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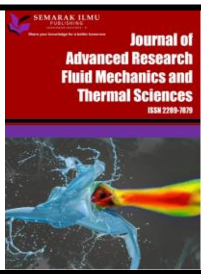

Flow Improvers and Pipeline Internal Coating Benefits and Limitations with Respect to Pipeline Capacity Enhancement

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ABSTRACT

This article illustrates the outcome of a theoretical examination of applying internal coating and flow improver to gas and liquid pipeline systems. A test case of a 12-inches, 18-inches, 24-inches, 30-inches, 36-inches, and 42-inches diameter gas and liquid transmission pipelines evaluates hypothetically, synergistic use of pipeline internal coating with flow improver to enhance flow rate of a pipeline and minimize internal friction. The improvements in pipeline hydraulics are recognized and the enhancement of pipeline capacity calculated over a broad range of parameters. The hydraulic benefits are presented as percentage increase in pipeline capacity using flow equations. Analysis shows that internal coating of pipelines plus injection of flow improver is hydraulically and economically viable for both gas and liquid pipelines with a typical capacity increase greater than 116%. Corrosion protection and safety is improved with low operating cost.

1. Introduction

Water, crude oil and natural gas, are examples of fluids usually transported through pipelines. It is widely known that as fluids flow through these pipelines, pressure drop develops along such pipelines due to friction or drag between the fluids and the pipe wall. To overcome these pressure drops, pump and or compressor stations are installed along the pipeline to raise the pressure of the flowing fluids back to or near their original values in order to keep the fluid flowing at the required flowrates and to ensure that the fluid reaches their destination [1].

However, because of the high cost involved with installation, maintenance, and operation of each compressor station, economics determines that the size and number of these stations for any specific pipeline is limited or restricted although the actual throughput or flowrate may end up being significantly less than the pipeline could otherwise carry. Other methods such as internal coating, drag reducing agent (flow improver) have been suggested to increase the maximum flowrate (i.e., Volume (of fluids) which can be transported through a pipeline at a constant pressure drop [1].

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Drag reduction involves lowering the friction or drag of the fluids within a pipeline and thereby increasing the volumetric flowrate of the fluid at a constant pressure drop due to the addition of a material known as “flow improver or drag reducing agent” to the flowing fluids.

For a pipeline, pressure drop is mainly caused by internal friction [2]. However, internally coating a pipeline lowers its internal friction and thereby reduces pressure drop which automatically increase the capacity or throughput [3-5].

Research gap identified is drag reduction/flow improver and internal coating studies in three-phase flows. This is very important because three-phase flow regime exist in some oil and gas pipeline systems. This research outlines the benefits and limitations of flow improvers and pipeline internal coating with respect to pipeline capacity enhancement.

1.1 Significance

This research is very important for readers to increase their awareness concerning alternatives for enhancing a pipeline capacity, pipeline internal coating and flow improver benefits and how to control internal corrosion.

1.2 Objectives

The objective of this research is to show the protective abilities, hydraulic and economic benefits of using a flow improver and pipeline internal coating synergistically [6].

Both internal coating and flow improver can lower the surface roughness, and ultimately, the frictional drag forces within a pipeline, enhancing throughput, lowering operational costs of pressurization and pumping, and permitting longer pipeline operation without shutdown [6].

The overarching goal is

i. to improve internal corrosion protection and safety
ii. to reduce the pressure, drop and increase flowrate
iii. to reduce operation cost
iv. to confirm what is stated in literature

1.3 Range of Parameters

The analysis is performed over the following range

Table 1
Technical data

Parameter	Range
Fluid specific gravity	0.55 – 0.95
Reynolds number (Re)	10^4 - 10^8
Liquid velocity (m/s)	1 – 3
Gas velocity (m/s)	5 – 20
Pipe internal roughness, e, (mm)	0.0045 – 0.04572
Pipe diameter (inch)	12 – 42
Pipe wall thickness (t), (mm)	10.31
Pipe length (km)	50 – 300
Compression ratio	2 – 10
Drag reduction rate (D.R), (%)	70

Table 2
Economic data

Parameter	Range
Discount factor (%)	10
Project life (years)	30
Adiabatic efficiency of pump	0.8
Thermal efficiency of gas turbine	0.25
Calorific value of gas (MJ/m^3)	38.73
Value of gas (€/m^3)	0.12
Coating cost (€/micron/metre/inch. diameter)	0.0040 (Polyamide epoxy)
	0.12 (Solvent free epoxy)

2. Theoretical Analysis

2.1 Analysis of Gas Pipelines

Since the improvement in surface roughness results in direct reduction in friction factor, it is important that the appropriate friction factor equations are used in the analysis.

Friction factor is dependent on flow regime (laminar, transition, or turbulent), fluid and pipeline parameters. There are numerous friction factor equations but most widely used for pipeline friction is the Modified Colebrook-White Equation [3-5,7-9].

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

where, Re is Reynolds number, D is pipeline diameter (m) and *f* is friction factor.

However, this is an implicit equation and require iterative techniques to obtain solutions. Eq. (1) is the foundation of all ensuing theory. Using Eq. (1), the "change of friction factor with surface roughness" can be determined. The results are presented in non-dimensional form as percentage reduction in friction factor with percentage reduction in surface roughness for different pipe diameter and Reynolds numbers.

Alternatively, the presentation of the "change of friction factor with surface roughness" is by using the term Transmission factor (F)[10]. This is described as:

$$F = \frac{1}{\sqrt{f}} \tag{2}$$

For a steady state natural gas flow at constant temperature in a horizontal pipe [2], the basic general flow equation is applied [2,4,5,11].

For analysing natural gas pipelines, Eq. (4) to Eq. (7) is used [4,5,11,12].

American Gas Association (AGA) equation

$$F = 4\log_{10}\left(\frac{3.7D}{e}\right) \tag{3}$$

Weymouth Equation

$$F = 11.18(D)^{1/6} \tag{4}$$

Panhandle "A" Equation

$$F = 6.87Re^{0.07305} \tag{5}$$

Panhandle "B" Equation

$$F = 16.49Re^{0.01961} \tag{6}$$

2.2 Analysis of Liquid Pipelines

For the analysis of liquid pipelines, pressure drop (ΔP) [2,3,8] is calculated by the Darcy-Weisbach equation as

$$\Delta P = \frac{fLV^2\rho}{2D} \tag{7}$$

where
V = fluid velocity (ms^{-1}),
L = pipe length (m),
p = fluid density (kgm^{-3})

All other parameters are as defined above. For a given pipeline system, the velocity of the fluid is equivalent or equal to the flowrate, Q.

2.3 Synergetic Effect

Considering the additive effect, Synergetic effect of injecting a flow improver in an internally coated pipeline is calculated as

$$\gg Q_c + Q_{DR} \tag{8}$$

Where Q_c and Q_{DR} is the increase in capacity from the use of an internal coating and a flow improver (drag reducing agent) respectively [4,5,13-16].

Refer to Mavis *et al.,* [4,5] for further details on the theoretical framework of this study.

3. Benefits of Using Pipeline Internal Coating and Flow Improver

3.1 Internal Coating

The benefits of pipeline internal coating can be expressed as

i. Reduced operating costs
ii. Increased product throughput
iii. Reduced steel costs associated with potential reduction in pipe diameter
iv. Enhanced pipeline internal corrosion protection

3.2 Flow Improver

Initially it was thought that only very large diameter pipelines delivering huge volumes could benefit from use of flow improvers (drag reducers). Test has demonstrated that smaller crude and product lines also can benefit. The use of flow improvers in pipelines results in the following advantages [4,5]

i. Flow increase
   - Increase flow rate of one or many pipeline segments. It increases flow rates with already installed facilities to gain extra throughput volume.
   - Increase tanker loading rate. Lowers penalty charge with faster loading and off-loading of tankers
   - Increase floating storage and offloading unit (FSO) loading rate
   - The most common use of Drag reducing additives (DRA) is to increase pipeline flow rates in a system that is at capacity.
   - DRA is injected at each segment to increase the overall pipeline capacity.

ii. Reduces capital expenditure
   DRA usage is very cost effective versus capital intensive mechanical expansion (limits the need for additional pumping facilities or looped pipe segments). In addition to no capital requirements to achieve the extra flow, the desired incremental increase is nearly instantaneous upon injection. This type of technology is utilized in many oil producing regions. The cost is minimal per incremental barrel produced.

iii. Pressure reduction
   - Reduce operating pressure to handle corrosion problems
   - Reduce operation pressure due to maintenance
   - De-bottleneck connected platform infrastructure

iv. Energy savings
   Drag reducing additives are commonly used to maintain a pipeline's flow rate while bypassing a pumping station that is down temporarily for service or repair. However, drag reducing additives can be used as a permanent pump replacement. Flow improvers can curb the need of extra pump or compressor or looped pipe segments.

3.2.1 Limitations of a flow improver

For the drag reducing additives to work [17]

i. The flow regime of the pipeline must be turbulent
ii. The additives can successfully increase flow rate up to more than 70%.
iii. For flow increase above 50%, there may be a need to use a flow improver together with additional pump/compressor or loop sections.

4. Results

For an internally coated pipeline, the change in friction factor with pipe relative roughness is shown in Figure 1 and 2 and Table 3 to Table 11. These show that the reduction in friction factor varies with the reduction in relative roughness, pipe diameter and Reynolds number. For commercial pipe with initial internal roughness of 0.04572mm, a 90% reduction in relative roughness will reduce friction by approximately 33%.

The change in transmission factor is shown in Figure 3 to 5 and Tables 3 to 11. Maximum increase in transmission factor for an internally coated pipeline is approximately 22%.

