معهد الكويت للأبحاث العلمية
Kuwait Institute for Scientific Research

Modeling of Co-Current Crude Oil-Gas Flow in a Commercial Pipeline

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Outline

- Examining the proposed model for two-phase flow

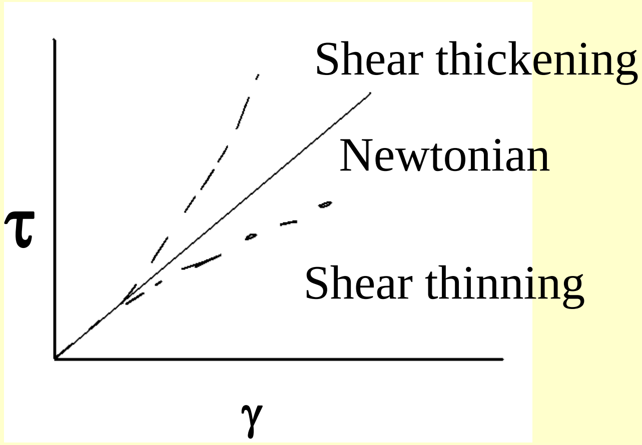
- Commercial Application

- Examine the adequacy of the model for real data of Crude Oil-Gas Pipeline

-Main conclusion and recommendations

Homogeneous Flow Model

- **Newtonian Flow ($\tau= -\mu\gamma$)**
- **Non-Newtonian**
  - **Viscoelastic**
  - **Pseudoplastic**
    - Bingham plastic **($\tau=\mu_0-\mu\gamma$)**
    - Power law **($\tau= -k\gamma^n$)**
    - Herschel Bulkley Model **($\tau=\mu_0-k\gamma^n$)**

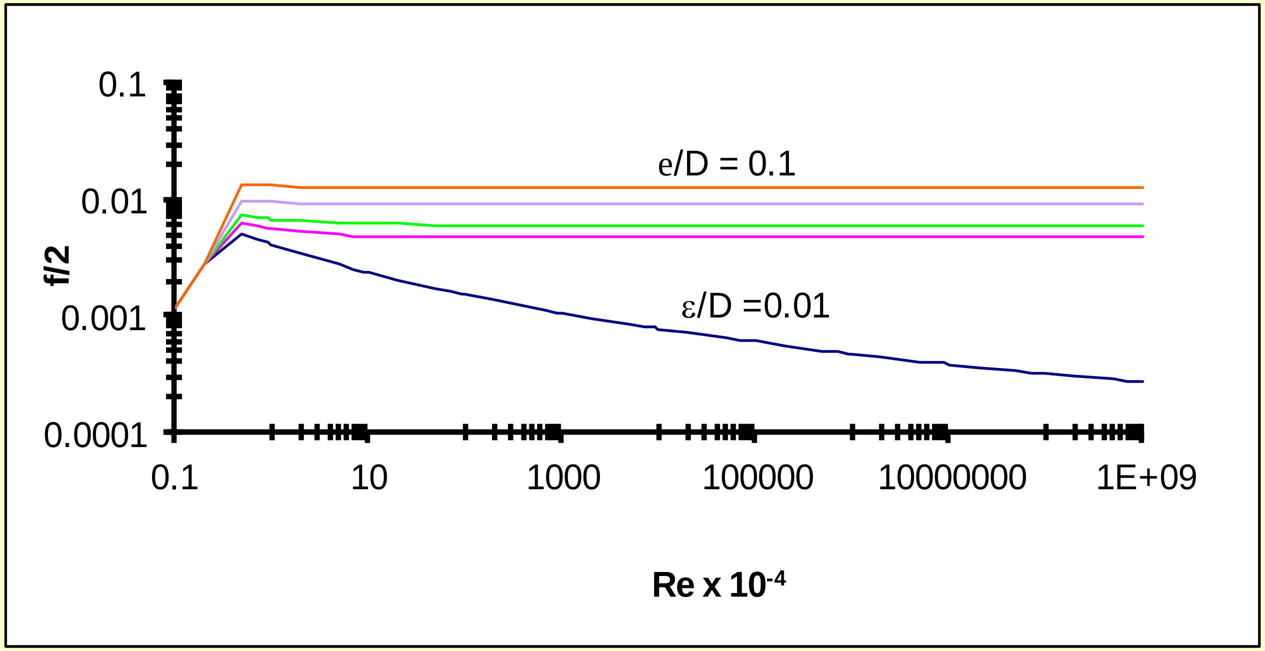


Pseudo-Homogeneous Model

Churchill Eqn.

