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SYNERGETIC EFFECT OF A DRAG REDUCER AND PIPELINE INTERNAL COATING ON CAPACITY ENHANCEMENT IN OIL AND GAS PIPELINES: A CASE STUDY

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Abstract

A case study of a 20-inch diameter gas transmission pipeline assesses theoretically how the synergetic use of pipeline internal coating and drag reducing agent increases the flow rate of a pipeline and its impact on the pipe internal friction. The American Gas Association (AGA) equation and Modified Colebrook-White equations were both used to estimate the capacity of the pipeline in its existing state, after internally coating and after injecting a drag reducing agent in the internally coated pipeline. By means of both AGA equations and Modified Colebrook–White equations, it was observed that Internal coating with surface roughness of 0.0045mm can increase the pipeline capacity (flowrate) by up to 22% for gas pipeline systems. Also, the synergetic use of a pipeline internal coating such as polyamide epoxy or solvent free epoxy and a drag reducing agent with a drag reduction rate of 70% can increase the pipeline capacity (throughput) above 115.53% for GNGC gas pipeline systems. The analysis shows that synergetic use of internal coatings and drag reducers increases the capacity of gas pipelines and is economically justified with a typical payback period of three years.

Keywords*:* *Friction factor, Internal coating, Pipeline capacity, Flowrate, Synergetic effect, Pipe roughness, Drag reducing agent.*

Introduction

The case study analyses theoretically, the synergetic effect of drag reducer and pipeline internal coating on capacity enhancement in Ghana National Gas Company (GNGC) pipelines [1-2]. The Early Phase Gas Infrastructure system comprises the following main elements (see Fig. 1):

a. Offshore gas export pipeline, comprising of a 12” ø 58km long subsea pipeline, transporting dense-phase gas from the Jubilee FPSO to the Gas Processing Plant.

b. Gas Processing Plant (GPP) at Atuabo. The design capacity of the plant is 150 MMscfd and normal design capacity is 120 MMscfd [5, 7-8].

c. Onshore gas transmission pipeline, comprising of a 20” ø 110 km pipeline, transporting sales gas from the GPP to an existing Thermal Power Plant at Aboadze, north-east of Takoradi.

d. A lateral pipeline from Essiama to Prestea, comprising of a 20” diameter 75 km pipeline, transporting sales gas from the Essiama distribution station (EDS) to an offtaker at Prestea. The gas export branch line starts from gas distribution station (EDS) located at Esiama, terminates at Prestea Regulating and Metering Station (PRMS) at Prestea.

e. LPG truck-loading gantry located approximately 2.5km from the GPP near Anochie.

f. The Karpowership project consisting of approximately 8 km onshore pipeline, approximately 2 km offshore pipeline and all other facilities required to transport gas from the

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Ghana Gas Facilities at Aboadze TRMS to the Karpowership Power Ship, Amandi Energy Power Plant and other yet to be identified end users.

Both Onshore and Offshore pipelines are protected against external corrosion with coating and cathodic protection systems to reduce the rate of corrosion in the pipeline.

Gas production from the Jubilee Field is 120 MMscfd, TEN Field 60 MMscfd and Sankofa 180 MMscfd; adding up to 360 MMscfd [5, 8]. However, the Atuabo gas plant has the capacity to produce 150 MMscfd out of the 560 MMscfd of natural gas demand by the country daily.

Ghana National Gas Company has connected with Eni by means of a tie-in to Atuabo plant and have increased daily production to 405 MMscfd. But there are still arrears of 155 MMscfd in gas supplied for power generation.

The projected arrears of about 155 MMscfd is within the break-even point for a synergetic use of a drag reducer and an internal coating to increase the capacity of GNGC pipeline, assuming we have enough gas supply from both Jubilee, Sankofa and Ten field.

The pipeline from Atuabo to Takoradi is used as a case study.