Approximately 33% decrease in friction factor will lead to 22% increase of pipeline capacity (throughput) and 8% reduction in pipe diameter for internally coated liquid and gas pipeline systems (see Table 3 to 11).

A flow improver having a 70% drag reduction rate can bring about 94% increase in the capacity of a pipeline.

Synergistic utilization of internal coating and flow improver having 70% drag reduction rate will lead to more than 116% enhancement of the capacity of both oil and gas pipelines. A graph of increase in pipeline capacity or pipeline throughput with reduction in pipe relative roughness is shown in Figure 7 to 11. The increase in pipeline throughput or capacity is due to the synergetic use of internal coating and a flow improver.

The changes in pipeline throughput are shown in Figure 9 to 11. The maximum enhancement of a pipeline throughput or capacity are 22% and 23% for liquid and gas pipeline systems respectively.

Figure 9 and 11 shows total enhancement of pipeline capacity with pipeline diameter from synergetic use of internal coating and flow improver at Reynolds number, $Re = 10^4\ to\ 10^8$ for gas and liquid pipelines respectively.

Table 3
Summary of findings for gas pipeline system at Reynolds number $(Re) = 1 \times 10^4$: Modified Colebrook-white equation

Modified Colebrook - White Equation						
Bare pipeline: no internal coating or flow improver						
Pipe diameter (inch)	12	18	24	30	36	42
Wall thickness, t, (mm)	10.31	10.31	10.31	10.31	10.31	10.31
Pipe inside diameter, D (mm)	284.18	436.58	588.98	741.38	893.78	1046.18
Pipe diameter, D_0 (mm)	304.80	457.20	609.60	762.00	914.40	1066.80
Reynold number	10000.0	10000.0	10000.0	10000.0	10000.0	10000.0
Pipe internal roughness, e_0 (mm)	0.04572	0.04572	0.04572	0.04572	0.04572	0.04572
$1/\sqrt{(f_0)}$	5.08	5.09	5.09	5.09	5.09	5.09
Friction factor, f_0	0.0387	0.0386	0.0386	0.0386	0.0385	0.0385
Repeating iteration						
$1/\sqrt{(f_0)}$	5.66	5.67	5.67	5.67	5.68	5.68
Friction factor, f_o	0.0312	0.0311	0.0311	0.0311	0.0310	0.0310
Transmission factor, F_0	11.32	11.34	11.34	11.35	11.35	11.35
Pipe relative roughness	0.00016	0.00010	0.00008	0.00006	0.00005	0.00004
Pipeline with internal coating						
Reynolds number (Re)	10000.0	10000.0	10000.0	10000.0	10000.0	10000.0
Pipe inside diameter, D (mm)	284.18	436.58	588.98	741.38	893.78	1046.18
Pipe internal roughness, e_c (mm)	0.0045	0.0045	0.0045	0.0045	0.0045	0.0045
Flow rate, Q_0, (MMSCFD)	150	150	150	150	150	150
$1/\sqrt{(f_c)}$	5.10	5.10	5.10	5.10	5.10	5.10
Friction factor, f_c	0.0385	0.0385	0.0385	0.0385	0.0385	0.0385
Repeating iteration						
$1/\sqrt{(f_c)}$	5.68	5.68	5.68	5.68	5.68	5.68
Friction factor, f_c	0.0310	0.0310	0.0310	0.0310	0.0310	0.0310
Transmission factor, F_c	11.36	11.36	11.36	11.36	11.36	11.37
Pipe relative roughness	0.000016	0.000010	0.000008	0.000006	0.000005	0.000004

Final results						
Reduction in friction factor (%)	0.75	0.49	0.36	0.29	0.24	0.21
Diameter of internally coated pipe, D_c, (mm)	304.34	456.75	609.16	761.56	913.96	1066.36
Reduction in pipeline diameter (%)	0.15	0.10	0.07	0.06	0.05	0.04
Maximum increase in transmission factor (%)	0.38	0.25	0.18	0.15	0.12	0.10
Reduction in pipe relative roughness (%)	90.16	90.16	90.16	90.16	90.16	90.16
Capacity of internally coated pipe, Q_c, (MMSCFD)	150.56	150.37	150.27	150.22	150.18	150.15
Increase in Pipeline capacity (%)	0.38	0.25	0.18	0.15	0.12	0.10
Flow improver and pipeline capacity enhancement						
% Drag reduction	70	70	70	70	70	70
Percent throughput increase (%)	94	94	94	94	94	94
Synergetic effect: internally coated pipeline plus flow improver						
Total enhancement of pipeline capacity (%)	94.28	94.15	94.08	94.05	94.02	94.01
Total pipeline capacity (MMSCFD)	291.42	291.22	291.13	291.07	291.03	291.01

Table 4
Summary of findings for gas pipeline system at Reynolds number $(Re) = 1 \times 10^5$: Modified Colebrook-White Equation

Modified Colebrook - White Equation						
Bare pipeline: no internal coating or flow improver						
Pipe diameter (inch)	12	18	24	30	36	42
Wall thickness, t, (mm)	10.31	10.31	10.31	10.31	10.31	10.31
Pipe inside diameter, D (mm)	284.18	436.58	588.98	741.38	893.78	1046.18
Pipe diameter, D_0 (mm)	304.80	457.20	609.60	762.00	914.40	1066.80
Reynold number	100000	100000	100000	100000	100000	100000
Pipe internal roughness, e_0 (mm)	0.04572	0.04572	0.04572	0.04572	0.04572	0.04572
$1/\sqrt{(f_0)}$	6.97	7.02	7.04	7.05	7.06	7.06
Friction factor, f_0	0.0206	0.0203	0.0202	0.0201	0.0201	0.0200
Repeating iteration						
$1/\sqrt{(f_0)}$	7.24	7.29	7.32	7.33	7.34	7.35
Friction factor, f_o	0.0191	0.0188	0.0187	0.0186	0.0185	0.0185
Transmission factor, F_0	14.48	14.58	14.63	14.66	14.69	14.70
Pipe relative roughness	0.00016	0.00010	0.00008	0.00006	0.00005	0.00004
Pipeline with internal coating						
Reynolds number (Re)	100000.0	100000.0	100000.0	100000.0	100000.0	100000.0
Pipe inside diameter, D (mm)	284.18	436.58	588.98	741.38	893.78	1046.18
Pipe internal roughness, e_c (mm)	0.0045	0.0045	0.0045	0.0045	0.0045	0.0045
Flow rate, Q_0, (MMSCFD)	150	150	150	150	150	150
$1/\sqrt{(f_c)}$	7.08	7.09	7.09	7.09	7.09	7.09
Friction factor, f_c	0.0199	0.0199	0.0199	0.0199	0.0199	0.0199
	Repeating iteration					
$1/\sqrt{(f_c)}$	7.38	7.38	7.39	7.39	7.39	7.39
Friction factor, f_c	0.0184	0.0183	0.0183	0.0183	0.0183	0.0183
Transmission factor, F_c	14.76	14.77	14.78	14.78	14.78	14.78
Pipe relative roughness	1.6e-05	1.0e-05	8.0e-06	6.0e-06	5.0e-06	4.0e-6
Final results						
Reduction in friction factor (%)	3.79	2.55	1.92	1.54	1.29	1.11
Diameter of internally coated pipe, D_c, (mm)	302.46	454.84	607.24	759.63	912.03	1064.43
Reduction in pipeline diameter (%)	0.77	0.52	0.39	0.31	0.26	0.22
Maximum increase in transmission factor (%)	1.95	1.30	0.98	0.78	0.65	0.56
Reduction in pipe relative roughness (%)	90.16	90.16	90.16	90.16	90.16	90.16

Capacity of internally coated pipe, Q_c, (MMSCFD)	152.92	151.95	151.46	151.17	150.98	150.84
Increase in Pipeline capacity (%)	1.95	1.30	0.98	0.78	0.65	0.56
Flow improver and pipeline capacity enhancement						
% Drag reduction	70	70	70	70	70	70
Percent throughput increase (%)	94	94	94	94	94	94
Synergetic effect: internally coated pipeline plus flow improver						
Total enhancement of pipeline capacity (%)	95.85	95.20	94.88	94.68	94.55	94.46
Total pipeline capacity (MMSCFD)	293.78	292.80	292.32	292.02	291.83	291.69

Table 5
Summary of findings for gas pipeline system at Reynolds number $(Re) = 1 \times 10^6$: Modified Colebrook-White equation

