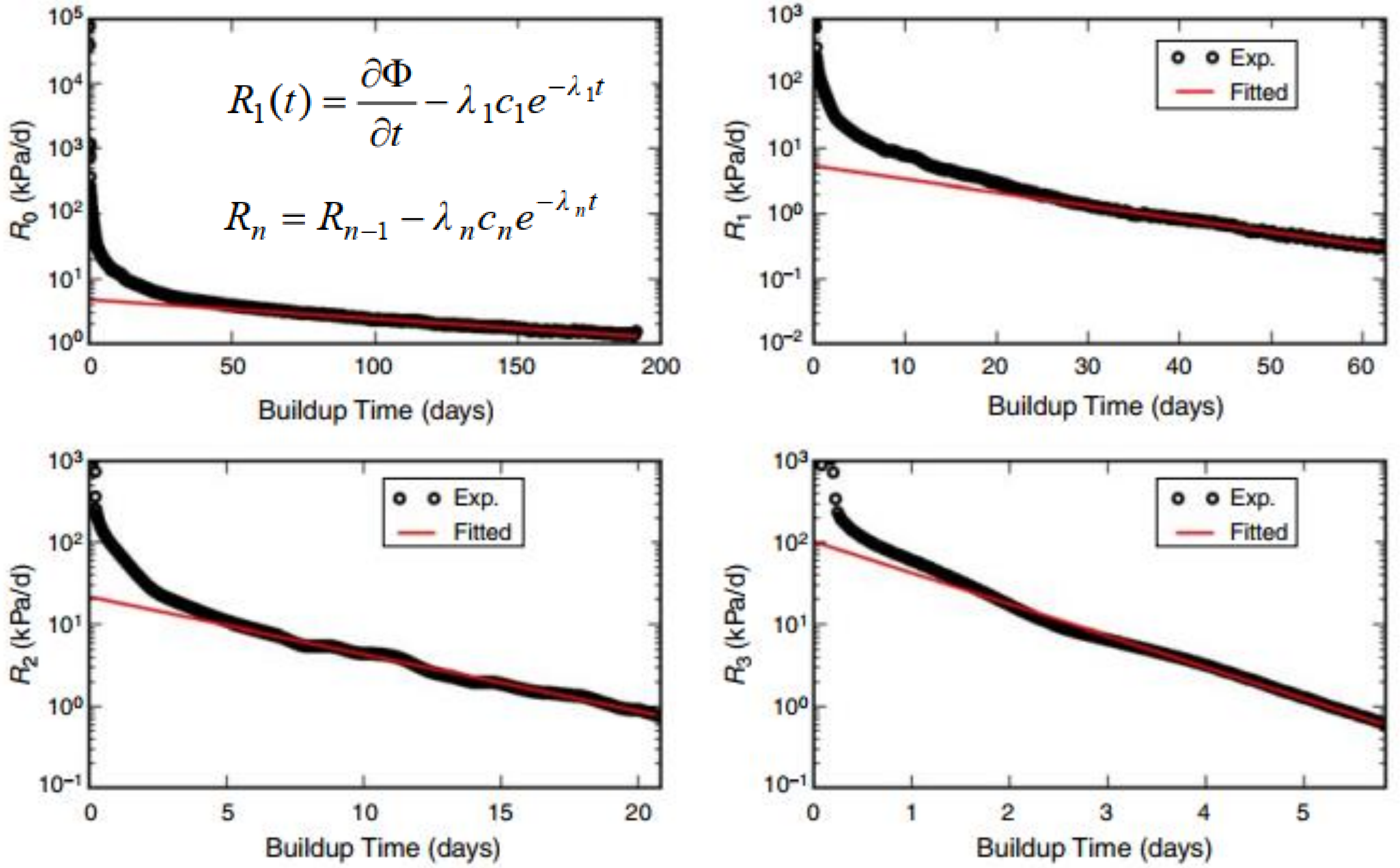


$$p_{ws} = a + \frac{b}{t}$$ Kuchuk (1999)

$$p_{ws} = a + \frac{b}{c + t}$$ Kabir and Hasan (1996)

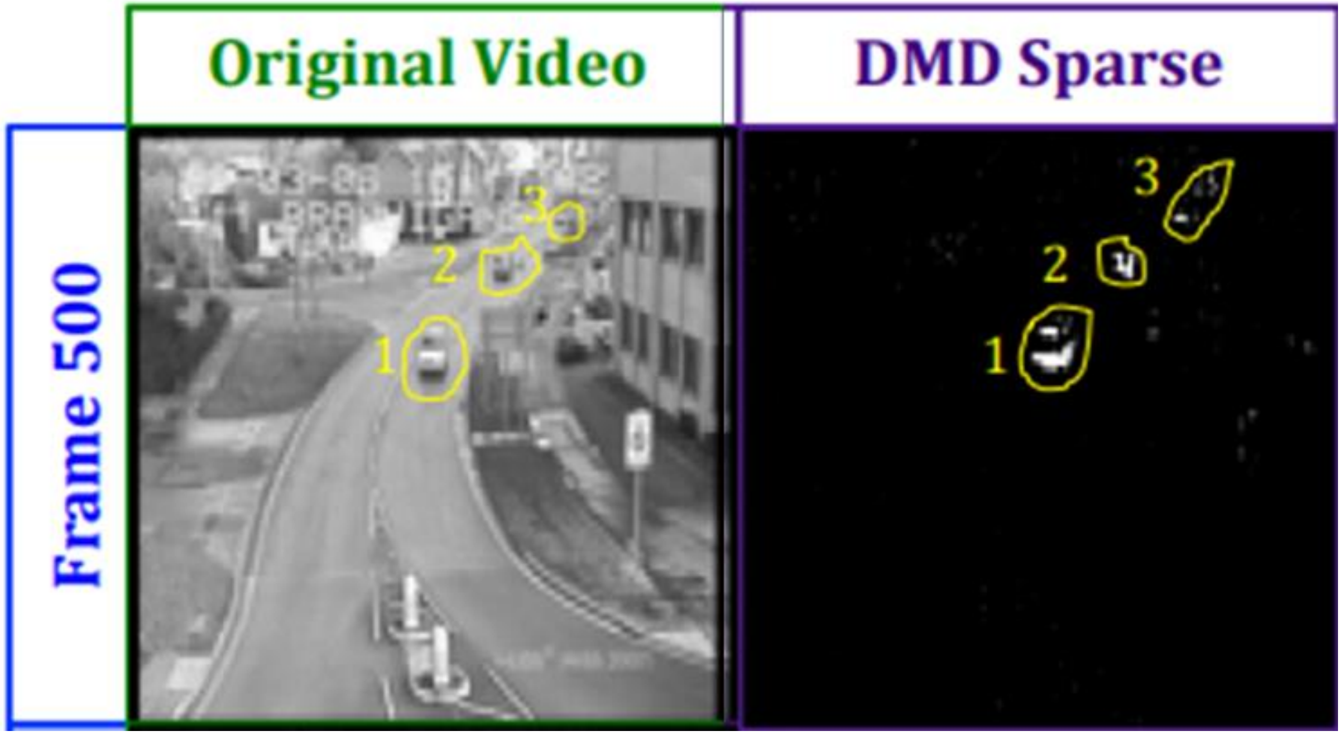
Unknown Drainage Configuration

- **Average Reservoir Pressure**



Crump and Hite (2006), Piccinini (2018)

Motivation



Background / foreground separation in real time video

Reference: Grosek and Kutz (2014)

Can reservoir signal be expressed as a combination of various dynamics?

Unknown Drainage Configuration

- **Average Reservoir Pressure**

Eigenvalue expansion: $P(t,x,y,z) = P_{avg} - \sum_{i=1}^{\infty} c_i a_i(x,y,z) e^{-\lambda_i t}$

coefficients

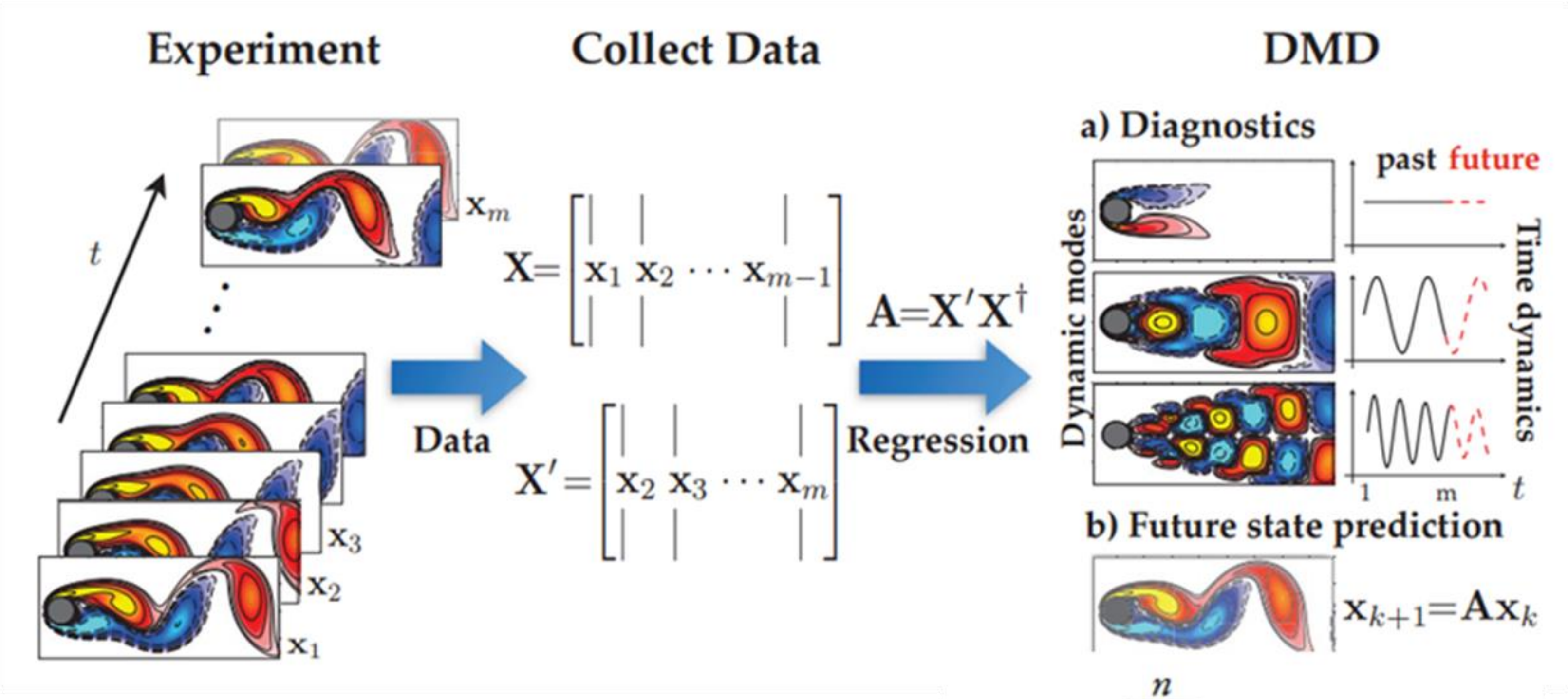
eigenfunctions

eigenvalues

$$\frac{\partial P}{\partial t} = \frac{1}{\varphi c_t} \nabla \cdot \left(\frac{K}{\mu} \cdot \nabla P \right)$$