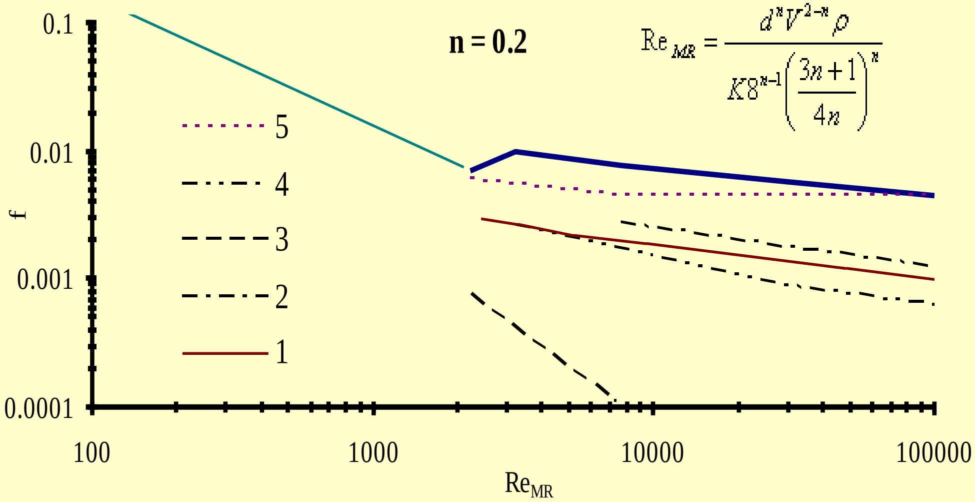
$$f = \sqrt[12]{\left(\frac{8}{Re^{12}} + \sqrt{(A+B)^3}\right)}$$

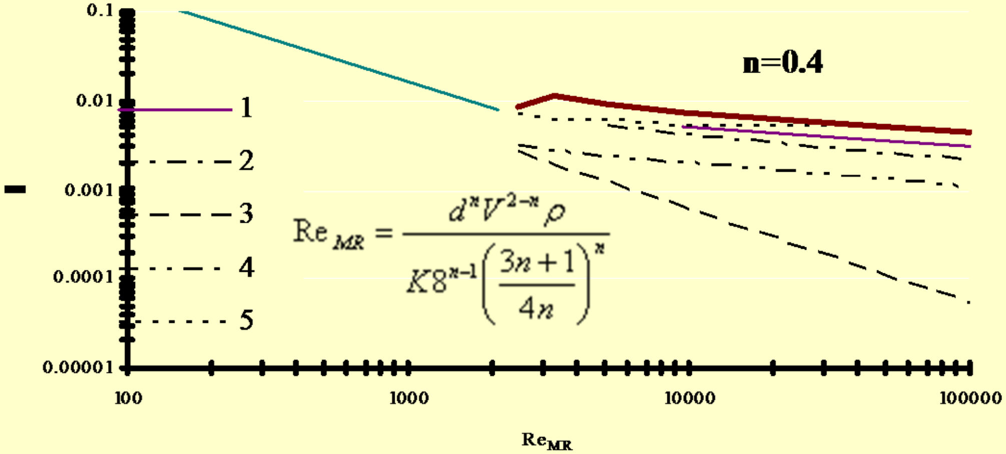
$$A = \left[-2.457\ln\left(\frac{7}{Re^{0.9}} + 0.27\frac{\varepsilon}{D}\right)\right]^{16} \text{ and } B = \left(\frac{37530}{Re}\right)^{16}$$



Non-Newtonian (Power Law)

5. Kembluoski et al. (1962), 4. Thomas (1978), 3. Shaver & Merrill (1959), 2. Tomita (1959), 1. Metzner & Reed (1955)





Study Objective

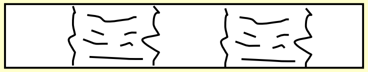
The aim of this study is to check the published models in the literature for two phase flow based on small laboratories experimental setups for air-water flow in 1” or 2” (25 mm, 50 mm) diameter pipes

1. To determine the characteristics of the specific Crude Oil
2. Formulating the problem by dividing total submarine pipeline of 42 km length into n continuous segments
3. Pressure drop calculation in each segment, knowing only the discharge pressure.
4. Applying Flash calculation for each segment to know the gas generated that equilibrate with flowing crude at given Pressure

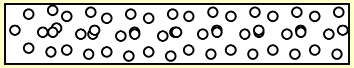
Two-phase flow and Flow pattern

- **Stratified flow**

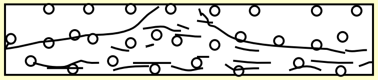
- **Plug flow**



- **Bubbly flow**



- **Segregated flow**



$$\chi = \sqrt{\frac{-\Delta P_G}{-\Delta P_L}}, \quad \phi_G = \sqrt{\frac{-\Delta P_{TP}}{-\Delta P_G}}, \quad \phi_L = \sqrt{\frac{-\Delta P_{TP}}{-\Delta P_L}}$$

$$\phi_G^2 = \lambda^{0.205} \qquad \text{for } 0.6 < \lambda < 1$$

$$\phi_G^2 = 1 - 0.031\lambda^{-2.25} \qquad \text{for } 0.35 < \lambda < 0.6$$

$$\phi_G^2 = 1.95\lambda \qquad \text{for } 0.05 < \lambda < 0.35$$

$$\text{where } \lambda \text{ is } \left(\frac{V_{SL}}{V_{SLC}}\right)^{1-n}$$

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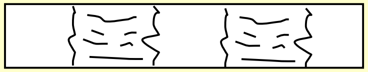