Modified Colebrook - White Equation						
Bare pipeline: no internal coating or flow improver						
Pipe diameter (inch)	12	18	24	30	36	42
Wall thickness, t, (mm)	10.31	10.31	10.31	10.31	10.31	10.31
Pipe inside diameter, D (mm)	284.18	436.58	588.98	741.38	893.78	1046.18
Pipe diameter, D_0 (mm)	304.80	457.20	609.60	762.00	914.40	1066.80
Reynold number	1.0e+06	1.0e+06	1.0e+06	1.0e+06	1.0e+06	1.0e+06
Pipe internal roughness, e_0 (mm)	0.04572	0.04572	0.04572	0.04572	0.04572	0.04572
$1/\sqrt{(f_0)}$	8.29	8.50	8.62	8.70	8.75	8.79
Friction factor, f_0	0.0146	0.0139	0.0135	0.0132	0.0131	0.0129
Repeating iteration						
$1/\sqrt{(f_0)}$	8.35	8.56	8.69	8.77	8.83	8.87
Friction factor, f_o	0.0143	0.0136	0.0133	0.0130	0.0128	0.0127
Transmission factor, F_0	16.70	17.13	17.37	17.54	17.66	17.74
Pipe relative roughness	0.00016	0.00010	0.00008	0.00006	0.00005	0.00004
Pipeline with internal coating						
Reynolds number (Re)	1.0e+06	1.0e+06	1.0e+06	1.0e+06	1.0e+06	1.0e+06
Pipe inside diameter, D (mm)	284.18	436.58	588.98	741.38	893.78	1046.18
Pipe internal roughness, e_c (mm)	0.0045	0.0045	0.0045	0.0045	0.0045	0.0045
Flow rate, Q_0, (MMSCFD)	150	150	150	150	150	150
$1/\sqrt{(f_c)}$	8.98	9.02	9.04	9.05	9.06	9.06
Friction factor, f_c	0.0124	0.0123	0.0122	0.0122	0.0122	0.0122
Repeating iteration						
$1/\sqrt{(f_c)}$	9.06	9.10	9.12	9.13	9.14	9.14
Friction factor, f_c	0.0122	0.0121	0.0120	0.0120	0.0120	0.0120
Transmission factor, F_c	18.11	18.20	18.24	18.26	18.28	18.29
Pipe relative roughness	1.6e-05	1.0e-05	8.0e-6	6.0e-06	5.0e-06	4.0e-06
Final results						
Reduction in friction factor (%)	15.01	11.41	9.23	7.76	6.69	5.88
Diameter of internally coated pipe, D_c, (mm)	295.05	446.25	597.91	749.80	901.82	1053.94
Reduction in pipeline diameter (%)	3.20	2.39	1.92	1.60	1.38	1.21
Maximum increase in transmission factor (%)	8.47	6.25	4.96	4.12	3.52	3.08
Reduction in pipe relative roughness (%)	90.16	90.16	90.16	90.16	90.16	90.16
Capacity of internally coated pipe, Q_c, (MMSCFD)	162.71	159.37	157.44	156.18	155.28	154.62
Increase in Pipeline capacity (%)	8.47	6.25	4.96	4.12	3.52	3.08
Flow improver and pipeline capacity enhancement						
% Drag reduction	70	70	70	70	70	70
Percent throughput increase (%)	94	94	94	94	94	94
Synergetic effect: internally coated pipeline plus flow improver						
Total enhancement of pipeline capacity (%)	102.37	100.15	98.86	98.02	97.43	96.98
Total pipeline capacity (MMSCFD)	303.56	300.22	298.29	297.03	296.14	295.47

Table 6
Summary of findings for gas pipeline system at Reynolds number $(Re) = 1 \times 10^7$: Modified Colebrook-White equation

Modified Colebrook - White Equation						
Bare pipeline: no internal coating or flow improver						
Pipe diameter (inch)	12	18	24	30	36	42
Wall thickness, t, (mm)	10.31	10.31	10.31	10.31	10.31	10.31
Pipe inside diameter, D (mm)	284.18	436.58	588.98	741.38	893.78	1046.18
Pipe diameter, D_0 (mm)	304.80	457.20	609.60	762.00	914.40	1066.80
Reynold number	1.0e+07	1.0e+07	1.0e+07	1.0e+07	1.0e+07	1.0e+07
Pipe internal roughness, e_0 (mm)	0.04572	0.04572	0.04572	0.04572	0.04572	0.04572
$1/\surd(f_0)$	8.67	9.01	9.25	9.42	9.56	9.67
Friction factor, f_0	0.0133	0.0123	0.0117	0.0113	0.0109	0.0107
Repeating iteration						
$1/\surd(f_0)$	8.68	9.02	9.25	9.43	9.56	9.67
Friction factor, f_o	0.0133	0.0123	0.0117	0.0113	0.0109	0.0107
Transmission factor, F_0	17.35	18.04	18.51	18.86	19.13	19.35
Pipe relative roughness	0.00016	0.00010	0.00008	0.00006	0.00005	0.00004
Pipeline with internal coating						
Reynolds number (Re)	1.0e+07	1.0e+07	1.0e+07	1.0e+07	1.0e+07	1.0e+07
Pipe inside diameter, D (mm)	284.18	436.58	588.98	741.38	893.78	1046.18
Pipe internal roughness, e_c (mm)	0.0045	0.0045	0.0045	0.0045	0.0045	0.0045
Flow rate, Q_0, (MMSCFD)	150	150	150	150	150	150
$1/\surd(f_c)$	10.30	10.50	10.62	10.70	10.76	10.80
Friction factor, f_c	0.0094	0.0091	0.0089	0.0087	0.0086	0.0086
Repeating iteration						
$1/\surd(f_c)$	10.29	10.48	10.59	10.66	10.71	10.75
Friction factor, f_c	0.0095	0.0091	0.0089	0.0088	0.0087	0.0087
Transmission factor, F_c	20.57	20.96	21.18	21.33	21.43	21.50
Pipe relative roughness	1.6e-05	1.00e-05	8.00e-06	6.00e-06	5.00e-06	4.00e-06
Final results						
Reduction in friction factor (%)	28.87	25.90	23.64	21.82	20.31	19.02
Diameter of internally coated pipe, D_c, (mm)	284.73	430.59	577.58	725.39	873.81	1022.73
Reduction in pipeline diameter (%)	6.59	5.82	5.25	4.80	4.44	4.13
Maximum increase in transmission factor (%)	18.57	16.17	14.44	13.10	12.02	11.12
Reduction in pipe relative roughness (%)	90.16	90.16	90.16	90.16	90.16	90.16
Capacity of internally coated pipe, Q_c, (MMSCFD)	177.85	174.26	171.66	169.65	168.03	166.68
Increase in Pipeline capacity (%)	18.57	16.17	14.44	13.10	12.02	11.12
Flow improver and pipeline capacity enhancement						
% Drag reduction	70	70	70	70	70	70
Percent throughput increase (%)	94	94	94	94	94	94
Synergetic effect: internally coated pipeline plus flow improver						
Total enhancement of pipeline capacity (%)	112.47	110.07	108.34	107.00	105.92	105.03
Total pipeline capacity (MMSCFD)	318.71	315.11	312.51	310.50	308.88	307.54

Table 7
Summary of findings for gas pipeline system at Reynolds number $(Re) = 1 \times 10^8$: Modified Colebrook-White equation

Modified Colebrook - White Equation						
Bare pipeline: no internal coating or flow improver						
Pipe diameter (inch)	12	18	24	30	36	42
Wall thickness, t, (mm)	10.31	10.31	10.31	10.31	10.31	10.31
Pipe inside diameter, D (mm)	284.18	436.58	588.98	741.38	893.78	1046.18
Pipe diameter, D_0 (mm)	304.80	457.20	609.60	762.00	914.40	1066.80
Reynold number	1.00e+08	1.00e+08	1.00e+08	1.00e+08	1.00e+08	1.00e+08

Pipe internal roughness, e_0 (mm)	0.04572	0.04572	0.04572	0.04572	0.04572	0.04572
$1/\sqrt{(f_0)}$	8.72	9.09	9.34	9.54	9.70	9.83
Friction factor, f_0	0.0132	0.0121	0.0115	0.0110	0.0106	0.0103
Repeating iteration						
$1/\sqrt{(f_0)}$	8.72	9.09	9.35	9.54	9.70	9.84
Friction factor, f_o	0.0132	0.0121	0.0114	0.0110	0.0106	0.0103
Transmission factor, F_0	17.44	18.18	18.69	19.08	19.40	19.67
Pipe relative roughness	0.00016	0.00010	0.00008	0.00006	0.00005	0.00004
Pipeline with internal coating						
Reynolds number (Re)	1.00e+08	1.00e+08	1.00e+08	1.00e+08	1.00e+08	1.00e+08
Pipe inside diameter, D (mm)	284.18	436.58	588.98	741.38	893.78	1046.18
Pipe internal roughness, e_c (mm)	0.0045	0.0045	0.0045	0.0045	0.0045	0.0045
Flow rate, Q_0, (MMSCFD)	150	150	150	150	150	150
$1/\sqrt{(f_c)}$	10.68	11.03	11.26	11.43	11.57	11.68
Friction factor, f_c	0.0088	0.0082	0.0079	0.0077	0.0075	0.0073
Repeating iteration						
$1/\sqrt{(f_c)}$	10.68	11.02	11.25	11.41	11.55	11.65
Friction factor, f_c	0.0088	0.0082	0.0079	0.0077	0.0075	0.0074
Transmission factor, F_c	21.36	22.04	22.49	22.83	23.09	23.30
Pipe relative roughness	0.000016	0.000010	0.000008	0.000006	0.000005	0.000004
Final results						
Reduction in friction factor (%)	33.33	31.96	30.94	30.11	29.39	28.76
Diameter of internally coated pipe, D_c, (mm)	281.06	423.31	566.10	709.32	852.92	996.86
Reduction in pipeline diameter (%)	7.79	7.41	7.14	6.91	6.72	6.56
Maximum increase in transmission factor (%)	22.48	21.23	20.33	19.61	19.01	18.47
Reduction in pipe relative roughness (%)	90.16	90.16	90.16	90.16	90.16	90.16
Capacity of internally coated pipe, Q_c, (MMSCFD)	183.71	181.85	180.50	179.42	178.51	177.71
Increase in Pipeline capacity (%)	22.48	21.23	20.33	19.61	19.01	18.47
Flow improver and pipeline capacity enhancement						
% Drag reduction	70	70	70	70	70	70
Percent throughput increase (%)	94	94	94	94	94	94
Synergetic effect: internally coated pipeline plus flow improver						
Total enhancement of pipeline capacity (%)	116.38	115.13	114.24	113.52	112.91	112.38
Total pipeline capacity (MMSCFD)	324.57	322.70	321.35	320.27	319.36	318.56

Table 8
Summary of findings using actual Reynolds number for gas pipeline system: Modified Colebrook-White equation