Reference: *Mikhailov and Ozisik (1984), Crump and Hite (2008)*

Dynamic Mode Decomposition (DMD)



Reference: *Kutz et al. (2016)*

$$\mathbf{x}(t) = \sum_{k=1}^{n} \phi_k \exp(\omega_k t) b_k$$

Variants: Exact DMD, Extended DMD, Optimized DMD, Compressive DMD, Multi-resolution DMD, Input-Output DMD, DMD with control, Ensemble DMD, Physics-constrained DMD

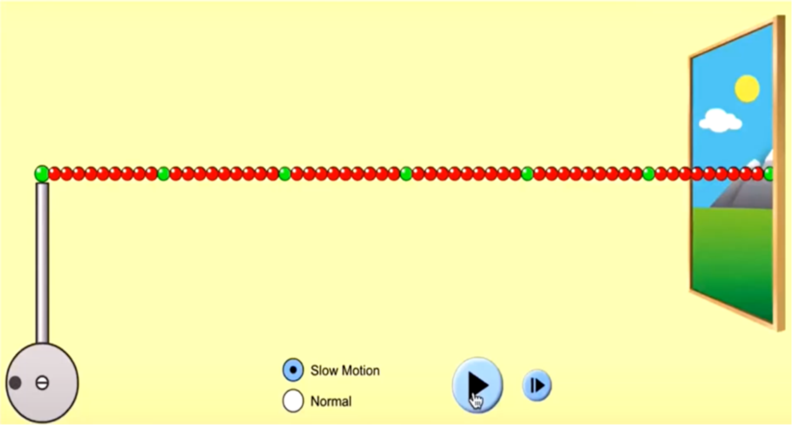
Applications: Fluid mechanics, neuroscience, epidemiology, video processing, robotics etc.

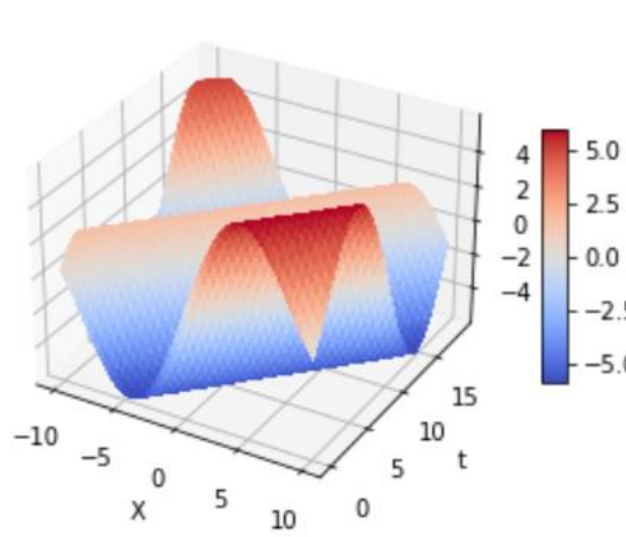
References: Tu et al. (2014), Sankaran et al. (2022)

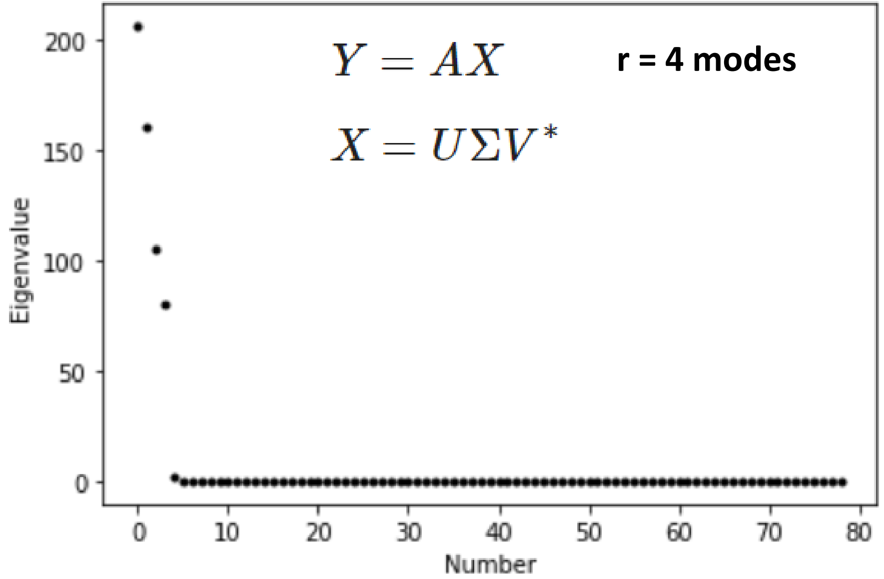
DMD – Example

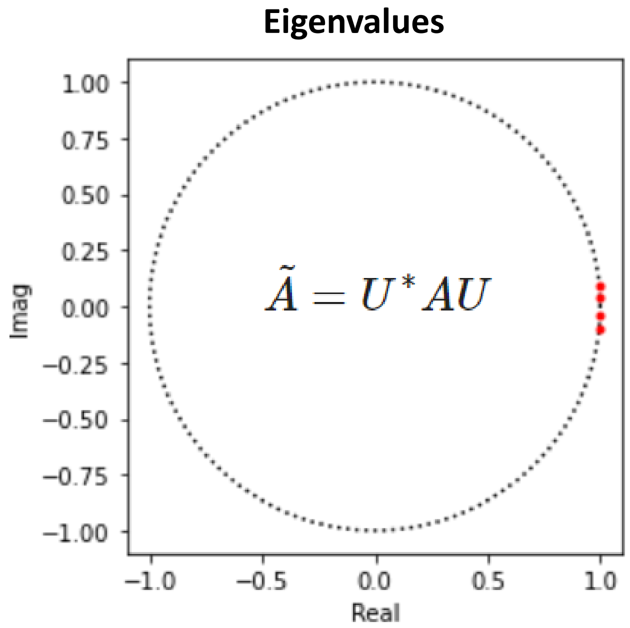
Traveling wave equation:

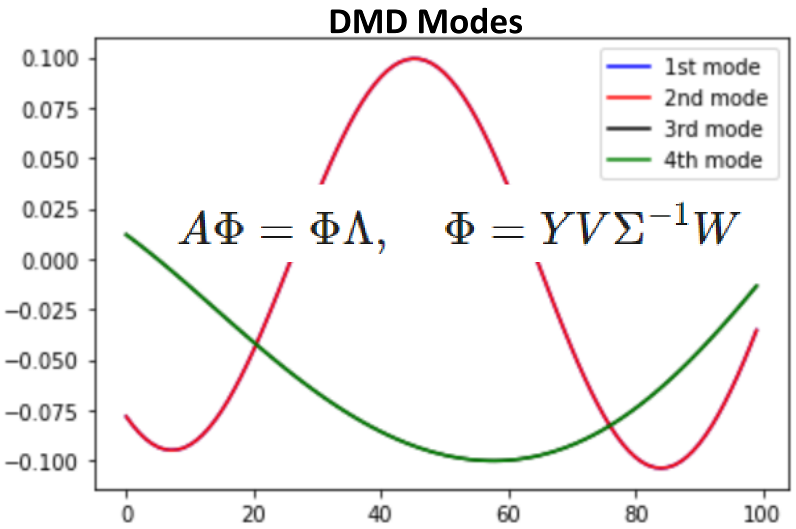
$$y = 1sin(0.1x - 0.1t) + 2sin(0.2x - 0.2t) + 4sin(0.4x - 0.4t)$$









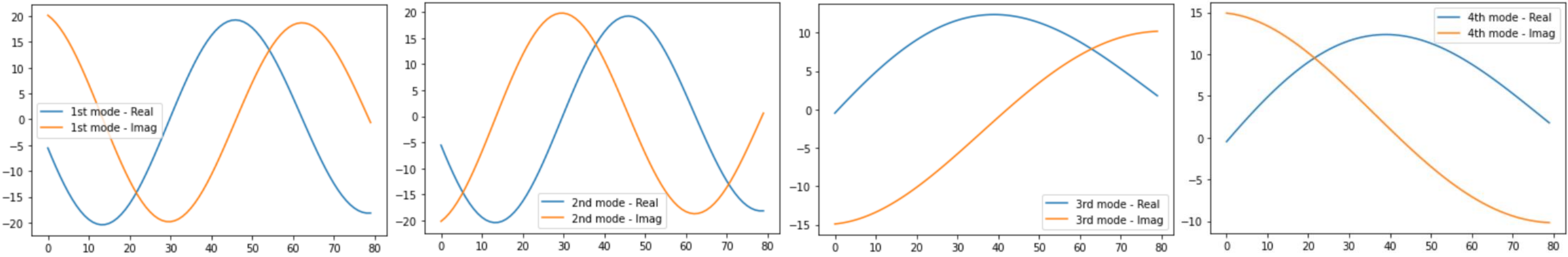


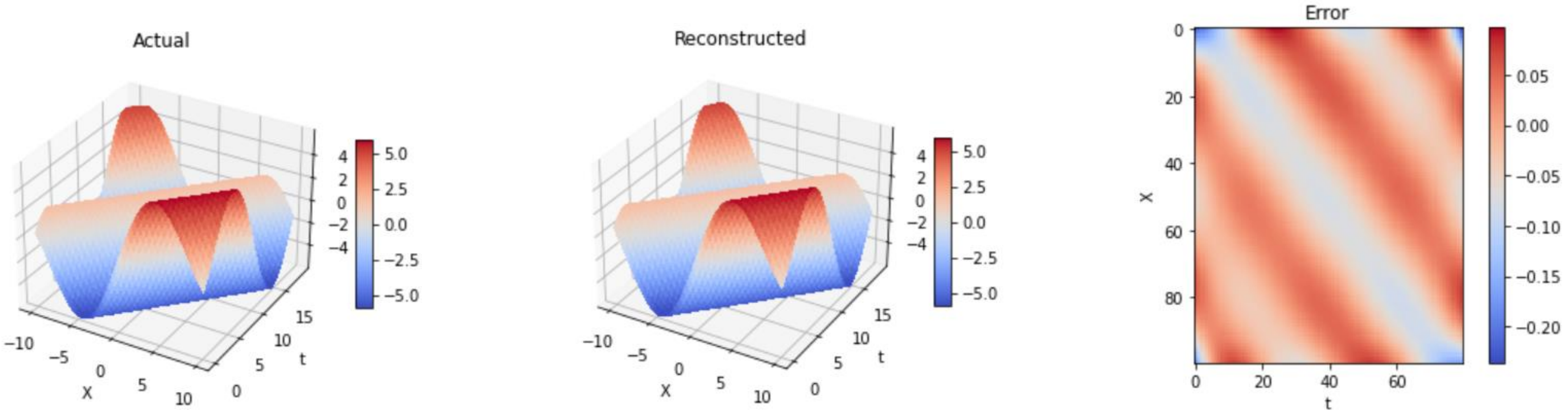
DMD – Example

Traveling wave equation:

$$y = 1sin(0.1x - 0.1t) + 2sin(0.2x - 0.2t) + 4sin(0.4x - 0.4t)$$

Time Dynamics of DMD Modes





DMD + Time Delay Embedding

- **Average Reservoir Pressure**
  - Reservoir diffusion

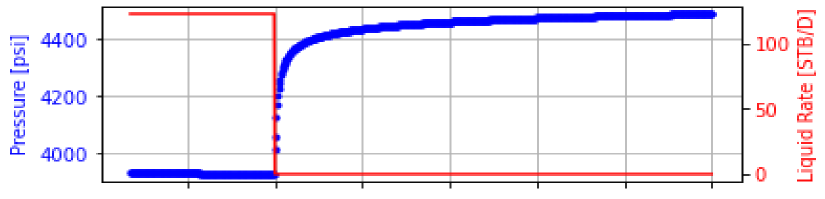
    Eigenvalue expansion:

$$P(t,x,y,z) = P_{avg} - \sum_{i=1}^{\infty} c_i a_i(x,y,z) e^{-\lambda_i t}$$

coefficients

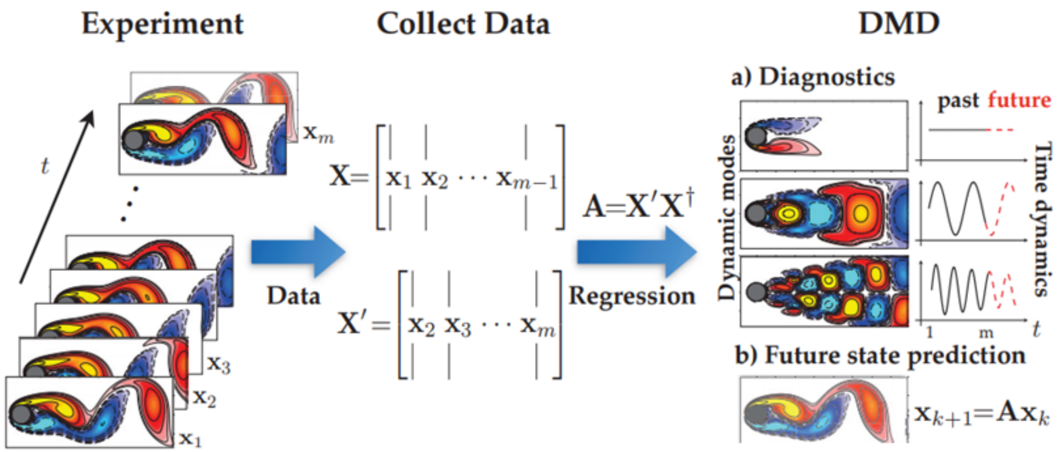
eigenfunctions

eigenvalues



DMD with Time Delay Embedding

Dynamic Mode Decomposition (DMD)



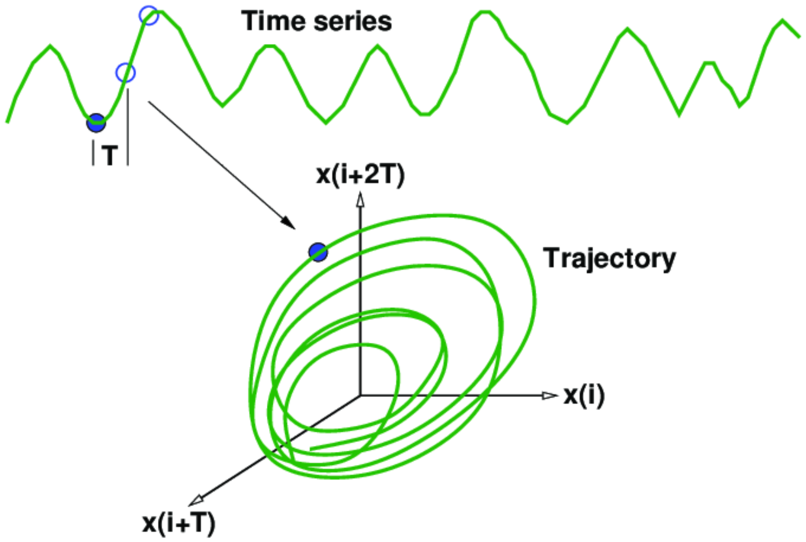
$$X = \begin{bmatrix} | & | & & | \\ x_1 & x_2 & \cdots & x_{m-1} \\ | & | & & | \end{bmatrix} \quad X' = \begin{bmatrix} | & | & & | \\ x_2 & x_3 & \cdots & x_m \\ | & | & & | \end{bmatrix}$$

$$x_{k+1} = A x_k$$

Reference: *Kutz et al. (2016)*

$$\mathbf{x}(t) = \sum_{k=1}^{n} \phi_k \exp(\omega_k t) b_k$$

Time Delay Embedding (TDE)



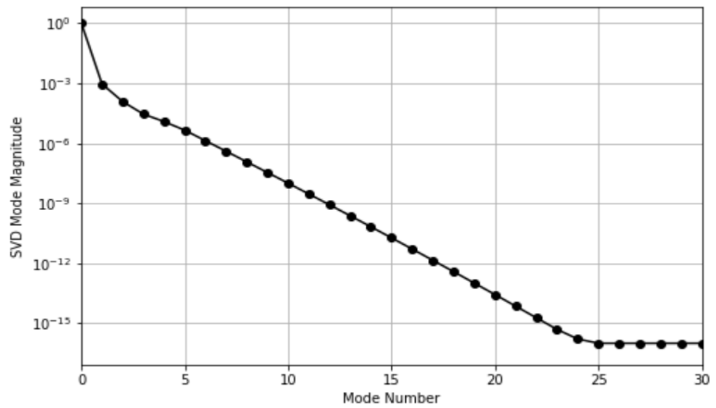
DMD + TDE – Validation With Physics

- **Average Reservoir Pressure**

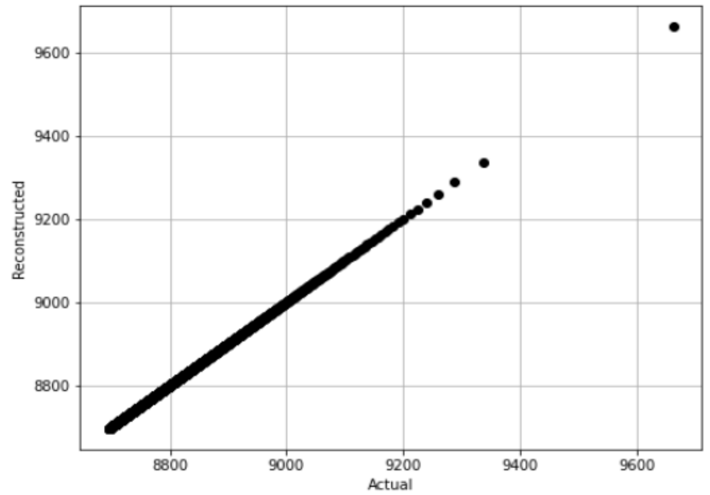
Line source: $P(t) = P_i + \frac{70.6\, qB\mu}{kh} Ei\left(\frac{-948.1\phi\mu c_t r_w^2}{kt}\right)$

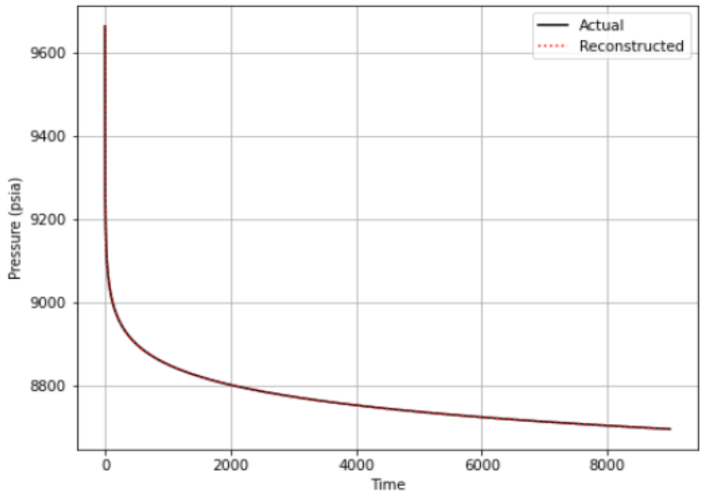
Reservoir and well properties

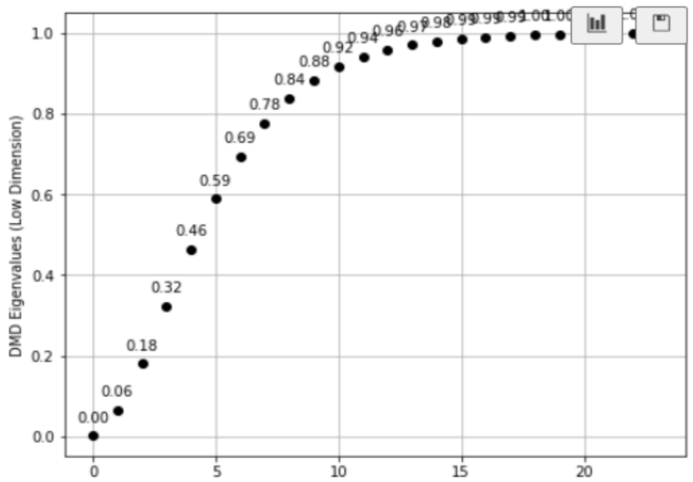
Initial Pressure	10000 psi
Permeability	100 md
Thickness	100 ft
Porosity	0.2
Total Compressibility	1.0E-6 psi^{-1}
Well Radius	0.5 ft
Viscosity	1.0 cp
Formation Volume Factor	1.0 RB/STB
Constant Flow Rate	10000 STB/d



1000 TDEs
24 DMD modes







Hybrid Sparse Regression

- **Average Reservoir Pressure**

$$P(t,x,y,z) = P_{avg} - \sum_{i=1}^{\infty} c_i a_i(x,y,z) e^{-\lambda_i t}$$

Sparse Identification of Nonlinear Dynamics (SINDy)

Hybrid analytical, physics-based, non-linear candidate functions

- Radial (Horner)

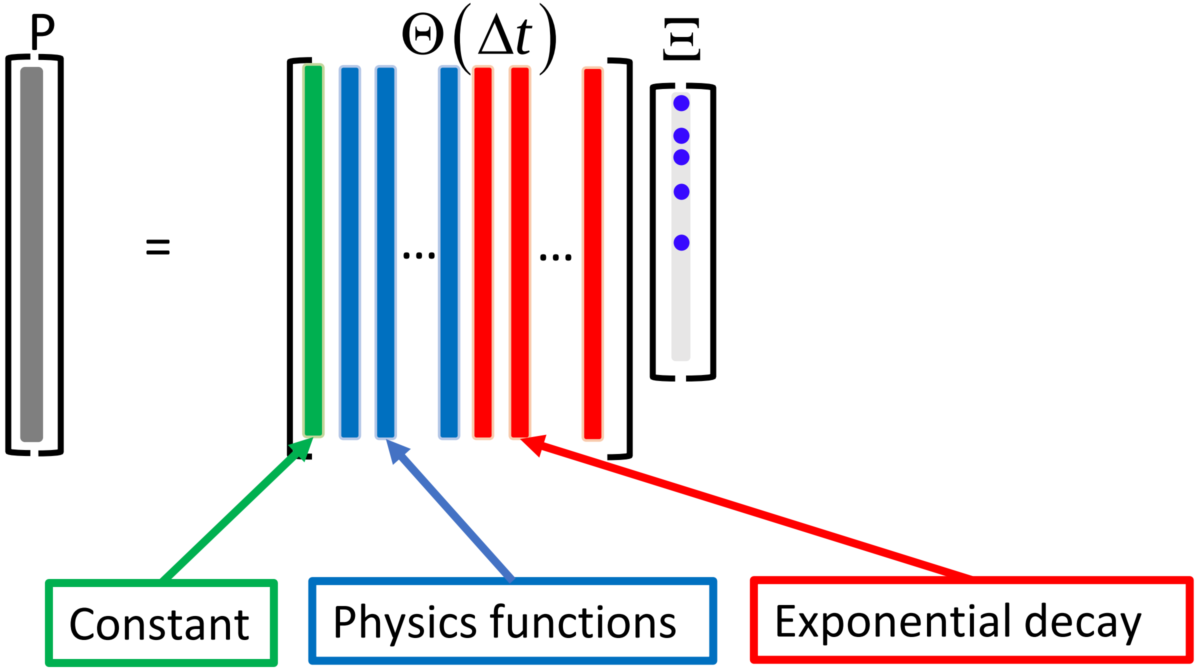
$$\mathrm{P}(t) = P_{avg} - m \cdot ln\left(\frac{t_p + \Delta t}{\Delta t}\right)$$