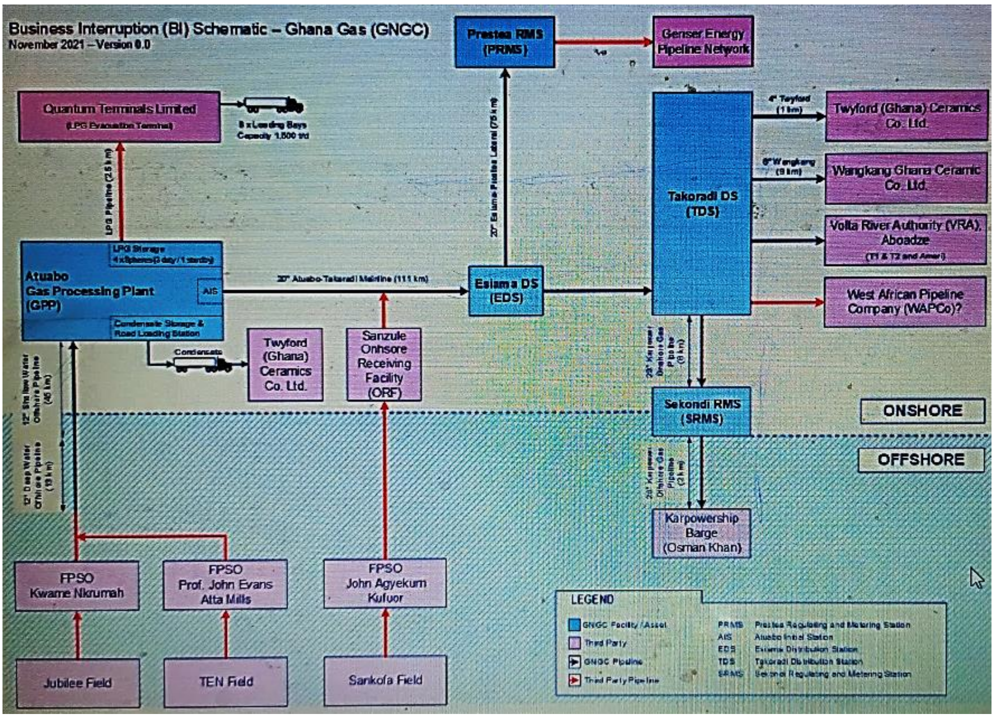

Fig. 1. An outline of GNGC gas infrastructure project [7]

Range of parameters

The analysis is performed over the following range:

Table 1. Technical data

Parameter	Range Onshore pipeline
Fluid specific gravity	0.6
Gas flow rate (Q), (MMSCFD)	150
Reynolds number	7821271336.424
Pipe diameter (inch)	20

Pipe internal diameter (mm)	487.38
Pipe length (Km)	111
Absolute roughness of bare commercial steel pipe (e), (mm)	0.045
Absolute roughness of internally coated pipeline (e_c), (mm)	0.0045
Drag reduction rate (%)	70

Theoretical analysis

Analysis of natural gas pipelines

Analysis of Friction Factor and Roughness

For steady state conditions, the Reynolds number (Re) for gases can be expressed as [3-6].

$$Re = \frac{DV\rho}{\mu} \tag{1}$$

Where: Re = Reynolds number;
D = pipeline diameter (m);
μ= fluid viscosity ($kgs^{-1}m^{-1}$);
V = fluid velocity (ms^{-1});
ρ = fluid density(kgm^{-3}).
Substituting for density (ρ), and velocity as flow rate/area, into Equation (1), we get:

$$Re = \frac{49.44QgP_b}{\mu DT_b} \tag{2}$$

Where:
Re = Reynolds number;
D = pipeline diameter (mm);
g = Gas specific gravity;
μ= fluid viscosity (Pa-S);
P_b = Base pressure (kPa);
Q = Gas flow rate (m^3day^{-1});
T_b = Base temperature (°K).
Colebrook, in the 1930's, proposed an equation which combined the smooth pipe law and the rough pipe law into a single equation.

$$\frac{1}{\sqrt{f}} = -2\log_{10}\left(\frac{e}{3.7D} + \frac{2.51}{Re\sqrt{f}}\right) \tag{3}$$

Equation (3) is effective for partially turbulent, transition and fully turbulent flow. The main difficulty in using it is that f appears on both sides, an iterative solution is required. Equation (3) forms the basis of all subsequent theoretical analysis [3-6]. The variation of friction factor with surface roughness is by using the term transmission factor (F).