Modified Colebrook-White Equation						
Bare pipeline: no internal coating or flow improver						
Pipe diameter (inch)	12	18	24	30	36	42
Flow rate, Q_0, (MMSCFD)	150	150	150	150	150	150
Reynold number	130354541 65.24	86903027 76.83	65177270 82.62	52141816 66.10	43451513 88.41	37244154 75.78
Wall thickness, t (mm)	10.31	10.31	10.31	10.31	10.31	10.31
Pipe inside diameter, D (mm)	284.18	436.58	588.98	741.38	893.78	1046.18
Pipe diameter, D_0 (mm)	304.80	457.20	609.60	762.00	914.40	1066.80
Pipe internal roughness, e_0 (mm)	0.04572	0.04572	0.04572	0.04572	0.04572	0.04572
$1/\sqrt{(f_0)}$	8.72	9.10	9.36	9.56	9.72	9.85
Friction factor, f_0	0.0131	0.0121	0.0114	0.0110	0.0106	0.0103
Repeating iteration						
$1/\sqrt{(f_0)}$	8.72	9.10	9.36	9.56	9.72	9.85
Friction factor, f_o	0.0131	0.0121	0.0114	0.0110	0.0106	0.0103
Transmission factor, F_0	17.45	18.19	18.71	19.11	19.44	19.71

Pipe relative roughness	0.00016	0.00010	0.00008	0.00006	0.00005	0.00004
Pipeline with internal coating						
Reynolds number (Re)	1.30e+10	8.69e+09	6.52e+09	5.21e+09	4.35e+09	3.72e+09
Pipe inside diameter, D (mm)	284.18	436.58	588.98	741.38	893.78	1046.18
Pipe internal roughness, e_c (mm)	0.0045	0.0045	0.0045	0.0045	0.0045	0.0045
Flow rate, Q_0, (MMSCFD)	150	150	150	150	150	150
$1/\sqrt{(f_c)}$	10.74	11.11	11.37	11.57	11.73	11.86
Friction factor, f_c	0.0087	0.0081	0.0077	0.0075	0.0073	0.0071
Repeating iteration						
$1/\sqrt{(f_c)}$	10.74	11.11	11.37	11.57	11.73	11.86
Friction factor, f_c	0.0087	0.0081	0.0077	0.0075	0.0073	0.0071
Transmission factor, F_c	21.47	22.22	22.74	23.13	23.46	23.72
Pipe relative roughness	0.000016	0.000010	0.000008	0.000006	0.000005	0.000004
Final results						
Reduction in friction factor (%)	33.99	32.95	32.26	31.75	31.33	30.98
Diameter of internally coated pipe, D_c, (mm)	280.50	422.07	563.91	705.96	848.18	990.54
Reduction in pipeline diameter (%)	7.97	7.68	7.50	7.35	7.24	7.15
Maximum increase in transmission factor (%)	23.08	22.13	21.50	21.04	20.68	20.37
Reduction in pipe relative roughness (%)	90.16	90.16	90.16	90.16	90.16	90.16
Capacity of internally coated pipe, Q_c, (MMSCFD)	184.62	183.19	182.25	181.56	181.01	180.56
Increase in Pipeline capacity (%)	23.08	22.13	21.50	21.04	20.68	20.37
Flow improver and pipeline capacity enhancement						
% Drag reduction	70	70	70	70	70	70
Percent throughput increase (%)	94	94	94	94	94	94
Synergetic effect: internally coated pipeline plus flow improver						
Total enhancement of pipeline capacity (%)	116.98	116.03	115.41	114.94	114.58	114.27
Total pipeline capacity (MMSCFD)	325.47	324.04	323.11	322.42	321.87	321.41

Table 9
Summary of findings using actual Reynolds number for gas pipeline system: AGA equation

AGA Equation						
Bare pipeline: no internal coating or flow improver						
Pipe diameter (inch)	12	18	24	30	36	42
Gas flowrate (Capacity), Q_0	150	150	150	150	150	150
Reynold number	1.3e+10	8.7e+09	6.5e+09	5.2e+09	4.3e+09	3.7e+09
Wall thickness, t, (mm)	10.31	10.31	10.31	10.31	10.31	10.31
Pipe inside diameter, D (mm)	284.18	436.58	588.98	741.38	893.78	1046.18
Pipe diameter, D_0 (mm)	304.80	457.20	609.60	762.00	914.40	1066.80
Pipe internal roughness, e_0 (mm)	0.04572	0.04572	0.04572	0.04572	0.04572	0.04572
transmission factor, F_0	17.45	18.19	18.71	19.11	19.44	19.71
Friction factor, f_0	0.013	0.012	0.011	0.011	0.011	0.010
Pipe relative roughness	0.00016	0.00010	0.00008	0.00006	0.00005	0.00004
Pipeline with internal coating						
Pipe size (inch)	12	18	24	30	36	42
Reynold number	1.3e+10	8.7e+09	6.5e+09	5.2e+09	4.3e+09	3.7e+09
Pipe inside diameter, D (mm)	284.18	436.58	588.98	741.38	893.78	1046.18
Pipe diameter, D_0 (mm)	304.80	457.20	609.60	762.00	914.40	1066.80
Pipe internal roughness, e_c (mm)	0.0045	0.0045	0.0045	0.0045	0.0045	0.0045

transmission factor, F_c	21.47	22.22	22.74	23.14	23.46	23.74
Friction factor, f_c	0.00867	0.00810	0.00774	0.00747	0.00726	0.00710
Pipe relative roughness	1.6e-05	1.0e-05	8.0e-06	6.0e-06	5.0e-06	4.0e-06
Final results: internal coating and pipeline capacity enhancement						
Reduction in friction factor (%)	33.99	32.97	32.29	31.78	31.38	31.05
Diameter of internally coated pipe, D_c, (mm)	280.50	422.05	563.87	705.89	848.05	990.34
Reduction in pipeline diameter (%)	7.97	7.69	7.50	7.36	7.26	7.17
Maximum increase in transmission factor (%)	23.08	22.14	21.52	21.07	20.72	20.43
Reduction in pipe relative roughness (%)	90.16	90.16	90.16	90.16	90.16	90.16
Capacity of internally coated pipe, Q_c, (MMSCFD)	184.63	183.21	182.28	181.61	181.08	180.65
Increase in Pipeline capacity (%)	23.08	22.14	21.52	21.07	20.72	20.43
Flow improver and pipeline capacity enhancement						
% Drag reduction rate	70	70	70	70	70	70
Percent throughput increase (%)	94	94	94	94	94	94
Synergetic effect: internally coated pipeline plus flow improver						
Total enhancement of pipeline capacity (%)	116.99	116.04	115.43	114.98	114.62	114.34
Total pipeline capacity (MMSCFD)	325.48	324.06	323.14	322.46	321.93	321.50

Table 10
Summary of findings for liquid pipeline system at Reynolds number (Re) = 10^6: Darcy Weisbach equation

Darcy Weisbach Equation						
Bare pipeline: no internal coating or flow improver						
Pipe diameter (inch)	12	18	24	30	36	42
Flowrate (m^3/s)	0.313	0.313	0.313	0.313	0.313	0.313
Wall thickness, t, (mm)	10.31	10.31	10.31	10.31	10.31	10.31
Pipe diameter, D_0 (mm)	304.80	457.20	609.60	762.00	914.40	1066.80
Pipe inside diameter, D (mm)	284.18	436.58	588.98	741.38	893.78	1046.18
Friction factor, f_0	0.0146	0.0139	0.0135	0.0132	0.0131	0.0129
Pipe internal area (m^2)	7.30	16.42	29.19	45.61	65.68	89.39
Velocity, (m/s)	4.29e-02	1.91e-02	1.07e-02	6.86e-03	4.77e-03	3.50e-03
Fluid viscosity, (cP)	0.001	0.001	0.001	0.001	0.001	0.001
API gravity	43	43	43	43	43	43
Relative density / Specific gravity	0.81	0.81	0.81	0.81	0.81	0.81
Length (L), m	55000	55000	55000	55000	55000	55000
Pipe internal roughness, e_0 (mm)	0.04572	0.04572	0.04572	0.04572	0.04572	0.04572
Pipe relative roughness	1.61e-04	1.05e-04	7.76e-05	6.17e-05	5.12e-05	4.37e-05
Fluid density (kg/m^3)	800	800	800	800	800	800
Reynolds number (Re)	1000000	1000000	1000000	1000000	1000000	1000000
Head loss, (m)	0.2641	0.0323	0.0074	0.0024	0.0009	0.0004
Pressure drop, (Pa)	2073.03	253.74	57.86	18.48	7.30	3.33
Pressure drop, (MPa)	2.07e-03	2.54e-04	5.79e-05	1.85e-05	7.30e-06	3.33e-06
Pipeline with internal coating						
Pipe size (inch)	12	18	24	30	36	42
Flowrate (m^3/s)	0.313	0.313	0.313	0.313	0.313	0.313
Pipe diameter, D_0 (mm)	304.80	457.20	609.60	762.00	914.40	1066.80
Pipe inside diameter, D (mm)	284.18	436.58	588.98	741.38	893.78	1046.18
friction factor, f_c	0.0124	0.0123	0.0122	0.0122	0.0122	0.0122
Pipe internal area (m^2)	7.30	16.42	29.19	45.61	65.68	89.39
Velocity, (m/s)	4.29e-02	1.91e-02	1.07e-02	6.86e-03	4.77e-03	3.50e-03
Fluid viscosity, (cP)	0.001	0.001	0.001	0.001	0.001	0.001
API gravity	43	43	43	43	43	43
Relative density / Specific gravity	0.81	0.81	0.81	0.81	0.81	0.81
length (L), m	55000	55000	55000	55000	55000	55000
Pipe internal roughness, e_c (mm)	0.0045	0.0045	0.0045	0.0045	0.0045	0.0045
Pipe relative roughness	1.58e-05	1.03e-05	7.64e-06	6.07e-06	5.03e-06	4.30e-06
Fluid density (kg/m^3)	800	800	800	800	800	800