- Linear

$$\mathrm{P}(t) = P_{avg} - m \cdot \Delta t^{\frac{1}{2}}$$

- Spherical

$$\mathrm{P}(t) = P_{avg} - m \cdot \Delta t^{-\frac{1}{2}}$$



Hybrid Sparse Regression

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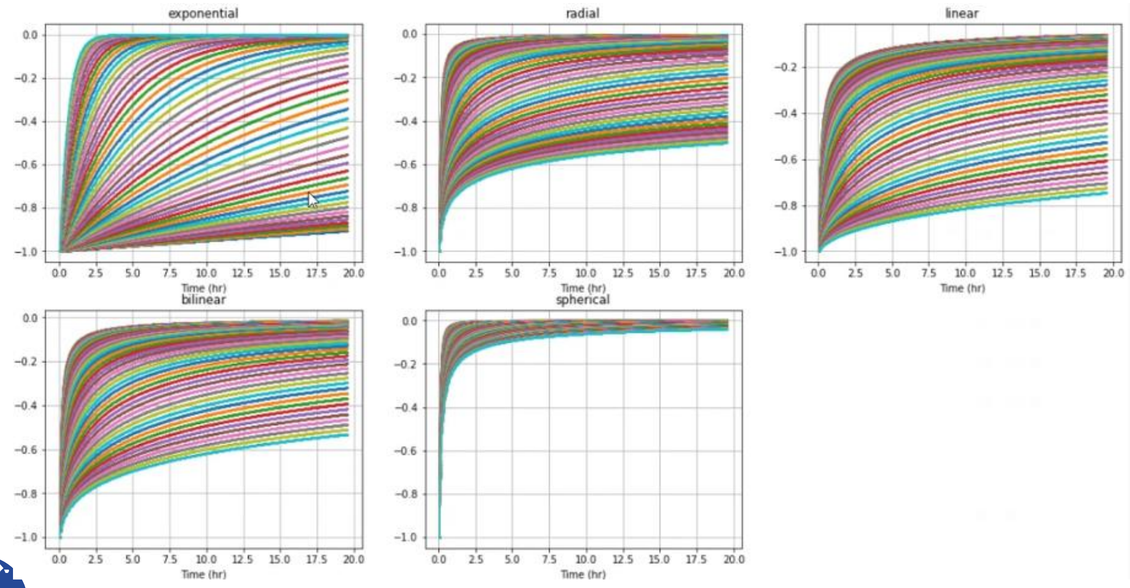
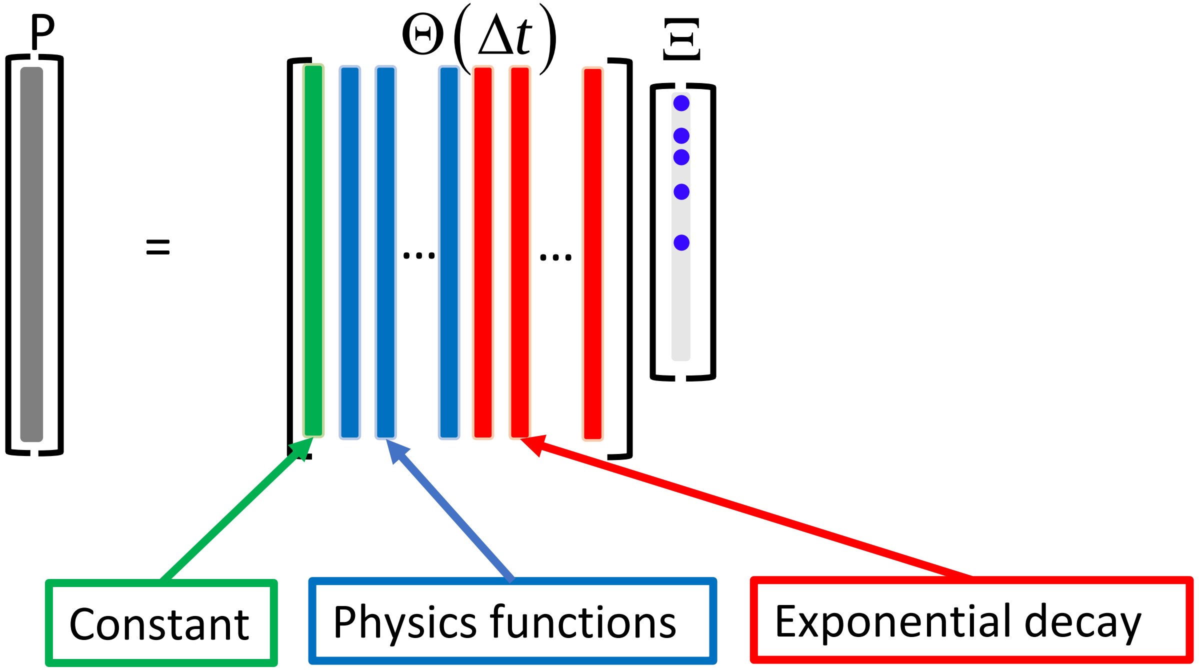
$$P(t,x,y,z) = P_{avg} - \sum_{i=1}^{\infty} c_i a_i(x,y,z) e^{-\lambda_i t}$$

<u>**Sparse Identification of Nonlinear Dynamics (SINDy)**</u>

Hybrid analytical, physics-based, non-linear candidate functions





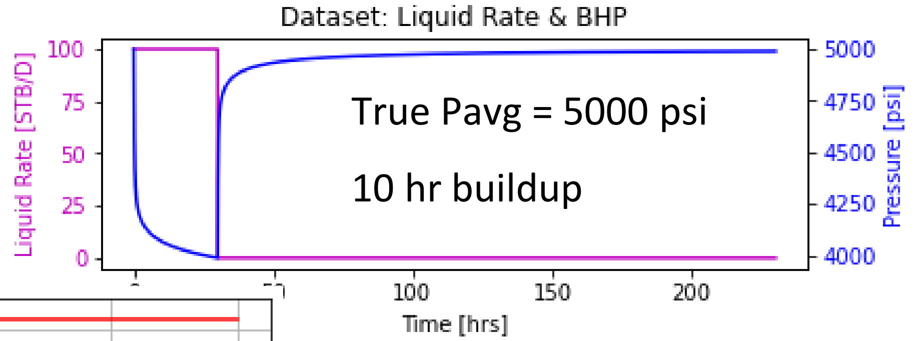
Case Studies

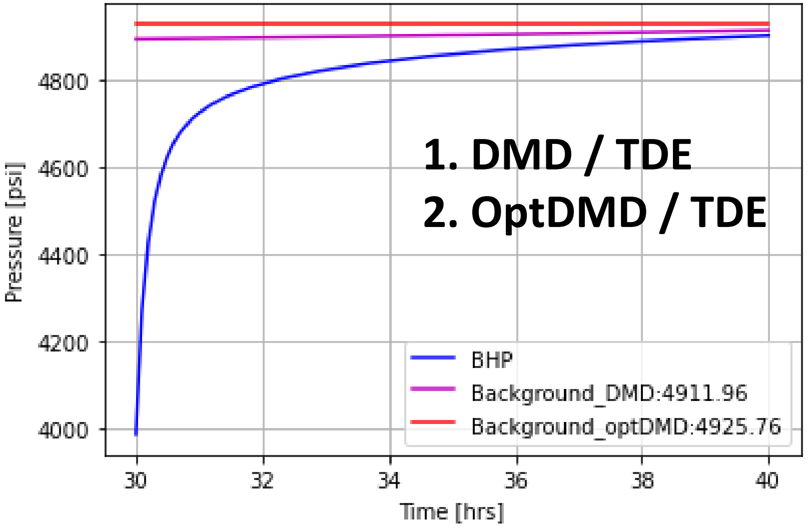
- **Average Reservoir Pressure**

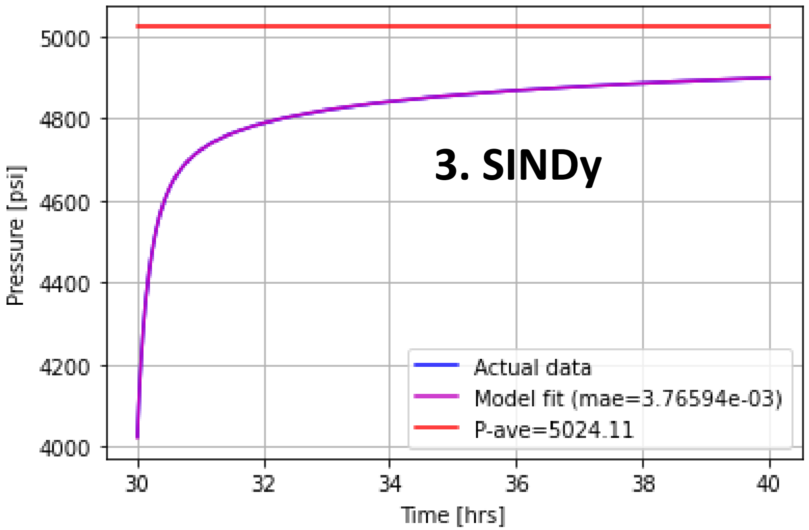
Case 1 – IARF reservoir with wellbore storage

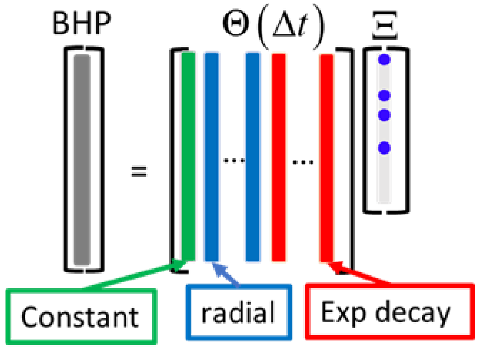
Method	Pavg (psi)	Error (%)
DMD / TDE	4911.96	1.76
OptDMD / TDE	4925.76	1.48
SINDy	5024.11	-0.48