Flow and Pressure Drop

For steady state isothermal flow in horizontal gas pipelines, the basic General Flow Equation derived from an energy balance over the length of the pipeline can be expressed as (general flow equation):

$$Q = 0.0011493E\left(\frac{T_b}{P_b}\right)\left(\frac{P_1^2 - P_2^2}{GTLZf}\right)^{0.5} D^{2.5} \tag{4}$$

Where:
Q = gas flow rate, ($m^3.day^{-1}$)
f = darcy-weisbach friction factor

P_b = base pressure (kPa)
T_b = base temperature (°K)
P_1 = inlet pressure (kPa)
P_2 = outlet pressure (kPa)
G = gas specific gravity (air = 1.00)
T = average gas flowing temperature (°K)
L = pipe segment length (km)
Z = gas compressibility factor at the flowing temperature
D = pipe diameter (mm)
E = pipe efficiency factor

Equation (4) can be re-arranged if the relationship for the friction factor (*f*) is known. The following empirical correlations suitably modified are usually used in the analysis of natural gas pipelines [6].

American Gas Association (AGA) equation $F = 4\log_{10}\left(\frac{3.7D}{e}\right)$ (5)

The equivalent friction factor for AGA equation is, $f = \frac{4}{\left(4\log_{10}\left(\frac{3.7D}{e}\right)\right)^2}$

Weymouth Equation $F = 11.18(D)^{1/6}$ (6)

The equivalent friction factor for Weymouth equation is, $f = \frac{4}{\left(11.18\left(D^{\frac{1}{6}}\right)\right)^2}$

Panhandle "A" Equation $F = 6.87Re^{0.07305}$ (7)

The equivalent friction factor for Panhandle "A" equation is, $f = \frac{4}{(6.87Re^{0.07305})^2}$

Panhandle "B" Equation $F = 16.49Re^{0.01961}$ (8)

The equivalent friction factor for Panhandle "B" equation is, $f = \frac{4}{(16.49Re^{0.01961})^2}$

$$F = \frac{2}{\sqrt{f}} \quad (9)$$

$$\therefore f = \left(\frac{2}{F}\right)^2 = \frac{4}{(F^2)}$$

Where f is the Darcy friction factor.
Substituting equations (5) to (8) individually into Equation (4) gives:

Weymouth Equation

$$Q = 433.49E\left(\frac{T_b}{P_b}\right)\left(\frac{P_1^2 - P_2^2 - H_c}{GTLZ}\right)^{0.5} D^{8/3} \quad (10)$$

Panhandle "A" Equation

$$Q = 0.0045965E\left(\frac{T_b}{P_b}\right)^{1.0788}\left(\frac{P_1^2 - P_2^2 - H_c}{G^{0.8538}TLZ}\right)^{0.5394} D^{2.6182} \quad (11)$$

Panhandle "B" Equation

$$Q = 0.010019E\left(\frac{T_b}{P_b}\right)^{1.02}\left(\frac{P_1^2 - P_2^2 - H_c}{G^{0.961}TLZ}\right)^{0.51} D^{2.53} \quad (12)$$

Where:
H_c = elevation correction (KPa^2)
Re = Reynolds number
All other parameters are as defined above.

Equation (10) is in USCS units (English units), and F is the transmission factor. Weymouth equation's original published form is presented in Equation (10) [6].

Modified Colebrook-White Equation

The transmission factor is calculated as:

$$\frac{1}{\sqrt{f}} = -2\log_{10}\left(\frac{e}{3.7D} + \frac{2.825}{Re\sqrt{f}}\right) \quad (13)$$

Where the variables in equation (5) to (13) are defined the same as in equation (4). The pipeline efficiency term 'E' is used to correlate measured and predicted data. For a new pipeline, a typical value of 'E' is 0.95 and is constant for a wide range of Reynolds number [3-6]. The effect of reduction in surface roughness on pipeline friction for AGA equation can be calculated directly from equation (5), depending on the flow regime. For Weymouth and Panhandle equations the effect of surface roughness can be estimated from equations (9), (10), and (11). This result in the following correlations [1]

AGA & Weymouth Equation

$$\frac{Q_c}{Q_0} = \left(\frac{f_0}{f_c}\right)^{0.5} \quad (14)$$

Panhandle "A" Equation

$$\frac{Q_c}{Q_0} = \left(\frac{f_0}{f_c}\right)^{0.5394} \quad (15)$$

Panhandle "B" Equation

$$\frac{Q_c}{Q_0} = \left(\frac{f_0}{f_c}\right)^{0.51} \quad (16)$$

Compression Analysis

For gas pipelines systems, the compression power can be calculated by:

$$P_w = \frac{k \cdot Z \cdot R \cdot T_1}{k-1} \times \left(\left(\frac{P_1}{P_2}\right)^{((k-1)/k)} - 1\right) \times Q_m \quad (17)$$