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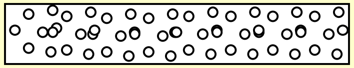

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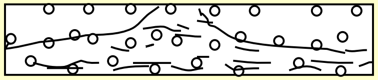

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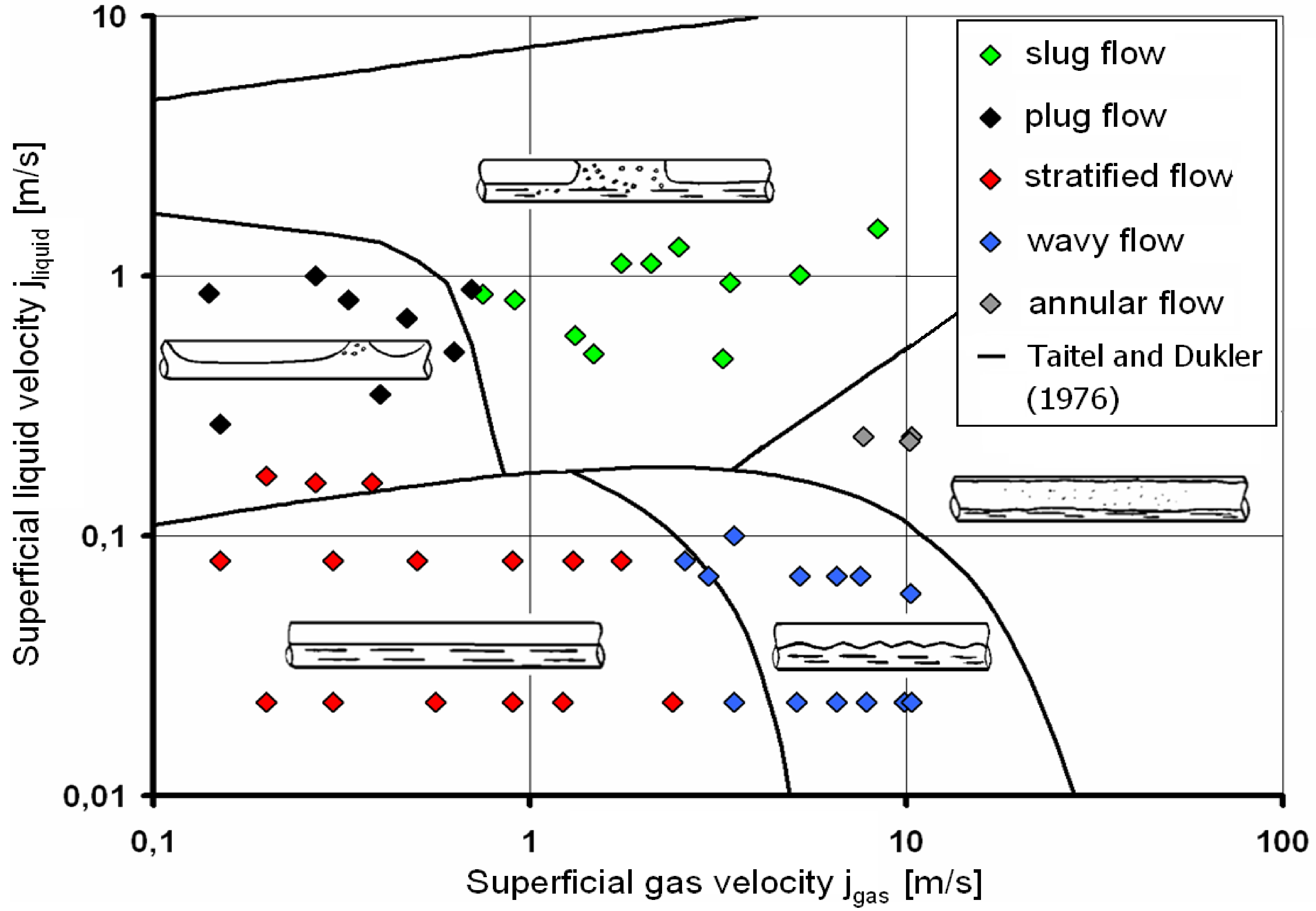
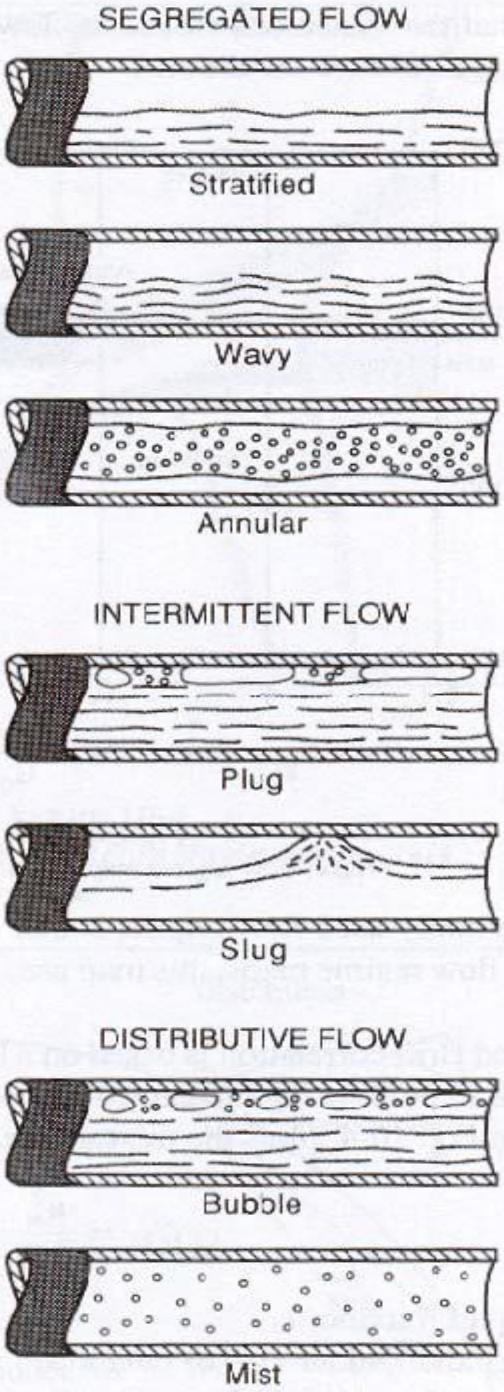
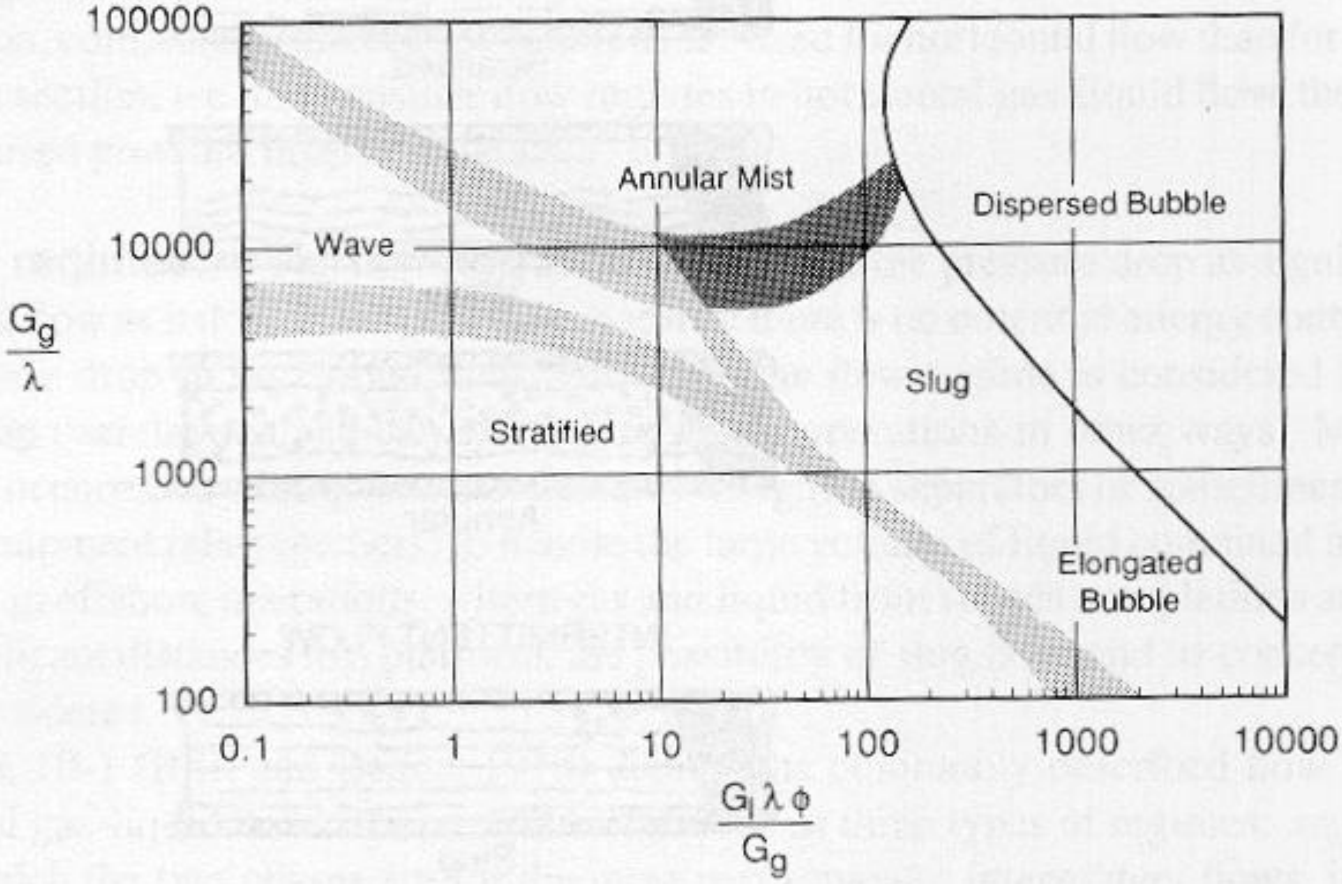