Porosity	0.2
Permeability (mD)	20.0
Reservoir height (ft)	10.0
Flowrate (stb/day)	100.0
Viscosity (cp)	2.0
Initial reservoir pressure (psi)	5000.0
Formation volume factor (RB/STB)	1.0
Wellbore storage coefficient (bbl/psi)	0.001









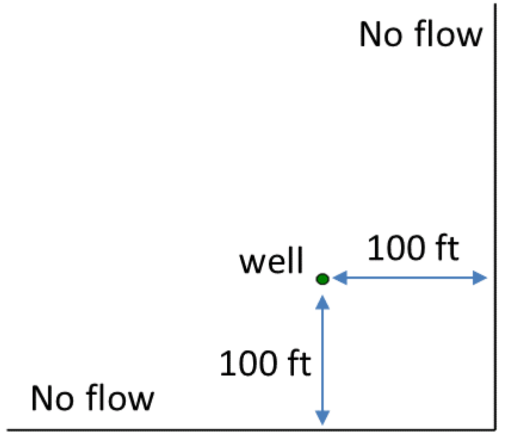
Case Studies

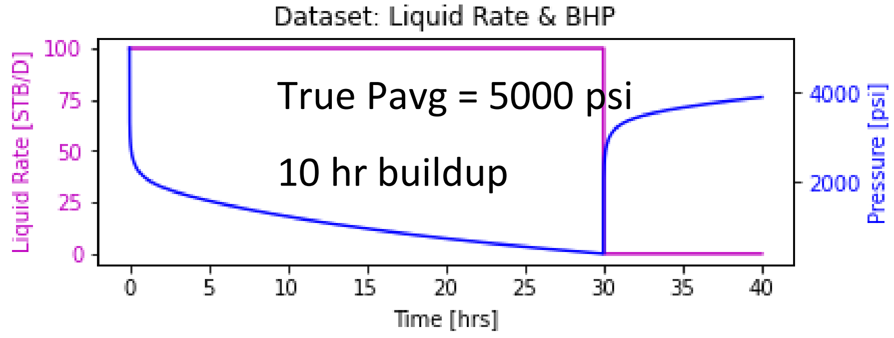
- **Average Reservoir Pressure**

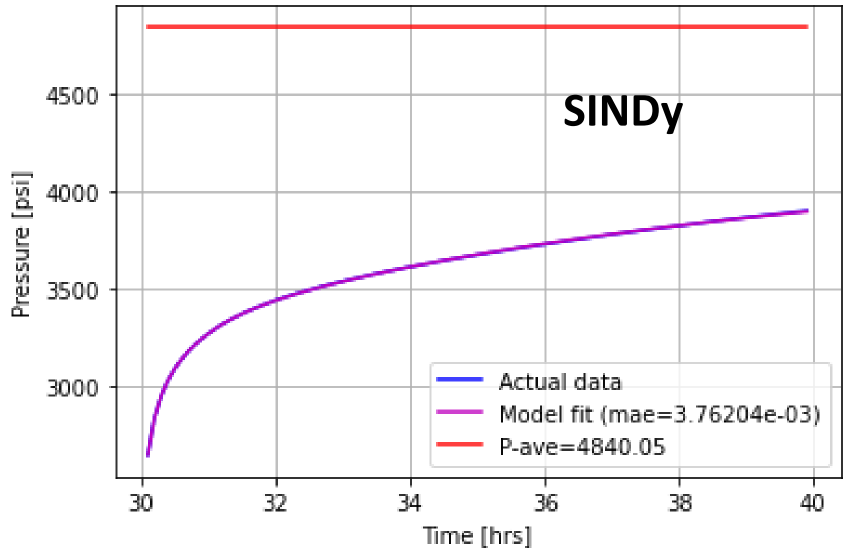
Case 2 – Two perpendicular no-flow boundaries

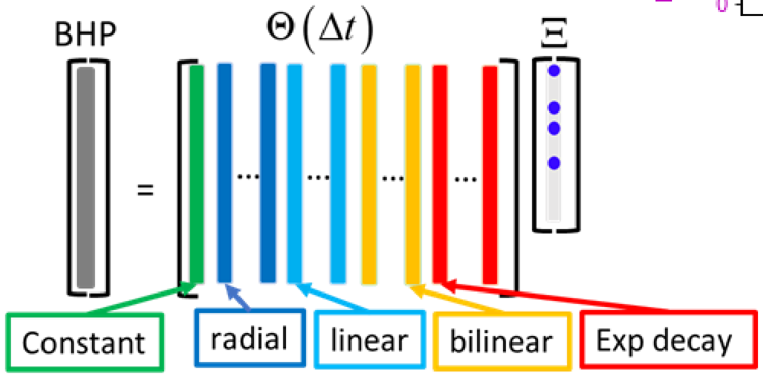
Method	Pavg (psi)	Error (%)
Horner	4459.00	10.82
Kuchuk	4262.57	14.75
Crump	4270.15	14.60
SINDy	**4840.05**	**3.20**

Porosity	0.2
Permeability (mD)	10.0
Viscosity (cp)	2.0
Formation volume factor (RB/STB)	1.0
Total compressibility (1/psi)	5.0E-6
Flowrate (stb/day)	100.0
Initial reservoir pressure (psi)	5000.0
Reservoir height (ft)	10.0
Wellbore radius (ft)	0.32







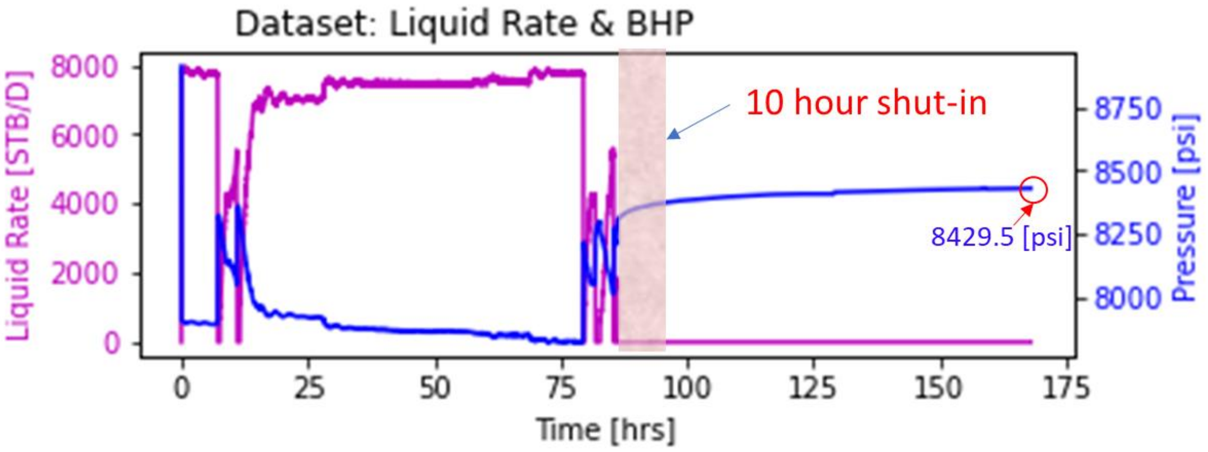


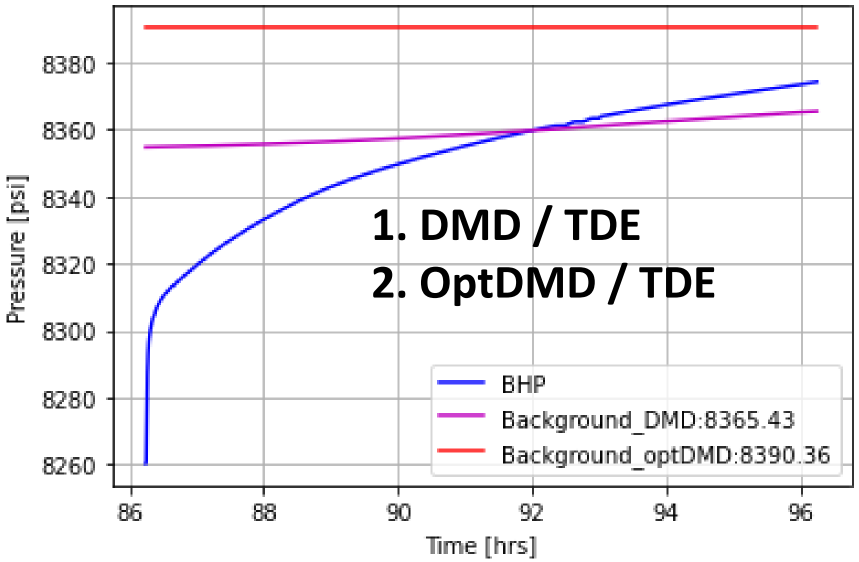
Case Studies

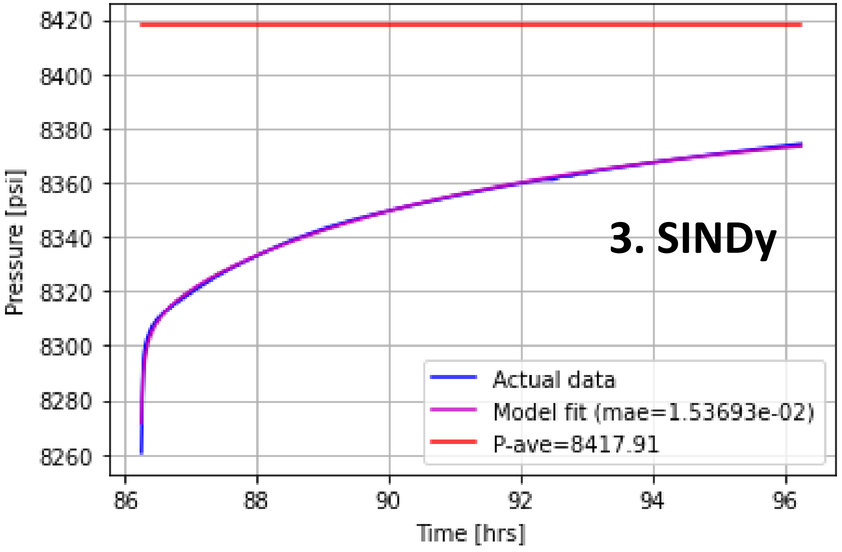
- **Average Reservoir Pressure**

Case 3 – Field A (Offshore Gulf of Mexico)

Method	Pavg (psi)	Error (%)
DMD / TDE	8365.43	0.76
OptDMD / TDE	8390.36	0.46
SINDy	8417.91	0.14