Reynolds number (Re)	1000000	1000000	1000000	1000000	1000000	1000000
head loss, (m)	0.2253	0.0287	0.0067	0.0022	0.0009	0.0004
Pressure drop, (Pa)	1767.89	225.26	52.59	17.07	6.81	3.14
Pressure drop, (MPa)	1.77e-03	2.25e-04	5.26e-05	1.71e-05	6.81e-06	3.14e-06
Final results						
Reduction in friction factor (%)	14.72	11.23	9.10	7.67	6.62	5.84
Diameter of internally coated pipe, D_c, (mm)	295.25	446.44	598.07	749.94	901.95	1054.05
Reduction in pipeline diameter (%)	3.13	2.35	1.89	1.58	1.36	1.20
Reduction in pipe relative roughness (%)	90.16	90.16	90.16	90.16	90.16	90.16
Capacity of internally coated pipe, Q_c, (m^3/s)	0.34	0.33	0.33	0.33	0.32	0.32
Increase in Pipeline capacity (%)	8.29	6.14	4.89	4.07	3.49	3.05
Reduction in pressure drop (%)	14.72	11.23	9.10	7.67	6.62	5.84
Flow improver and pipeline capacity enhancement						
% Drag reduction	70	70	70	70	70	70
Percent throughput increase (%)	94	94	94	94	94	94
Synergetic effect: internally coated pipeline plus flow improver						
Total enhancement of pipeline capacity (%)	102.19	100.04	98.79	97.97	97.39	96.95
Total pipeline capacity (m^3/s)	0.63	0.63	0.62	0.62	0.62	0.62

Table 11
Summary of findings for liquid pipeline system at Reynolds number (Re) = 10^8: Darcy Weisbach equation

Darcy Weisbach Equation						
Bare pipeline: no internal coating or flow improver						
Pipe diameter (inch)	12	18	24	30	36	42
Flowrate (m^3/s)	0.313	0.313	0.313	0.313	0.313	0.313
Wall thickness, t, (mm)	10.31	10.31	10.31	10.31	10.31	10.31
Pipe diameter, D_0 (mm)	304.80	457.20	609.60	762.00	914.40	1066.80
Pipe inside diameter, D (mm)	284.18	436.58	588.98	741.38	893.78	1046.18
friction factor, f_0	0.0132	0.0121	0.0115	0.0110	0.0106	0.0103
Pipe internal area (m^2)	7.30	16.42	29.19	45.61	65.68	89.39
	0.042891	0.019062	0.010722	0.006862	0.004765	0.003501
Velocity, (m/s)	2	8	8	6	7	3
Fluid viscosity, (cP)	0.001	0.001	0.001	0.001	0.001	0.001
API gravity	43	43	43	43	43	43
Relative density / Specific gravity	0.81	0.81	0.81	0.81	0.81	0.81
Length (L), m	55000	55000	55000	55000	55000	55000
Pipe internal roughness, e_0 (mm)	0.04572	0.04572	0.04572	0.04572	0.04572	0.04572
Pipe relative roughness	1.61e-04	1.05e-04	7.76e-05	6.17e-05	5.12e-05	4.37e-05
Fluid density (kg/m^3)	800	800	800	800	800	800
Reynolds number (Re)	1.00e+08	1.00e+08	1.00e+08	1.00e+08	1.00e+08	1.00e+08
Head loss, (m)	0.2388	0.0283	0.0063	0.0020	0.0008	0.0003
Pressure drop, (Pa)	1873.94	221.73	49.18	15.35	5.94	2.67
Pressure drop, (MPa)	1.87e-03	2.22e-04	4.92e-05	1.54e-05	5.94e-06	2.67e-06
Pipeline with internal coating						
Pipe size (inch)	12	18	24	30	36	42
Flowrate (m^3/s)	0.313	0.313	0.313	0.313	0.313	0.313
Pipe diameter, D_0 (mm)	304.80	457.20	609.60	762.00	914.40	1066.80
Pipe inside diameter, D (mm)	284.18	436.58	588.98	741.38	893.78	1046.18
Friction factor, f_c	0.0088	0.0082	0.0079	0.0077	0.0075	0.0073
Pipe internal area (m^2)	7.30	16.42	29.19	45.61	65.68	89.39
	0.042891	0.019062	0.010722	0.006862	0.004765	0.003501
Velocity, (m/s)	2	8	8	6	7	3
Fluid viscosity, (cP)	0.001	0.001	0.001	0.001	0.001	0.001
API gravity	43	43	43	43	43	43
Relative density / Specific gravity	0.81	0.81	0.81	0.81	0.81	0.81
Length (L), m	55000	55000	55000	55000	55000	55000

Pipe internal roughness, e_0 (mm)	0.0045	0.0045	0.0045	0.0045	0.0045	0.0045
Pipe relative roughness	1.58e-05	1.03e-05	7.64e-06	6.07e-06	5.03e-06	4.30e-06
Fluid density (kg/m^3)	800	800	800	800	800	800
Reynolds number (Re)	1.00e+08	1.00e+08	1.00e+08	1.00e+08	1.00e+08	1.00e+08
Head loss, (m)	0.1590	0.0192	0.0043	0.0014	0.0005	0.0002
Pressure drop, (Pa)	1248.22	150.62	33.88	10.69	4.18	1.89
Pressure drop, (MPa)	1.25e-03	1.51e-04	3.39e-05	1.07e-05	4.18e-06	1.89e-06
Final results						
Reduction in friction factor (%)	33.39	32.07	31.11	30.34	29.68	29.10
Diameter of internally coated pipe, D_c, (mm)	281.01	423.17	565.82	708.85	852.22	995.89
Reduction in pipeline diameter (%)	7.81	7.44	7.18	6.97	6.80	6.65
Reduction in pipe relative roughness (%)	90.16	90.16	90.16	90.16	90.16	90.16
Capacity of internally coated pipe, Q_c, (m^3/s)	0.38	0.38	0.38	0.38	0.37	0.37
Increase in Pipeline capacity (%)	22.53	21.33	20.48	19.81	19.25	18.76
Reduction in pressure drop (%)	33.39	32.07	31.11	30.34	29.68	29.10
Flow improver and pipeline capacity enhancement						
% Drag reduction	70	70	70	70	70	70
Percent throughput increase (%)	94	94	94	94	94	94
Synergetic effect: internally coated pipeline plus flow improver						
Total enhancement of pipeline capacity (%)	116.43	115.23	114.38	113.71	113.15	112.67
Total pipeline capacity (m^3/s)	0.68	0.67	0.67	0.67	0.67	0.67

5. Discussion

The analysis demonstrates that the combined utilization of a flow improver and an internal coating will lower the pipe relative roughness and subsequently decrease friction factor, increase flowrate, and reduce pipe material and operating cost [4,10,18].

A decrease in a pipe friction factor decreases it relative roughness. An increase in Reynolds number and decrease in pipe diameter increases the percentage by which the friction factor decreases. At high Reynolds numbers, the influence of a pipe diameter on reduction of friction factor decreases [4,10]. The effect of Reynolds number is significant or highest within the range of 10^5 – 10^7.

The advantage of lowered friction arising from the synergetic use of a flow improver and internal coating is dependent on the uncoated pipe relative roughness. The results presented here is for a bare/uncoated commercial pipe with internal roughness of 0.04572mm (i.e., 0.0018 inch) and an internally coated pipeline with internal roughness of 0.0045mm [4,10]. Assuming preliminary/initial internal roughness is less than 0.04572mm, the benefits is going to be relatively decreased [10].

Pipeline capacity or volumetric flow rate is enhanced with an increase in Reynolds number. In the experimentation, the Reynolds number (Re) was varied from 10^4 to 10^8. The analysis presented in Figures 9 and 11 and Tables 3 through 11, shows that the volume flow rate or pipeline capacity is enhanced with rising Reynolds number. The volume flow rate (Q) governs the mean velocity through the pipe. This is the velocity scale used for the pipe Reynolds number. Therefore, for a pipe with diameter (D) and fluid kinematic viscosity (ν), increasing the Reynolds number harmoniously enhances the volume flow rate (see Eq. (9)). Reynolds number is given by

$$Re = \frac{(Q \times D)}{(\nu \times A)} \tag{9}$$

where
Re = non-dimensional Reynolds Number.
D = pipe's internal diameter (m),
Q = flow rate (m^3/s),
A = pipe's cross-sectional area (m^2),
v = kinematic viscosity ($v = \mu/\rho$) (m^2/s),

It was observed that in a pipe of the same cross section and diameter, where a fluid of same kinematic viscosity (v) flows, the only parameter controlling Reynolds number (Re) is the volumetric flow rate (Q) as in Figure 9 and 11. This confirms Professor Osborne Reynolds' finding at Manchester University in 1880, that when he increased the flow rate in a glass tube, using a dye injector at the flow centre, the dye streamline stayed central until he increased flow to a critical flow rate, where the flow became turbulent, and the dye mixed though the whole fluid downstream. This is the laminar/turbulent flow transition.

As the fluid passes through the pipe, the smaller size pipe diameters (i.e., 12-inch) has higher capacity (i.e., flowrate) than large diameter pipeline (42-inch). This is because reducing the diameter of the pipe restrict the flowing fluid (see Eq. (10)) and hence, it flows faster (i.e., velocity of flow is high), thereby enhancing the flow rate. However, the flow rate (capacity) reduces with an increase in pipe diameter (see Figure 9 and 11, Table 3-11).

$$Q = U \times A \tag{10}$$

All parameters are as defined above.