10
1
0,1
0,01
0,1
1
10
100
Superficial liquid velocity j_{liquid} [m/s]
Superficial gas velocity j_{gas} [m/s]
slug flow
plug flow
stratified flow
wavy flow
annular flow
Taitel and Dukler (1976)


SEGREGATED FLOW
Stratified
Wavy
Annular
INTERMITTENT FLOW
Plug
Slug
DISTRIBUTIVE FLOW
Bubble
Mist


100000
10000
1000
100
0.1
1
10
100
1000
10000
$\frac{G_g}{\lambda}$
$\frac{G_l \lambda \phi}{G_g}$
Wave
Annular Mist
Dispersed Bubble
Stratified
Slug
Elongated Bubble

Multistage separation Test

Stage No	First		Second	
Pressure (kPa)	2171	2171	517	517
Temp. (^oC)	41	41	38	38
Method	measured	Flash Calc.	measured	Flash Calc.
Component	Mole Fraction	Mole Fraction	Mole Fraction	Mole Fraction
H_2S	0.00009	0.0013	0.0002	0.0029
N_2	0.01	0.0099	0.0023	0.0025
CO_2	0.0187	0.0168	0.0228	0.021
CH_4	0.7296	0.7062	0.5116	0.4136
C_2H_6	0.1527	0.163	0.2759	0.1913
C_3H_8	0.0632	0.0725	0.1361	0.0138
i-C_4H_{10}	0.0041	0.0046	0.0088	0.0484
n- C_4H_{10}	0.0131	0.0157	0.027	0.0078
i-C_5H_{12}	0.0022	0.0025	0.0041	0.0114
n- C_5H_{12}	0.0032	0.0037	0.0059	0.0059
C_6-Group	0.0022	0.0024	0.0038	0.007
C_7 Group	0.0006	0.0008	0.0009	0.0023
C_8-Group	0.0002	0.0004	0.0	0.001
C_9-Group	0.0001	0.0	0.0001	0.0002
C_{10}-Group	0.0001	0.0	0.0001	0.0001
C_{11}-Group	0.0	0.0	0.0	0.0
Total	1.00	1.00	1.0	1.0

Comparison

Pressure (kPa)	Temperature (^{o}C)	Gas/Oil Ratio Measured	Gas/Oil Ratio calc.	Abs. % error
2171	41	312	324	3.84
517	38	78	95	21.7
103	32	93	70	24.73
Mean				16.8

Calculation of Thermo-physical properties

- **Thermo-physical properties were calculated for oil and gas over pressure range 1790-687 kPa using Hysys version 3.1 The UIQUAC equation of state was used.**

$$\rho_{\mathrm{L}}\,(kg\,m^{-3}) = -6.605x10^{-3}\,\mathrm{P} + 839.07$$

$$\rho_{\mathrm{G}}\,(kg\,m^{-3}) = 7.7x10^{-3}\,\mathrm{P} + 1.82$$

$$\mu_{\mathrm{L}}\,(Pa\ s) = -8.139x10^{-7}\,\mathrm{P} + 0.0059$$

$$\mu_{\mathrm{G}}\,(Pa\ s) = 6.657x10^{-6}\,\mathrm{P}^{0.0714}$$

$$\sigma_{\mathrm{L}}\,(N\ m^{-1}) = 2.999x10^{-10}\,\mathrm{P}^{2} - 2.223\mathrm{x}10^{-6}\,\mathrm{P} + 0.022$$

$$\frac{\mathrm{Q_G}}{Q_{inlet}} = 11.091\left(\frac{P_i}{P_{inlet}}\right)^4 - 37.605\left(\frac{P_i}{P_{inlet}}\right)^3 + 49.352\left(\frac{P_i}{P_{inlet}}\right)^2 - 30.91\left(\frac{P_i}{P_{inlet}}\right) + 8.09$$

Pressure Drop Models

Total ΔP per unit length is sum of frictional, gravitational and accelerational

$$-\left(\frac{dP}{dz}\right)_T = -\left(\frac{dP}{dz}\right)_f - \left(\frac{dP}{dz}\right)_g - \left(\frac{dP}{dz}\right)_a$$