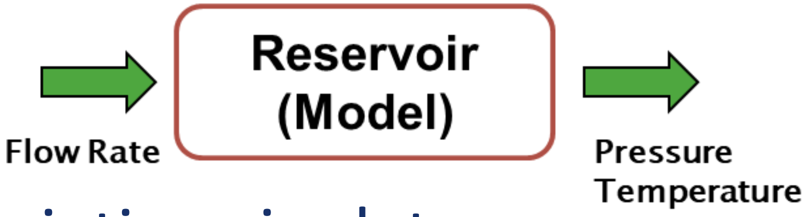


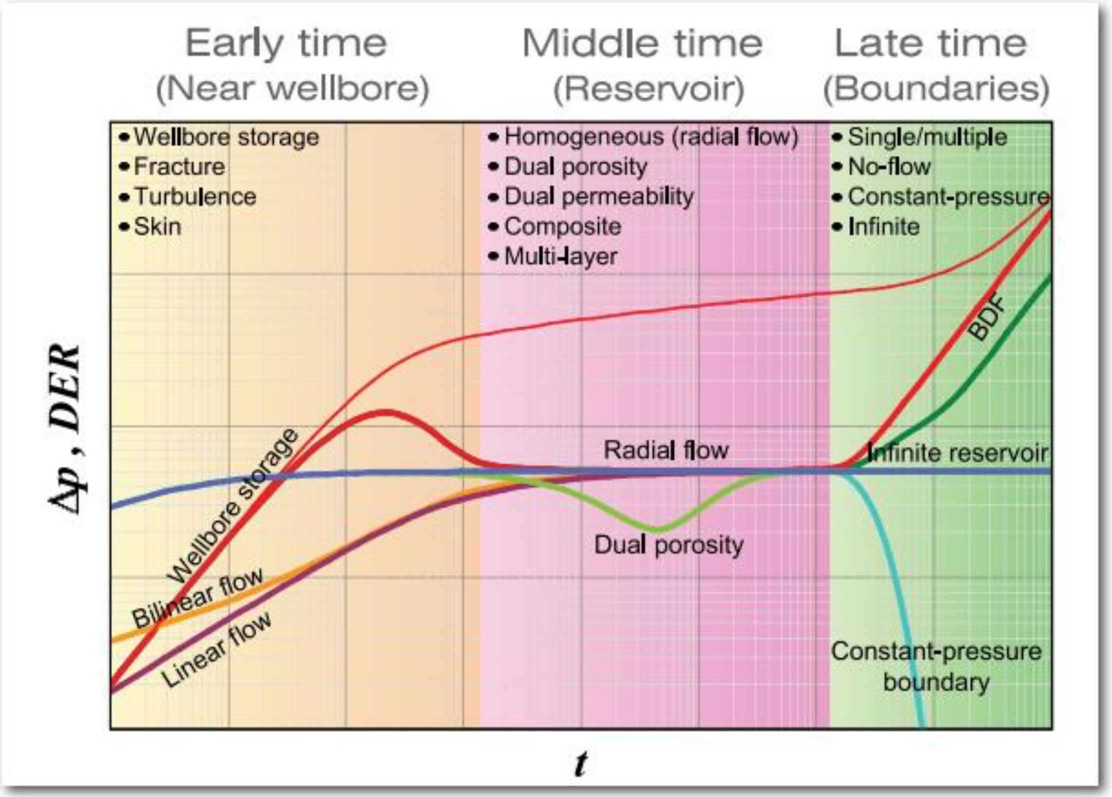




Pressure Transient Analysis

- **Productivity Index**
  - Could we estimate PI without shutin?
  - Build reservoir model from routine operational variations in data





Flow regime		Derivative Slope	Time Function*
Wellbore storage		1	t
Bilinear flow		1/4	$\sqrt[4]{t}$
Linear flow	fracture	1/2	$\sqrt{t}$
	horiz. well		
Spherical flow		-1/2	$1/\sqrt{t}$
Vertical radial flow in horizontal wells		0	$\log(t)$
Radial flow (∞-acting)		0	$\log(t)$
Linear flow – Channel		1/2	$\sqrt{t}$
Boundary-Dominated Flow		1	t

Physics-Inspired ML Features

- **Productivity Index**

Develop hybrid models (physics + ML) describing relationships between well rate and BHP

Solve regression problem: $$\boxed{y^{(i)} = \theta^T x^{(i)}\,,\; i = 1,\ldots,n}$$

Response variable: Pressure

$$y^{(i)} = \Delta p^{(i)}\,,\; i = 1,\ldots,n$$

BHP Prediction
(virtual shut-in)

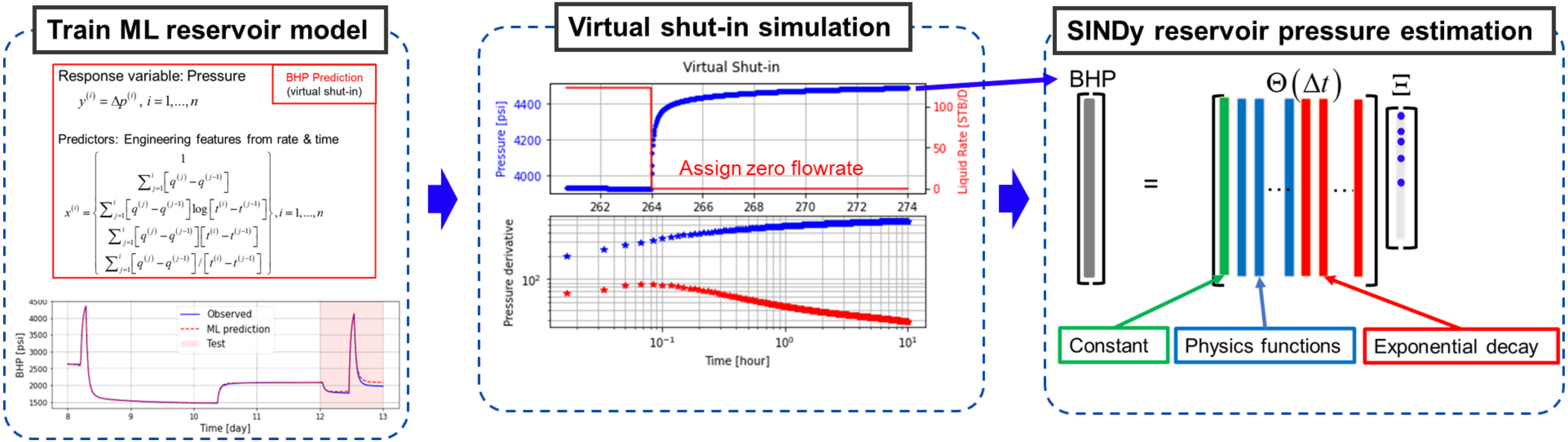
Predictors: Engineering features from rate & time

$$x^{(i)} = \left\{\begin{array}{c} 1 \\ \sum_{j=1}^{i}\left[q^{(j)} - q^{(j-1)}\right] \\ \sum_{j=1}^{i}\left[q^{(j)} - q^{(j-1)}\right]\log\left[t^{(i)} - t^{(j-1)}\right] \\ \sum_{j=1}^{i}\left[q^{(j)} - q^{(j-1)}\right]\left[t^{(i)} - t^{(j-1)}\right] \\ \sum_{j=1}^{i}\left[q^{(j)} - q^{(j-1)}\right]/\left[t^{(i)} - t^{(j-1)}\right] \end{array}\right\},\; i = 1,\ldots,n$$

Reference: Tian et al (SPE 174034), Nagao et al (SPE-209300-MS)

Workflow Methodology

• Productivity Index

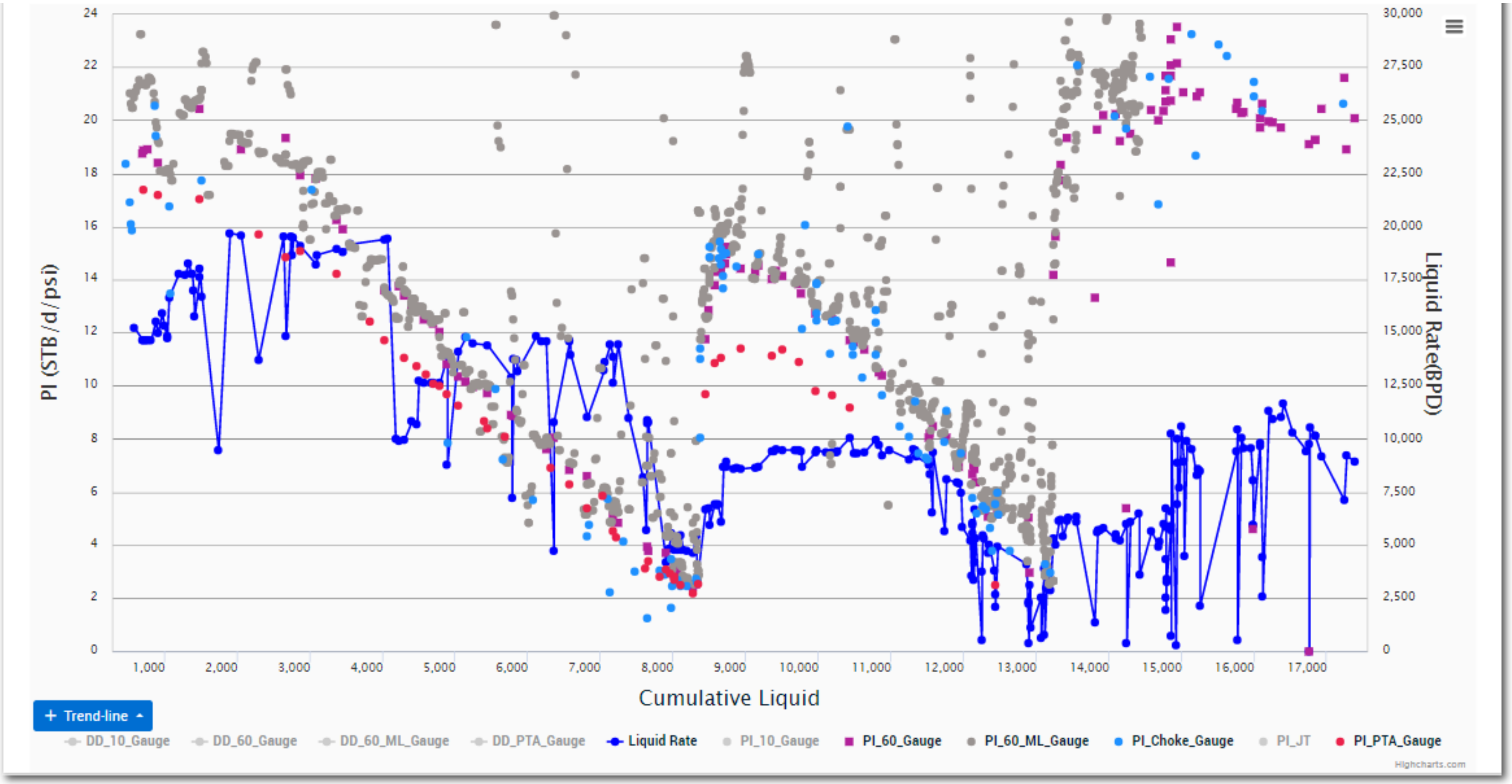


Reference: *Tian and Horne (2015), Sankaran et al (2017)*

Physics-Inspired ML Features

- **Productivity Index**

Develop hybrid models (physics + ML) describing relationships between well rate and BHP