Where:
P_w=Power (kW)
Z = gas compressibility factor (assuming Z=1)
P_1 = Pressure inlet compressor (kPa)
P_2 = Pressure outlet compressor (kPa)
Q_m=Compressor throughput (kg/s)
k= Gas isentropic (adiabatic) coefficient
R = Universal gas constant, 8314/Molecular weight (J/(kg.K)).

The discharge temperature for an isentropic (adiabatic) compression can be calculated as:

$$T_2 = T_1 \times \left[\left(\frac{P_2}{P_1}\right)^{(\gamma-1)/\gamma}\right] \quad (18)$$

$$\gamma = \frac{C_p}{C_v} \quad (19)$$

where γ is the ratio of the specific heats (Cp/Cv) of the gas. This ratio is approximately 1.29 for natural gas. Air and a number of other gases have a value of k = 1.39 to 1.41 [15]. For air, k is 1.4.

Equation (17) together with pressure drop equations can be used to estimate the variation of compression power with pipe surface roughness. It is clear that for gas pipelines, unlike the liquid pipelines, the variation of compression requirements with surface roughness is a function of both friction factor (surface roughness) and pressure. Hence an explicit mathematical equation cannot be developed [1].

Reduction in Pipeline Diameter

For given flow conditions of pressure, flow rate, fluid properties and pipeline length, the friction factor (*f*) depends only on the pipeline diameter.

Exact relationship between *friction factor* and pipeline diameter will depend upon the correlation used to predict pressure drop [1].

AGA Equation

$$\frac{D_c}{D_0} = \left(\frac{f_c}{f_0}\right)^{0.2} \quad (20)$$

Panhandle 'A' Equation

$$\frac{D_c}{D_0} = \left(\frac{f_c}{f_0}\right)^{0.2059} \quad (21)$$

Where, subscript "c" denotes internally coated and "0" denotes uncoated.

Drag Reduction and Pipeline Capacity Enhancement

The usefulness of a drag reducer is generally expressed in terms of percentage drag reduction [16 -17]. For a given flow rate, the percentage drag reduction is calculated as:

$$\%\, D.R = \frac{P-P_p}{P} \times 100 \quad (22)$$

Where

P = base pressure drop of the untreated fluid

Pp = pressure drop of the fluid containing drag-reducing polymer

D.R = Drag Reduction

Generally, Equation (23) is used to calculate the percentage throughput increase.

$$Percent\ throughput\ increase = \left[\left(\frac{1}{1-\frac{\%D.R}{100}}\right)^{0.55} - 1\right] \times 100 \quad (23)$$

Where

% D.R = is the percentage drag reduction as defined in equation (35).

Synergetic effect of injecting a Polyacrylamide drag reducing agent in an internally coated gas pipeline with respect to capacity enhancement

Theoretically, the synergetic effect of injecting a drag reducing agent in an internally coated pipeline, is the condition where the combined effect of pipeline internal coating and drag reducer on the pipe's capacity is bigger than the sum of the effects of each agent (i.e. internal coating, drag reducing agent) given alone [12] (see Table 4), for example:

3 + 3 >> 6 (maybe 10 times or more).

A drag reducing agent with a drag reduction rate (%DR) of 70% is assumed and used for the calculations in the Appendix.

Results

The variation of transmission factor is in Table 2 and Table 3 (see Appendix for detailed calculation). Maximum increase in transmission factor is 22%.

A 33% reduction in friction factor will result in 8% reduction in pipe diameter for gas pipeline systems.

The variation of pipeline throughput is shown in Table 2 and Table 3. The maximum increases are 22% for gas pipeline systems. Table 3 shows the synergetic effect of combining an internal coating with a drag reducer with 70% drag reduction rate..