Beggs & Brill (1973

$$-\left(\frac{\mathrm{dP}}{\mathrm{dz}}\right) = \frac{f_{\varphi}\mathrm{G_m v_m}}{2\mathrm{g_c d}} \quad \text{and } f\varphi = f_{\mathrm{ns}}.e^{\mathrm{S}}$$

$$\lambda = \frac{\mathrm{Q_L}}{\mathrm{Q_L}+\mathrm{Q_G}} \quad \text{and } \mathrm{y} = \frac{\lambda}{\left[\mathrm{H_L}(\theta)\right]^2} \quad \text{For } 1<\mathrm{y}<1.2,\ \mathrm{S}=\ln(2.2\mathrm{y}-1.2)$$

$$S = \left[\frac{\ln(y)}{-0.0523+3.182\ln(y)-0.8725[\ln(y)]^2+0.01853[\ln(y)]^4}\right]$$

$$f_{ns} = \left[2\log\left(\frac{\mathrm{Re}_{ns}}{4.5223\log(\mathrm{Re}_{ns})-3.8215}\right)\right]^{-2} \quad \text{and } \mathrm{Re_{ns}} = \frac{[\rho_L\lambda+\rho_G(1-\lambda)]v_m d}{[\mu_L\lambda+\mu_G(1-\lambda)]}$$

1. Continued

Mukherjee & Brill (1985)

$$-\left(\frac{\mathrm{dP}}{\mathrm{dz}}\right)=\frac{f_{ns}\mathrm{v}_{\mathrm{m}}^{2}\gamma_{\mathrm{m}}}{2\mathrm{gd}} \quad \text{and } \gamma_{\mathrm{m}}=\mathrm{H}_{\mathrm{L}}\gamma_{\mathrm{L}}+\mathrm{H}_{\mathrm{g}}\gamma_{\mathrm{g}}$$

$$f_{ns}=\left[2\log\left(\frac{\mathrm{Re}_{ns}}{4.5223\log(\mathrm{Re}_{ns})-3.8215}\right)\right]^{-2} \quad \text{and } \mathrm{Re}_{ns}=\frac{[\rho_L\lambda+\rho_G(1-\lambda)]v_m d}{[\mu_L\lambda+\mu_G(1-\lambda)]}$$

$$H_L=\frac{A_L}{A}=\frac{1}{2\pi}(\delta-\sin(\delta)) \quad \text{where } \delta=2\cos^{-1}\left(1-2\frac{\mathrm{h}_{\mathrm{L}}}{\mathrm{d}}\right)$$

Oliemans$^{1\,\&2}$(1976)

$$-\left(\frac{\mathrm{dP}}{\mathrm{dz}}\right)_{f,tp}=\frac{f_\varphi G_\varphi^2}{2\rho_\varphi \mathrm{d}_{\mathrm{eff}}} \quad \text{where } G_\varphi=\frac{1}{[1-(H_L-\lambda)]}\frac{w_t}{A_p},\ \mathrm{D}_{\mathrm{eff}}=\sqrt{1-(\mathrm{H}_{\mathrm{L}}-\lambda)}.d$$

$$\rho_\varphi=\rho_{\mathrm{L}}\frac{\lambda}{1-(\mathrm{H}_{\mathrm{L}}-\lambda)}+\rho_{\mathrm{g}}\frac{1-\mathrm{H}_{\mathrm{L}}}{1-(\mathrm{H}_{\mathrm{L}}-\lambda)},\ \mu_\varphi=\mu_{\mathrm{L}}\frac{\lambda}{(\mathrm{H}_{\mathrm{L}}-\lambda)}+\mu_{\mathrm{g}}\frac{1-\mathrm{H}_{\mathrm{L}}}{1-(\mathrm{H}_{\mathrm{L}}-\lambda)} \quad \mathrm{Re}_\varphi=\frac{G_\varphi D_{eff}}{\mu_\varphi}$$

$$\frac{1}{\sqrt{f_\varphi}}=-2\log\left[\frac{2\varepsilon}{D_{eff}}+\frac{18.7}{\mathrm{Re}_\varphi\sqrt{f_\varphi}}\right]+1.74$$

^{1}H$_\mathrm{L}$ calculated using (Mukherjee and Brill)
^{2}H$_\mathrm{L}$ calculated using (Beggs and Brill)