The mechanisms of corrosion in gas pipelines include microbiological corrosion, galvanic corrosion, crevice corrosion, pitting corrosion, intergranular corrosion, stress corrosion cracking (SCC) and fatigue corrosion and are usually due to chlorides or acid conditions, carbon dioxide, hydrogen sulphide, water, organic acids, micro-organisms, and other molecules [19]. Internal coating prevents internal corrosion and smoothen the pipe internal profile so that fluids flow more readily and hence increases a pipes capacity. A thin film epoxy {XE "epoxy"} coating is applied at 1.5 – 3 mils (37 – 75 microns) dry film thickness[19-21].

Pipeline internal coating and flow improvers, enhances internal corrosion protection of a pipeline, and hence, the incidence of particle accumulation and ultimately "black powder" production is prevented. For midstream pipelines, a problem called black powder occurs because sales gas that is presumed to be dry can still contain some water vapor, which can condense and cause corrosion. The corrosion product can then settle as a powder in the pipeline, as well as clog or erode valves and metering equipment. Black powder in gas pipelines is usually corrosion products formed by internal pipeline corrosion, but can also be particles from mill scale, weld splatter, formation cuttings, salts, etc. In order to reduce black powder formation in midstream pipelines, moisture content should be kept low, pipelines should be internally coated and measures to reduce oxygen contamination should be taken [19,21].

Internally coating the pipeline will ensure, pipe length protected prior to laying: no corrosion which would damage the smoothness, and create product contamination. Reduction in paraffin and other deposition – which reduces gas flow. By internally coating the pipeline, the gas or liquid product will be pure: no contamination from corrosion dust which might block, or damage pipelines [19,21].

In an internally coated pipeline, pigging is infrequently needed and cleaning is easier. Practical observation indicates that, compared with a bare pipeline, around half the pressure would be required to propel a pig (pipeline intelligent gauge) through a pipeline with internal coating. The need for pigging varies with pipelines, however, based on experience of some gas transmission companies, for an internally coated pipeline, pigging is necessary only every twelve (12) to eighteen (18) months. In a pipeline, with no internal coating, pigging is normally required thrice yearly. This will reduce maintenance of coated lines, due to less frequent pigging being required, and due to easier cleaning. By experience, in running pigs, about half the pressure is required to move a pig through an internally coated line as compared to an uncoated line. Internal coating helps pipe inspection: the light-reflecting internal coating reveals lamination, and other pipe defects [19,21].

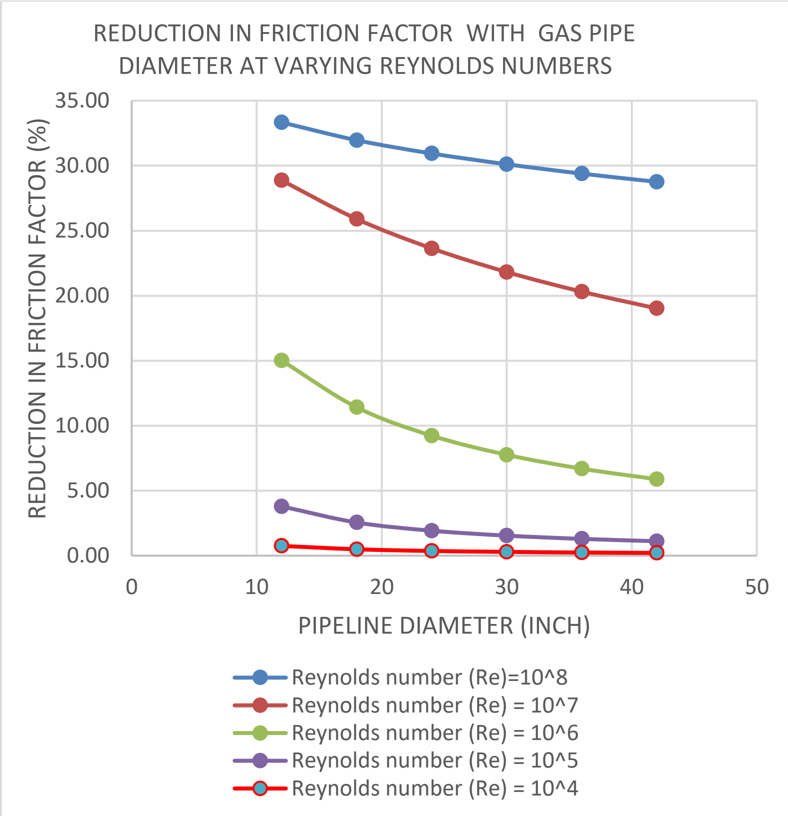

Fig. 1. Reduction in friction factor with pipe diameter at varying Reynolds number and internal roughness, e_0 = 0.04572mm

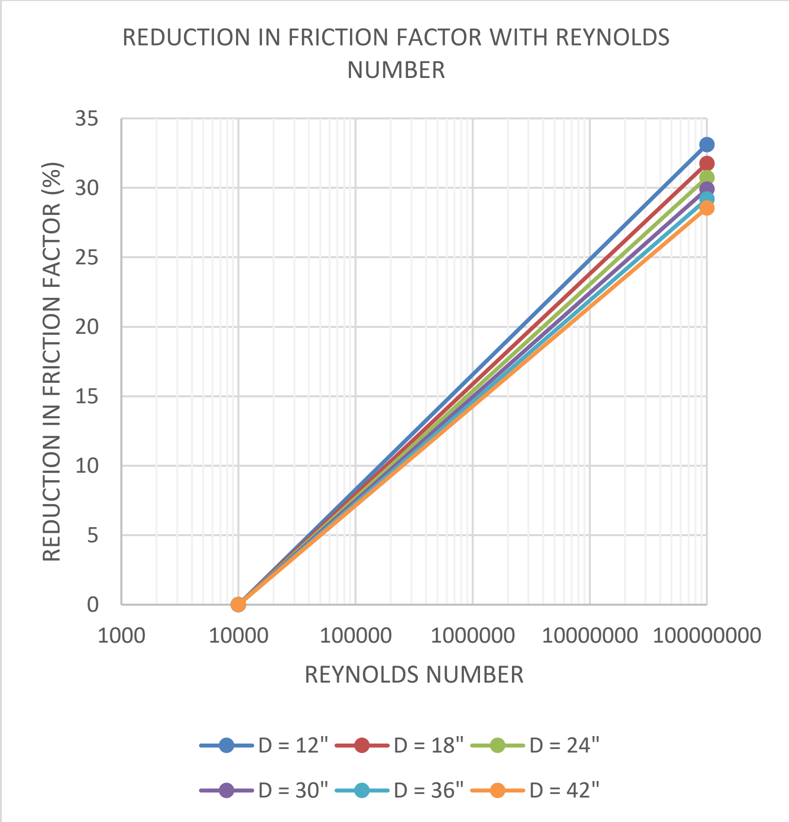

Fig. 2. Reduction in friction factor with Reynolds number, $Re = 1 \times 10^8$, and internal roughness, e_0 = 0.04572mm, E/e_0 = 0.6

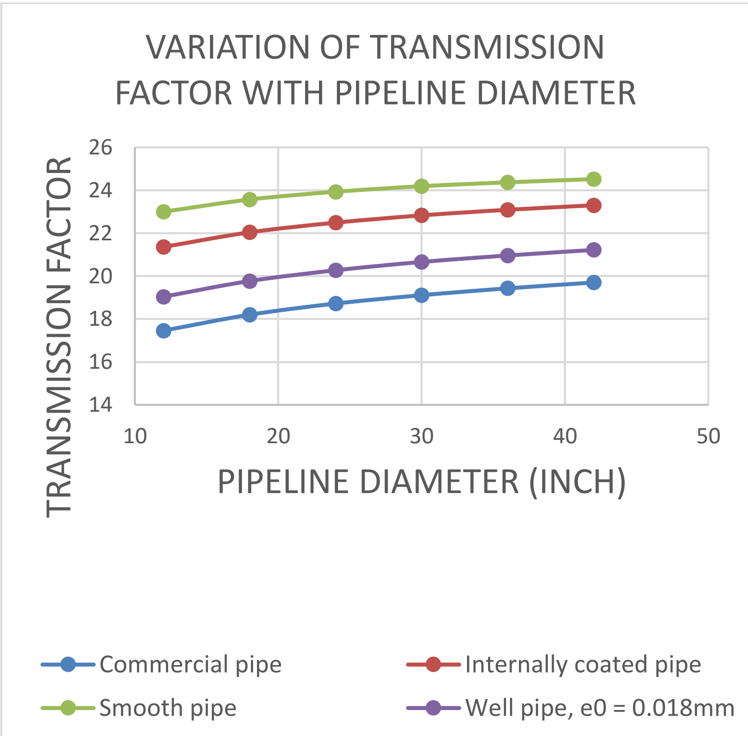

Fig. 3. Variation of transmission factor with pipeline diameter at Reynolds number, $Re = 1 \times 10^8$, and internal roughness of commercial pipe, e_0 = 0.04572mm, smooth pipe, e_0 = 0.001524mm, well pipe, e_0 = 0.018mm