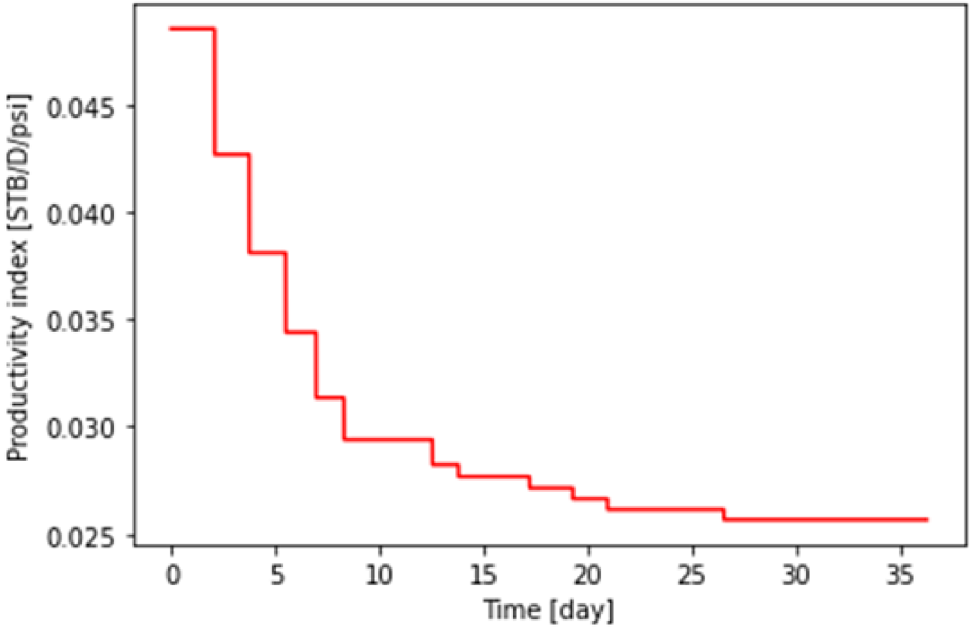
Reference: Sankaran et al (SPE 187222)

Case Studies

- **Productivity Index**

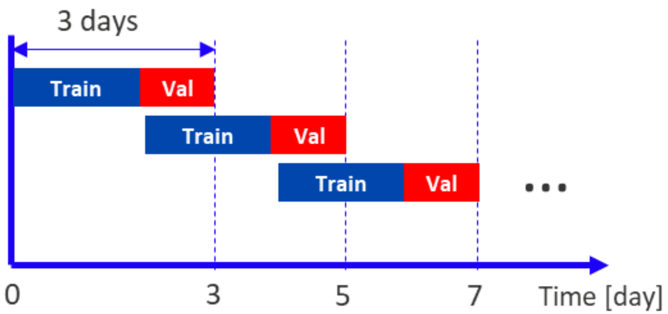
Case 4 – Declining well productivity

- Finite radial flow with closed boundary
- Variable skin, wellbore storage
- PI decline

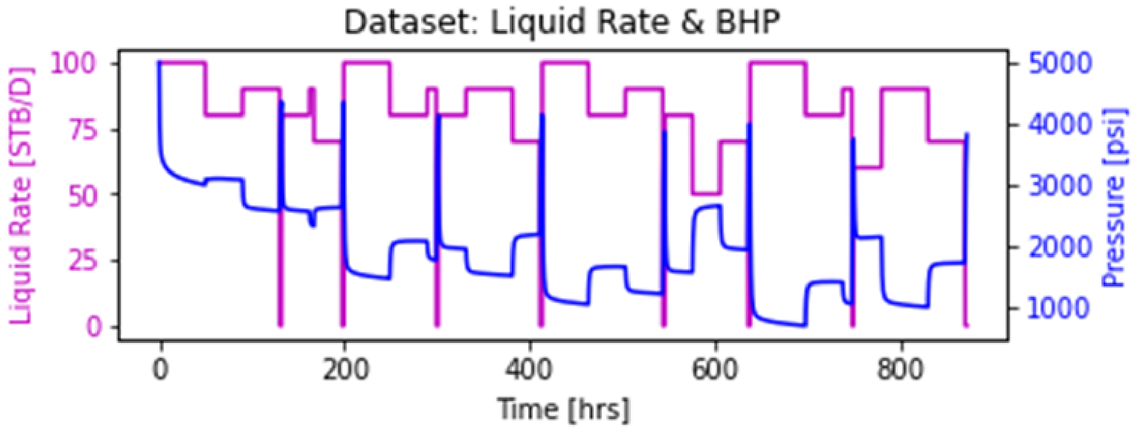


Reservoir and well properties

perm	20 md
h	10 ft
poro	0.2
Ct	5E-6 1/psi
r_w	0.32
viscosity	2 cp
Pi	5000 psi
B	1 RB/STB
r_e	1000 ft
C	0.001 STB/psi



Sliding window for model training

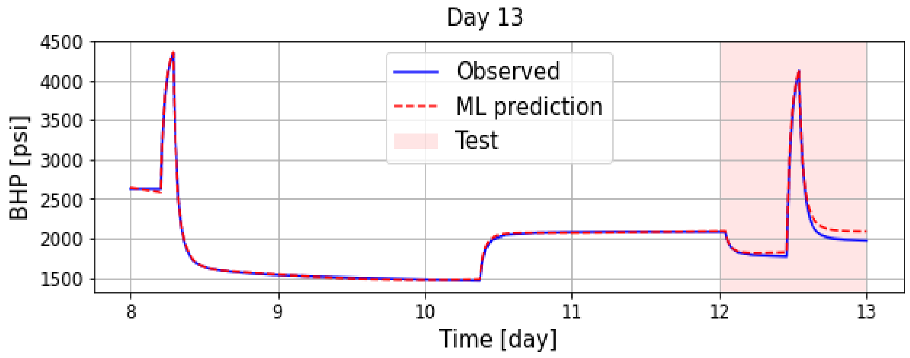


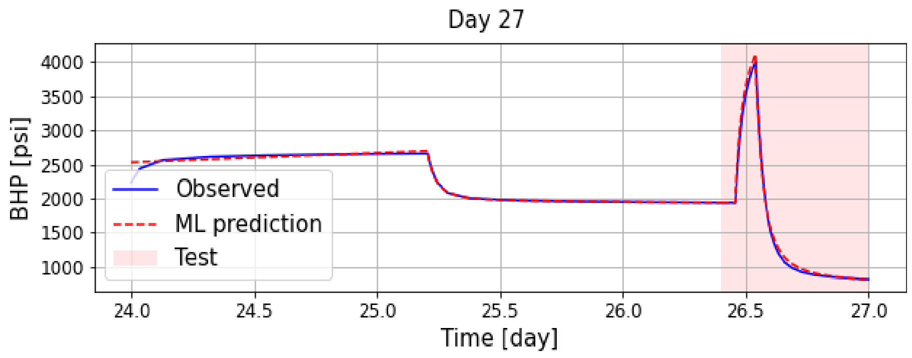
Reference: Nagao et al (SPE-209300-MS)

Case Studies

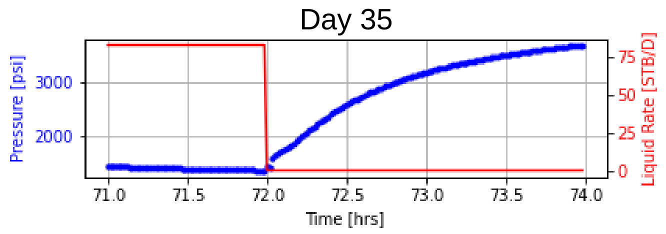
- **Productivity Index**

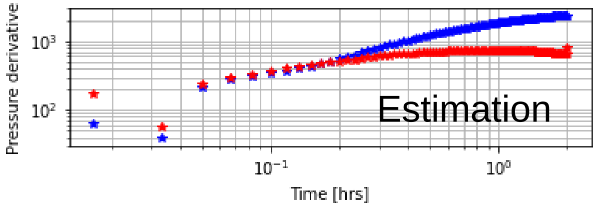
BHP prediction results for selected time frames