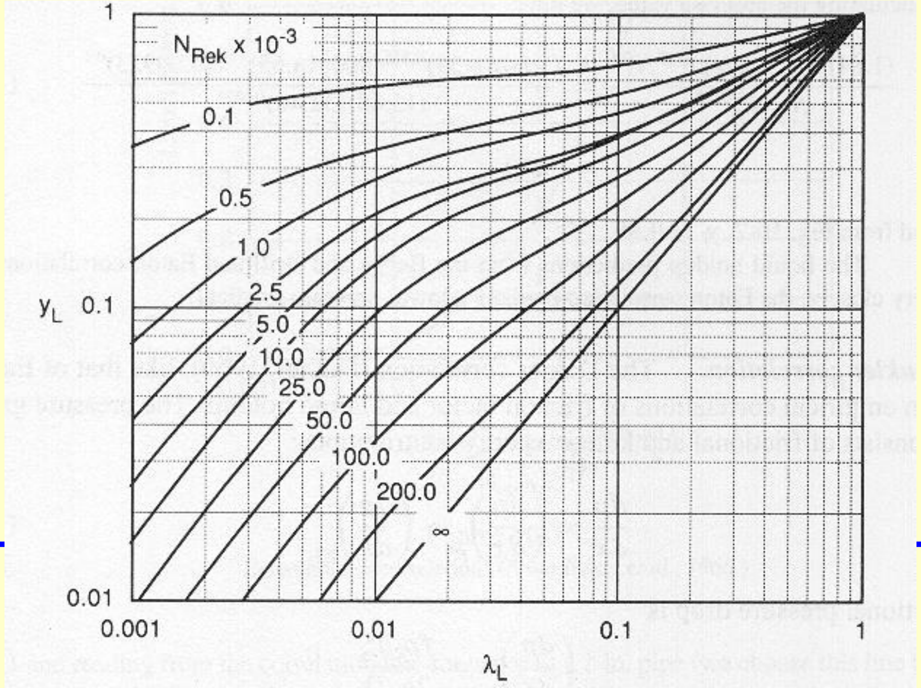
2. Continued

Dukler(1969)

$$-\left(\frac{\mathrm{dP}}{\mathrm{dz}}\right)_f = \frac{f\rho_k v_m^2}{2\mathrm{d}_{\mathrm{eff}}} \quad \text{where } \rho_k = \frac{\rho_L\lambda_L^2}{H_L}+\frac{\rho_g\lambda_g^2}{H_g}, \lambda_{\mathrm{L}} = \frac{v_{SL}}{v_m},\ \ \lambda_{\mathrm{g}} = \frac{v_{Sg}}{v_m}$$

$$\mu_k = \mu_{\mathrm{L}}\lambda_L + \mu_{\mathrm{g}}\lambda_g, \mathrm{Re}_k = \frac{\rho_k v_m d}{\mu_k},\ \ \mathrm{y} = \text{-}\ln\left(\lambda_{\mathrm{L}}\right) \text{and } f_{\mathrm{k}} = 0.0056 + 0.5\mathrm{Re}_{\mathrm{k}}^{-0.32}$$

$$\frac{f}{f_k} = 1 + \frac{y}{1.281 - 0.478y + 0.444y^2 - 0.094y^3 + 0.0084y^4}$$



Outlet pressure calculated and measured

Correlation	Mean% error	Abs Error	Std. Dev.	NSME	Roughness (μm)
B&B (1973)	**6.24**	**20.16**	**212.98**	**0.102**	**950**
M&B (1985)	**4.77**	**17.98**	**193.57**	**0.0864**	**1335**
O^1(1976)	**5.02**	**20.69**	**229.72**	**0.1325**	**980**
O^2(1976)	**3.0**	**18.0**	**188.93**	**0.1325**	**980**
D(1969)	**-27.36**	**27.36**	**225.49**	**0.0638**	**>2500**

The results are based on optimum roughness values

Outlet pressure calculated and measured

Correlation	Mean% error	Abs Error	Std. Dev.	NSME	Equivalent Diameter
B&B (1973)	**-8.25**	**12.45**	**190.68**	**0.0542**	**0.605**
M&B (1985)	**4.06**	**12.64**	**207.24**	**0.0728**	**0.509**
O^1(1976)	**10.86**	**15.14**	**204.63**	**0.061**	**0.604**
O^2(1976)	**5.42**	**10.67**	**195.59**	**0.0655**	**0.567**
D(1969)	**12.9**	**17.44**	**196.31**	**0.0707**	**0.538**

The results are based on optimum Equivalent Diameter

Conclusion remarks

- **Flash calculations were performed using the process simulator Hysys version 3.1 based on PVT data obtained from the PVT laboratory in PRC in KISR**
- **Flow through the pipeline was simulated using a comprehensive computer program written using the C++. The program calculated outlet pressure based on inlet pressure, volumetric flow, thermo-physical properties, size of pipeline and its elevation as a function of distance along its length.**

- Five most commonly used correlations were used to evaluate surface roughness in the pipe.

- The same exercise was repeated fixing the roughness value and determining equivalent diameter as pipeline had particle deposition.