Table 2. Summary of findings: AGA Equation

Item	Pipeline without internal coating	Internally coated pipeline
Friction factor	0.011800	0.007964
Transmission factor	18.411428	22.411428
Reduction in friction factor (%)		32.5
Reduction in pipe diameter (%)		7.56
Maximum increase in transmission factor (%)		21.76
Capacity increase (%)		**21.724**

Table 3. Summary of findings: Modified Colebrook-White Equation

Item	Pipeline without internal coating	Internally coated pipeline
Friction factor	0.011800	0.007966
Transmission factor	18.411196	22.408613
Reduction in friction factor (%)		32.49520
Reduction in pipe diameter (%)		7.558
Maximum increase in transmission factor (%)		21.7118
Capacity increase (%)		**21.7118**

Table 4. Summary of findings: synergetic use of pipeline internal coating and a Polyacrylamide drag reducer

AGA Equation		Colebrook-White Equation	
Item	**Capacity increase (%)**	**Item**	**Capacity increase (%)**
Polyacrylamide	93.902	Polyacrylamide	93.902
Internally coated pipeline	21.724	Internally coated pipeline	21.7118
Synergetic effect			
Total Capacity increase (%)	>> 115.63	Total capacity increase (%)	>> 115.613
Synergetic effect (MMSCFD)	**>> 323.445**	**Synergetic effect (MMSCFD)**	**>> 323.421**

Note:

1. $Synergetic\ effect = \left[\frac{total\ capacity\ increase\ (\%)}{100} \times 150MMSCFD\right] + 150MMSCFD$

2. 150 MMSCFD is the flow rate or capacity (f_o) of GNGC pipeline without internal coating

3. GNGC pipeline from Essiama to Prestea have the same design parameters as the pipeline from Atuabo to Takoradi. Therefore, the summarized results in Tables 3, 4, and 5, also applies to Essiama to Prestea pipeline.

Discussion of Results

The analysis confirms that internally coating a pipeline can significantly decrease the pipe surface roughness resulting in lower friction factor, increased product throughput, and lower pipeline material and operating costs. Using both AGA equations and Modified Colebrook–White equations, it was observed that the internally coated pipe transported about 21.726% and 21.712% more flow (Q) respectively than the pipelines which are not internally coated, when other conditions remained constant. Using AGA equation, transmission factors 'F' were 18.411428 and 22.411428 respectively for pipelines not internally coated and internally coated pipelines. Colebrook-White equation also achieved transmission factors 'F' 18.411196 and 22.408613 respectively for pipelines not internally coated and internally coated pipelines.

The profits/benefits of reduced friction resulting from the use of both internal coating and drag reducer is governed by the surface roughness of uncoated pipe. The results of the case study are for a bare pipe surface roughness of 0.04572mm (0.0018 inch) which is typical for commercial pipes. If the initial surface roughness is less than 0.045mm, then the profits will be somewhat reduced.

The analysis shows that, based on reduced operating costs, using a drag reducer (flow improver) in an internally coated pipeline can be justified in most cases.

Conclusion and recommendation

Conclusion

i. Synergetic use of a pipeline internal coating and a drag reducer with a drag reduction rate of 70% can increase the pipeline capacity (throughput) above 115.53% for GNGC gas pipeline systems. Therefore, from Tables 2 and 3, theoretically, the synergetic effect of combining a flow improver (70% drag reduction rate) with an internal coating on the Atuabo to Takoradi pipeline of GNGC, will increase (enhance) the pipeline capacity to >> 323.29 MMSCFD.

ii. Internal coating with surface roughness of 0.0045mm can;

- reduce the pipe friction factor by up to 33% for gas pipeline systems;
- increase the pipeline throughput by up to 22% for gas pipeline systems;
- decrease the pipeline diameter by 8% for commercial pipe;
- increase the pipeline transmission factor by 22% for gas pipeline systems;
- pipe maintenance cost reduction.

iii. Synergetic use of an internal coating and a drag reducer can be economically acceptable based on reduced operating costs under most cases. Typical payback period is three (3) years.

iv. Pipe friction factor decrease with decrease in surface roughness. The percentage reduction in friction factor increases with increase in Reynolds number and decrease in pipe diameter.

v. Drag reducing agent (flow improver) can also decrease internal corrosion of the pipeline inner surface. Therefore, by combining a drag reducer and an internal coating, the total friction will be reduced considerably and the pipeline can be maintained for a long time due to the anti-corrosion effects by the drag reducer and pipeline internal coating.