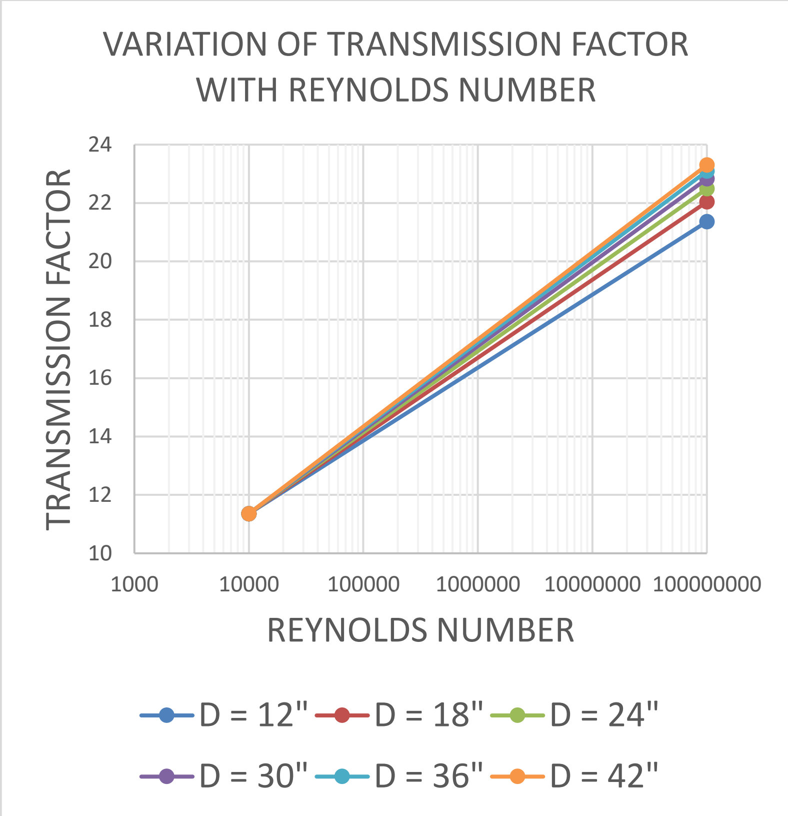

Fig. 4. Variation of transmission factor with Reynolds number, $Re = 1 \times 10^8$, and internal roughness, e_c = 0.0045mm

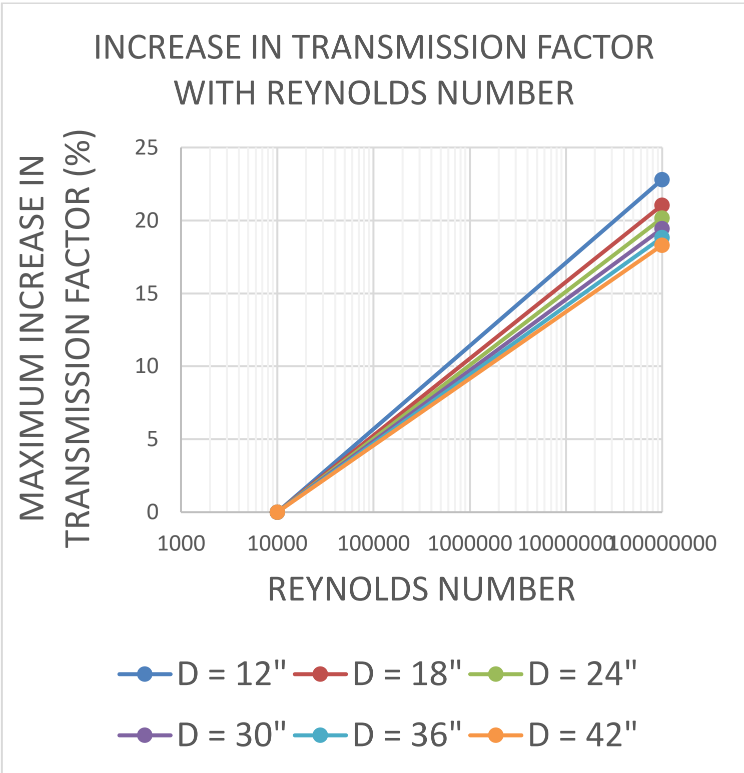

Fig. 5. Increase in transmission factor with Reynolds number, $Re = 1 \times 10^8$, and internal roughness, e_0 = 0.04572mm, E/e_0 = 0.1

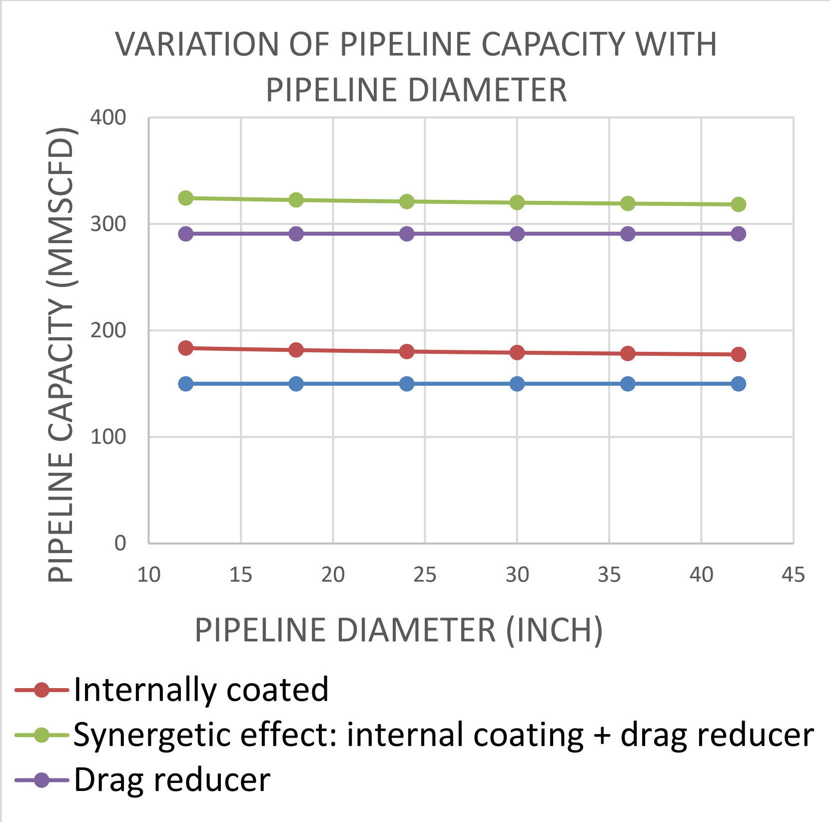

Fig. 6. Variation of pipeline capacity with pipeline diameter; Reynolds number, $Re = 1 \times 10^8$, and internal roughness, e_0 = 0.04572mm

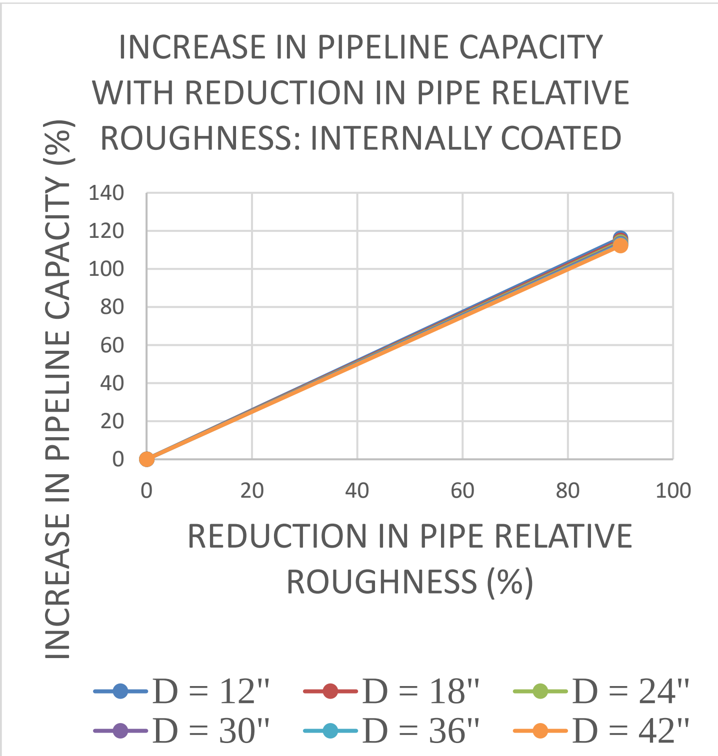

Fig. 7. Increase in pipeline capacity with reduction in pipe relative roughness when internally coated; Reynolds number, $Re = 1 \times 10^8$, and internal roughness, e_0 = 0.04572mm for gas pipelines

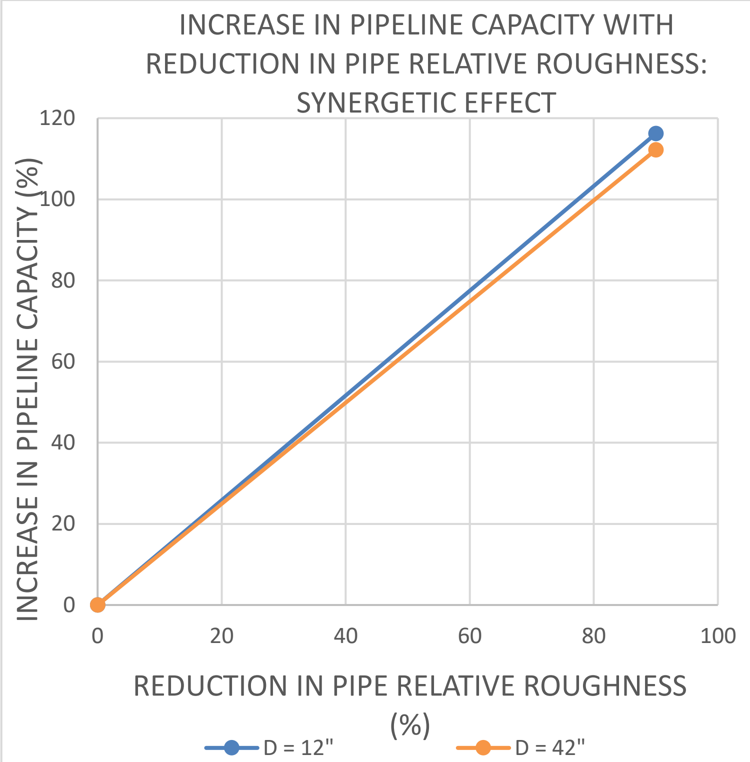

Fig. 8. Increase in pipeline capacity with reduction in pipe relative roughness from synergetic use of internal coating and drag reducer at Reynolds number, $Re = 1 \times 10^8$, and internal roughness, e0 = 0.04572mm for gas pipelines