Conclusion remarks

- **All correlation presented that single-phase flow occured initially within the pipeline due to high inlet pressure. The onset of two phase flow was predicted to occur within the second half of the 42km pipeline.**

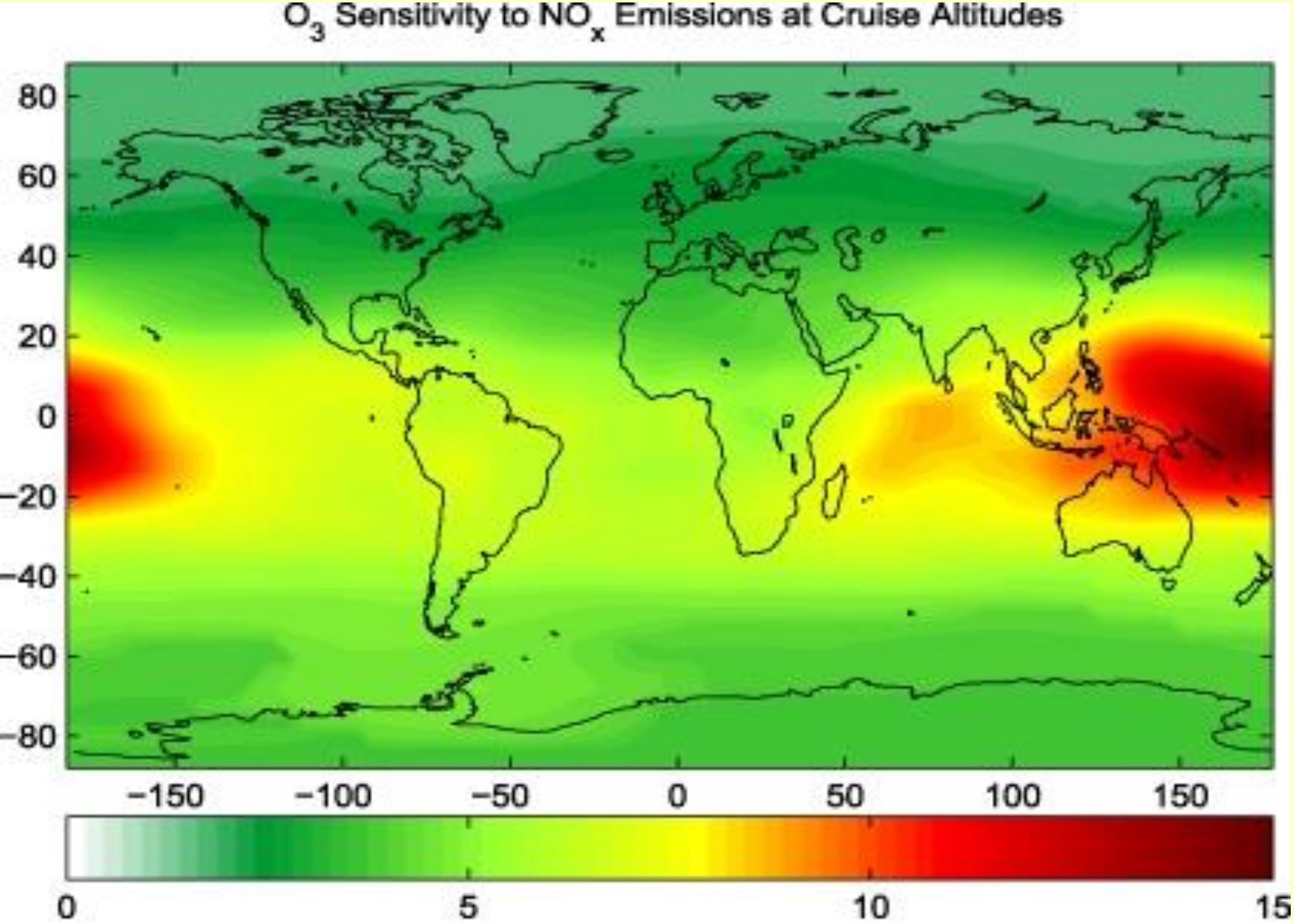
- **Two approached were adopted, first one determining pipe-roughness was used as fitting parameter. The obtained values for 30 different flow conditions were 20 to 50 times the published value for new wrought iron pipe.**

- **In second approach, the possibility of partial blockage by deposition of sand and silt was explored. The results showed 8.1% to 14.3% solid holdup that was somehow satisfactory as the pipeline has been laid before 30 years.**

Conclusion remarks

- **Both methods indicated that Oliemans (1976) correlation with liquid holdup calculated using Beggs and Brill(1973) has provided the best overall fit to the entire data.**

NOx-related O_3 impact from Temporal and spatial variability in the aviation Industry



Gilmore, C.K., Barrett, S.R.H., Koo, J and Wang, O. , **“Temporal and spatial variability in the aviation NO_x-related O_3 impact”,** *Environ. Res. Lett.* **8**:(3) doi:10.1088/1748-9326/8/3/034027

Figure 3 from Temporal and spatial variability in the aviation NOx-related O_3 impact