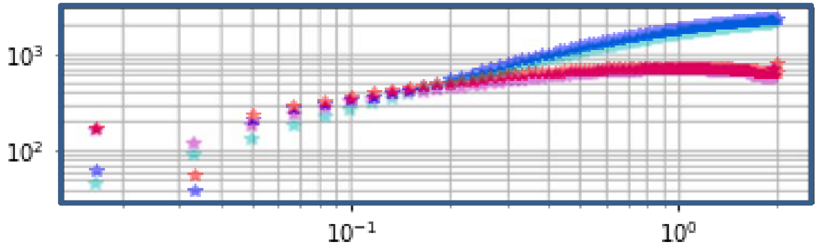


Virtual shut-in results

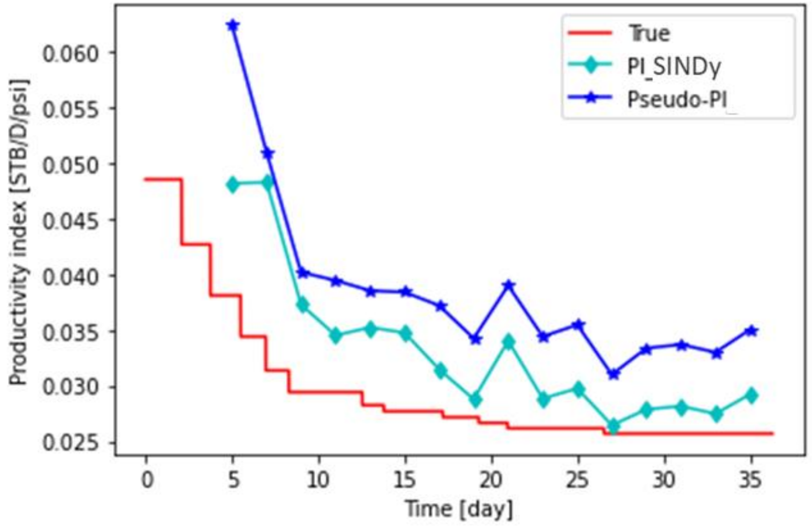




True vs Calculated
Pressure Derivatives



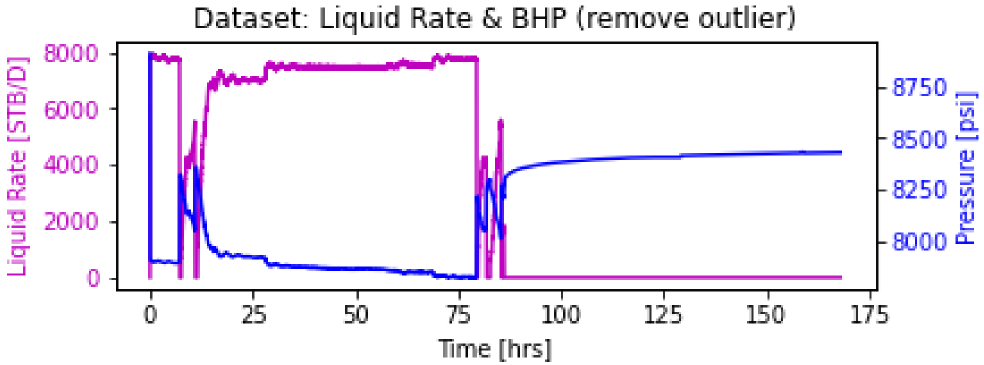
Productivity Index

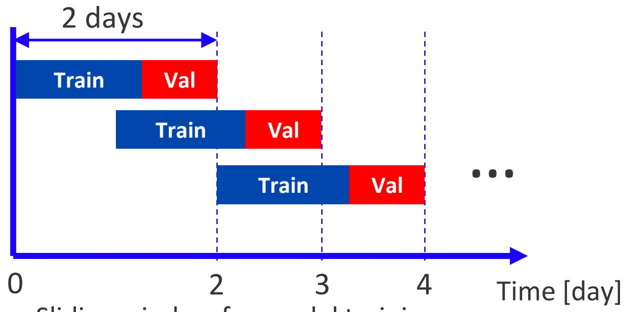


Case Studies

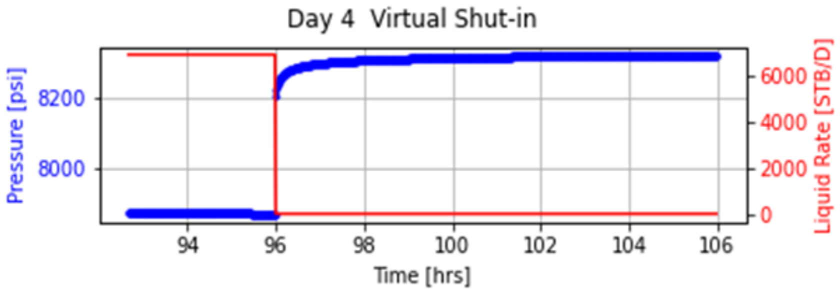
- **Productivity Index**

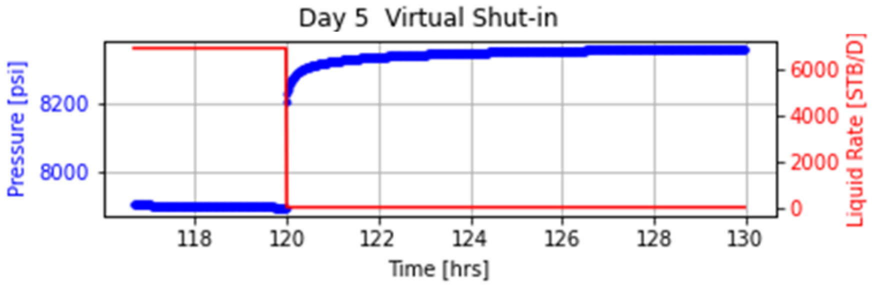
  Case 5 – Field Application

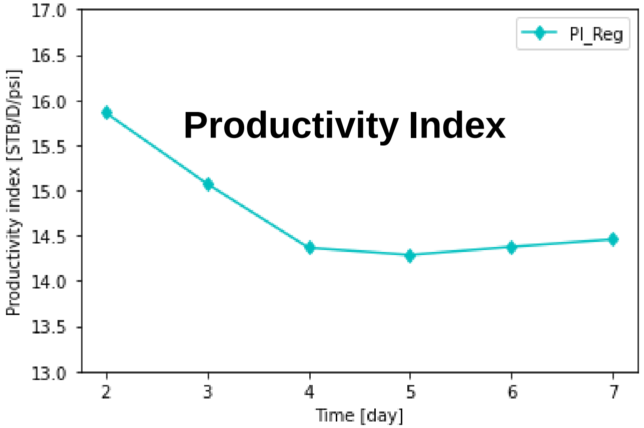




Sliding window for model training







Reference: Nagao et al (SPE-209300-MS)

Virtual Metering

- **Estimate rates from pressure**

$$y^{(i)} = \theta^T x^{(i)}, \; i = 1, \ldots, n$$

Response variables: Rate

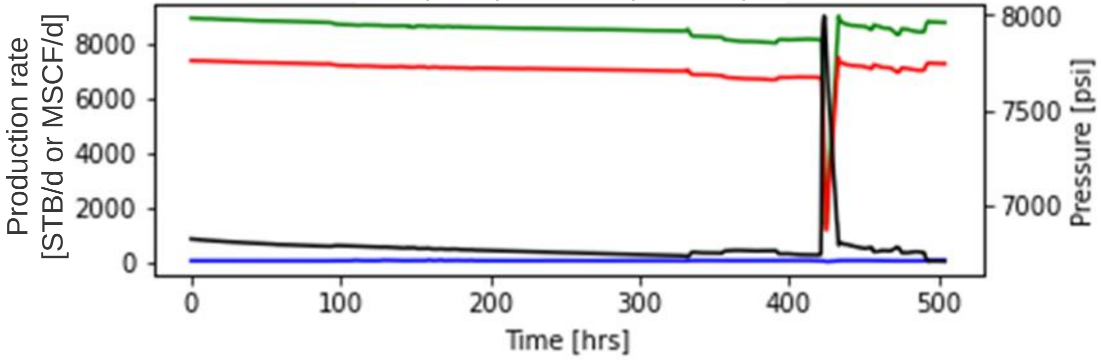
$$y^{(i)} = \Delta q^{(i)}, \; i = 1, \ldots, n$$

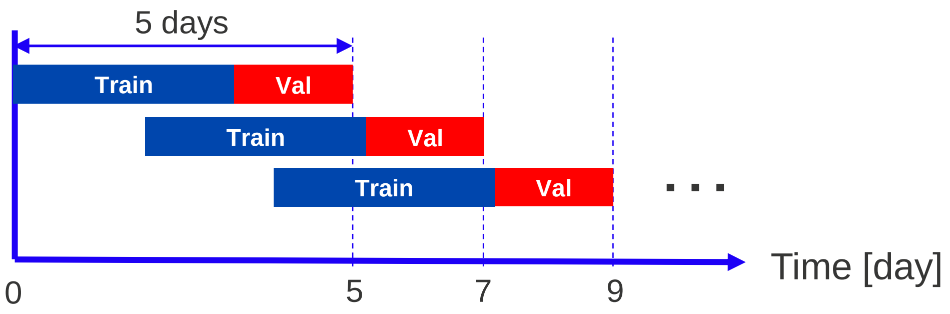
Rate Prediction
(virtual metering)

Predictors: Engineering features from BHP & time

$$x^{(i)} = \left\{ \begin{array}{c} 1 \\ \sum_{j=1}^{i} \left[p^{(j)} - p^{(j-1)} \right] \\ \sum_{j=1}^{i} \left[p^{(j)} - p^{(j-1)} \right] \log \left[t^{(i)} - t^{(j-1)} \right] \\ \sum_{j=1}^{i} \left[p^{(j)} - p^{(j-1)} \right] \left[t^{(i)} - t^{(j-1)} \right] \\ \sum_{j=1}^{i} \left[p^{(j)} - p^{(j-1)} \right] / \left[t^{(i)} - t^{(j-1)} \right] \end{array} \right\}, i = 1, \ldots, n$$

Field data: multiphase flow rate and BHP
(data point: every minute)



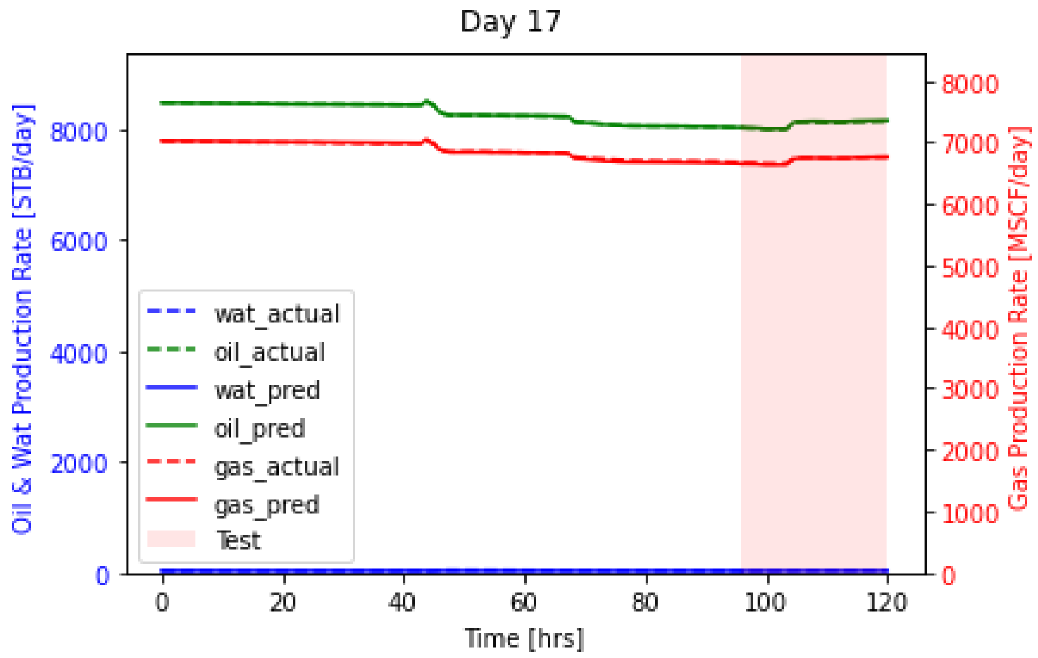


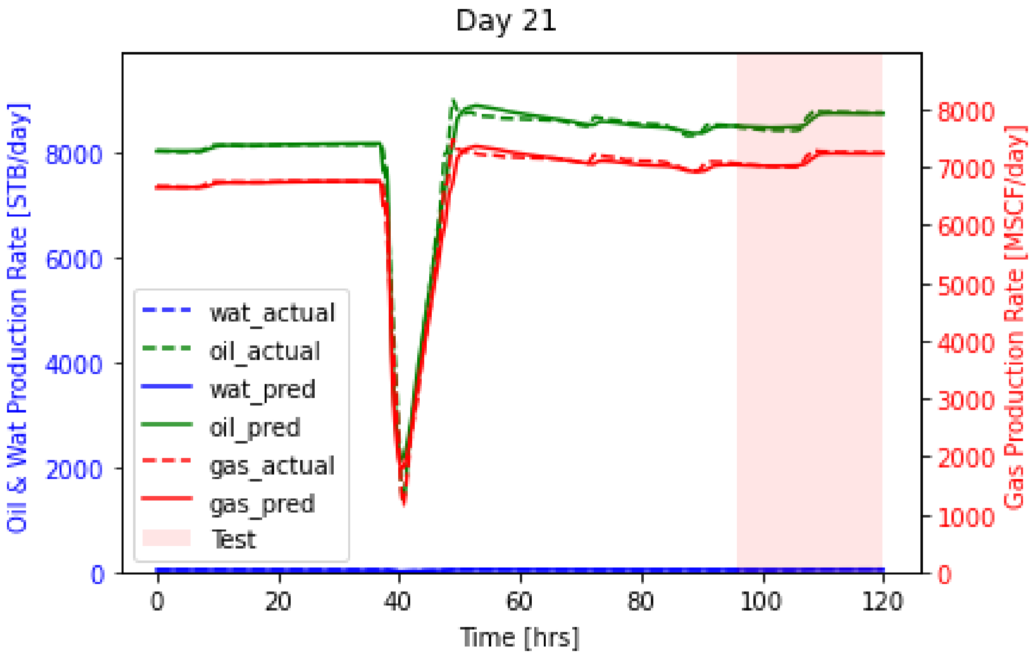
Reference: Nagao et al (SPE-209300-MS)

Case Studies

- **Virtual Metering**

Case 6 – Field application





Summary

- **Hybrid models enable field-scale automation**
  - Balances speed, fidelity, physical consistency and interpretability for field optimization

- **Data-driven discovery of reservoir physics could lead to better interpretations for traditional workflows or new understanding**

Knowledge is of two kinds. We know a subject ourselves, or we know where we can find information upon it.

Samuel Johnson (1709 – 1784)

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