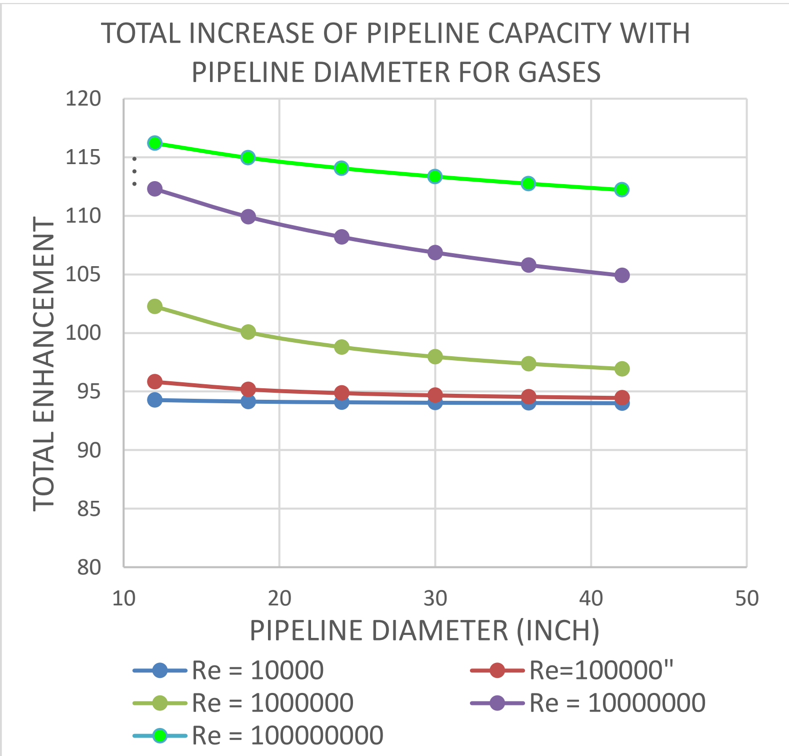

Fig. 9. Total enhancement of gas pipeline capacity with pipeline diameter from synergetic use of internal coating and flow improver at Reynolds number, $Re = 10^4 \; to \; 10^8$, and internal roughness, e_0 = 0.04572mm and e_c = 0.0045mm for gas pipelines

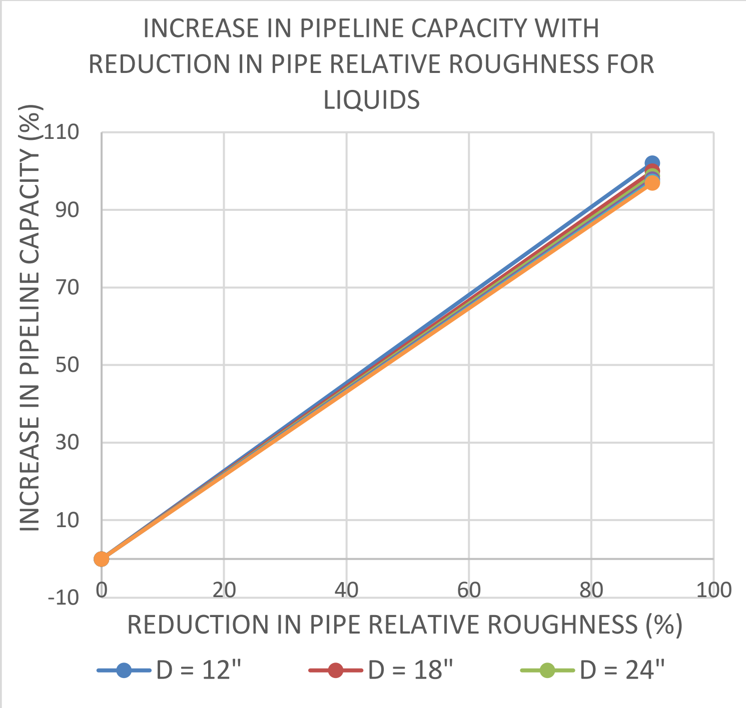

Fig. 10. Increase in pipeline capacity with reduction in pipe relative roughness from synergetic use of internal coating and drag reducer at Reynolds number, $Re = 1 \times 10^6$, and internal roughness, e_0 = 0.04572mm for liquid pipelines

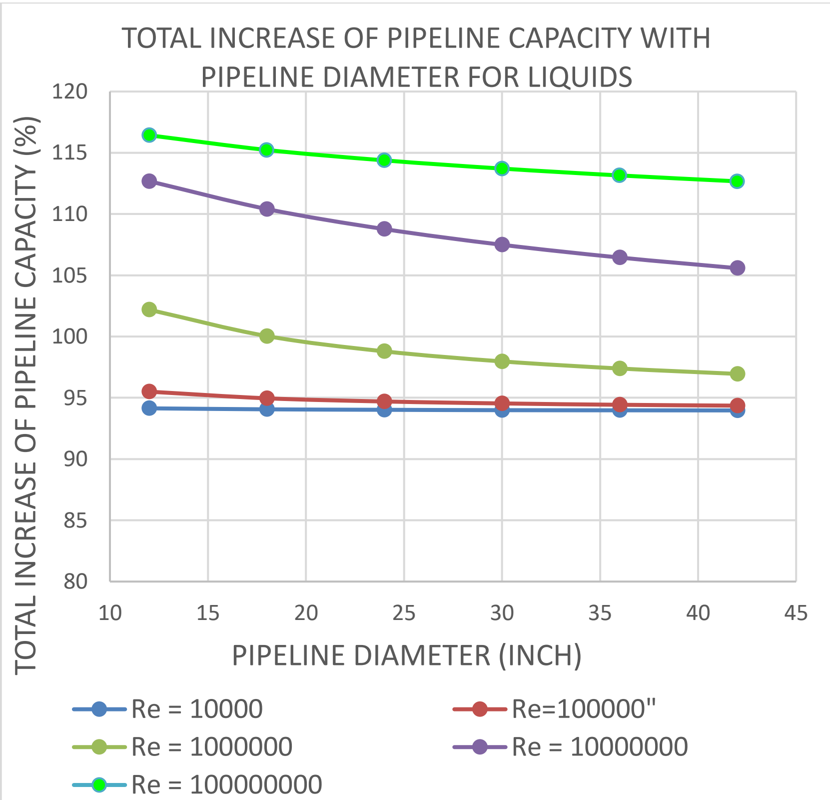

Fig. 11. Total enhancement of liquid pipeline capacity with pipeline diameter from synergetic utilization of internal coating and flow improver at Reynolds number Re= 10^4 to 10^8 and internal roughness e0=0.04572mm, ec=0.0045mm

6. Conclusions

A study of gas and liquid pipeline flow rate increase due to the combined or synergetic use of an internal coating and a flow improver (drag reducing agent) is presented in this study. The current study of the synergetic effect of a flow improver and an internal coating on pipeline capacity enhancement has led to the following important conclusions.

i. Synergistic use of a flow improver with 70% drag reduction and an internal coating, will increase (enhance) capacity above 116% [4].
ii. Based on Figure 1 - 2. And Table 3 -11, reduction of relative roughness lowers friction factor.
iii. As the Reynolds number increases, the influence of a pipe's diameter on reduction in friction factor reduces.
iv. The change in friction factor is greatest between Reynolds numbers of $10^5 – 10^7$(see Tables 3-9) [4,10].
v. Internal coating with specified pipe internal roughness of 0.0045mm could lower friction factor of a commercial pipe by up to 33% (see Tables 3-9).
vi. Internal coating with specified pipe internal roughness of 0.0045mm could increase the throughput or capacity of a liquid pipeline by up to 22% and 23% for a gas pipeline system (see Table 10-11).
vii. Internal coating with specified pipe internal roughness of 0.0045mm could decrease the diameter of a commercial pipe by 8% (see Table 3-11).
viii. Internal coating with specified pipe internal roughness of 0.0045mm could lower the pressure drop of a commercial liquid pipe by 33% (see Table 10-11).
ix. Internal coating with specified pipe internal roughness of 0.0045mm could increase the transmission factor of a gas pipeline system by 22% (see Table 3-9).
x. Internal coating and flow improvers can be financially acceptable on due to lowered operating cost.
xi. Pipe maintenance cost reduction – regularity of cleaning is considerably reduced.
xii. Internal corrosion protection from the use of a flow improver and internal coating.
xiii. Use of internal coating can inhibit black powder formation within the gas pipeline.
xiv. Another advantage is where for safety a reduction of operating pressure is required. The pipe must then be replaced, or a loop added if pressure reduction is not acceptable. However, the use of an internal coating or flow improver will permit compensating increased flow at lower operating pressures, and is a lower cost alternative.
xv. Economically, initial cost of coating plus flow improver (drag reducer) utilization could be recovered. Although, the installed pipe diameter could be sufficient for current throughput requirements, synergistic use of internal coating and flow improver is considered prudent for an increased future demand.

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