Recommendation

Synergetic use of an internal coating and a drag reducer with a drag reduction rate of 70% to increase the capacity of GNGC pipeline to about 323 MMSCFD.

i. In-situ internal coating of GNGC pipeline

"In-situ internal coating" or "in place" coating permits the coating of pipelines already laid- new or old- and avoids the welding problem.

ii. Use of a flow improver or drag reducer such as Polyacrylamide with a drag reduction rate of 70% to reduce friction along the pipeline and increase the pipeline capacity.

Authors contributions

Author M.S.O. conceived and presented the idea, developed the theory, performed the analytical computations and wrote the manuscript. Author L.N.W.D. supervised the findings of this work. Authors E.N. and D.S.K. helped supervise the project. All authors discussed the results and contributed to the final manuscript.

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Appendix

Table 5. Summary of findings: Modified Colebrook-White equation

Pipeline without internal coating: Bare pipeline	
Pipe size (inch)	**20**
Flow rate, Q_0, (MMSCFD)	150
Reynold number	7821271336.42
Wall thickness, t (mm)	10.31
Pipe inside diameter, D (mm)	487.38
Pipe diameter, D_0 (mm)	508.00
Pipe internal roughness, e_0 (mm)	0.04572
$1/\sqrt{(f_0)}$	9.19
Friction factor, f_0	0.0118
Repeating iteration: bare pipeline	
$1/\sqrt{(f_0)}$	9.19
Friction factor, f_o	0.0118
Transmission factor, F_0	18.38
Pipe relative roughness	0.00009
Internally coated pipeline	
Reynolds number (Re)	7821271336.42
Pipe inside diameter, D (mm)	487.38
Pipe internal roughness, e_c (mm)	0.0045
Flow rate, Q_0, (MMSCFD)	150
$1/\sqrt{(f_c)}$	11.20
Friction factor, f_c	0.0080
Repeating iteration: internally coated pipeline	
$1/\sqrt{(f_c)}$	11.20
Friction factor, f_c	0.0080
Transmission factor, F_c	22.41
Pipe relative roughness	0.000009
Final results: internally coated pipeline	
Reduction in friction factor (%)	32.70
Diameter of internally coated pipe, D_c, (mm)	469.32
Reduction in pipeline diameter (%)	7.61
Maximum increase in transmission factor (%)	21.89
Reduction in pipe relative roughness (%)	90.16
Capacity of internally coated pipe, Q_c, (MMSCFD)	182.84
Increase in Pipeline capacity (%)	21.89
Drag reducer and pipeline capacity enhancement	
% Drag reduction	70
Percent throughput increase (%)	94
Synergetic effect of a pipeline internal coating and drag reducer	
Total increase of pipeline capacity (%)	115.80
Total pipeline capacity (MMSCFD)	323.70

Note:

1. Synergetic effect $= \left[\frac{\text{total capacity increase (\%)}}{100} \times 150\text{MMSCFD}\right] + 150\text{MMSCFD}$

2. 150 MMSCFD is the flow rate or capacity (f_o) of GNGC pipeline without internal coating

3. GNGC pipeline from Essiama to Prestea have the same design parameters as the pipeline from Atuabo to Takoradi. Therefore, the summarized results in Tables 2, and 3, also applies to Essiama to Prestea pipeline.

Table 6. Summary of findings: AGA equation

Pipeline without internal coating: bare pipeline	
Pipe size (inch)	**20**
Gas flowrate (Capacity), Q_0	**150**
Reynold number	7821271336.42
Wall thickness, t, (mm)	10.31
Pipe inside diameter, D (mm)	487.38
Pipe diameter, D_0 (mm)	508.00
Pipe internal roughness, e_0 (mm)	0.04572
transmission factor, F_0	18.38
Friction factor, f_0	0.012
Pipe relative roughness	0.00009
Internally coated pipeline	
Pipe size (inch)	**20**
Reynold number	7821271336.42
Pipe inside diameter, D (mm)	487.38
Pipe diameter, D_0 (mm)	508.00
Pipe internal roughness, e_c (mm)	0.0045
transmission factor, F_c	22.41
Friction factor, f_c	0.00796
Pipe relative roughness	0.000009
Final results: internal coating and pipeline capacity enhancement	
Reduction in friction factor (%)	32.71
Diameter of internally coated pipe, D_c, (mm)	469.30
Reduction in pipeline diameter (%)	7.62
Maximum increase in transmission factor (%)	21.91
Reduction in pipe relative roughness (%)	90.16
Capacity of internally coated pipe, Q_c, (MMSCFD)	182.86
Increase in Pipeline capacity (%)	21.91
Drag reducer and pipeline capacity enhancement	
% Drag reduction rate	70
Percent throughput increase (%)	94
Synergetic effect of pipeline internal coating and drag reducer	
Total increase of pipeline capacity (%)	115.81
Total pipeline capacity (MMSCFD)	323.72

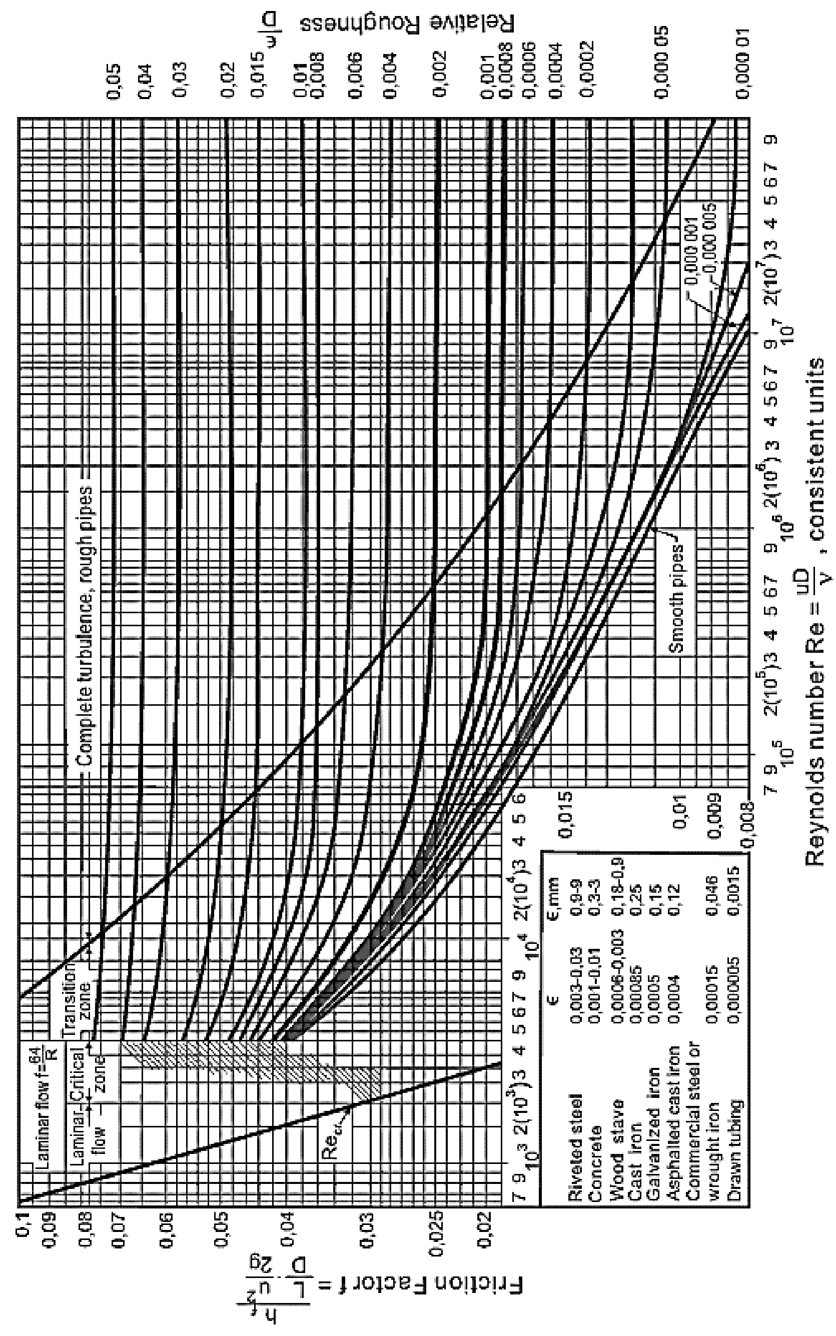

Fig. 2 Moody chart [13-14]

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