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The Proven Efficiency of Epoxy Flow Coats for the Protection of Gas Transmission Pipelines

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1. Introduction

The concept of internally lining gas pipelines – known as internal flow coating – was first developed in the 1950s to counter the adverse effects on pipeline capacity, operation and pumping costs caused by the rough internal surface of steel pipes and the build-up of deposits and corrosion products.

This paper reviews the benefits of considering an internal lining for gas transmission pipelines, and the relationship between the internal surface roughness, the pressure drop across the pipeline and the maximum flow rate of gas through the pipeline. This paper also outlines the benefits of internal flow coatings and the developments that have been made over recent decades in terms of coating materials, taking into account new challenges associated with gas production and transmission, and how they meet the current requirements of international standards and specifications.

2. Frictional resistances affecting fluid flow

A fluid in motion in a pipeline is subjected to various frictional resistances. Friction occurs between the fluid and the pipe wall, but also occurs within the fluid itself. Some of the main factors affecting fluid flow in pipes include :

- The length, internal diameter and internal roughness of the pipe.
- The viscosity, density and velocity of the fluid.
- Changes in fluid temperature, which will affect the viscosity and density of the fluid.
- The geometry of the pipeline, including bends, risers, valves and other fittings.

How surface roughness dictates laminar or turbulent flow

Fluid flow in a pipeline can either be laminar flow or turbulent flow. The transportation of natural gas in pipelines at high flow rates exhibits turbulent flow. In turbulent flow conditions, a laminar film can be formed at the pipe wall / fluid interface, which will reduce the friction between the fluid and pipe wall with subsequent reduction in the pressure drop through the pipeline and increased flow capacity. The creation of this laminar film is dependent upon the surface roughness at the pipe wall / fluid interface, and to a lesser degree the extent of the turbulent flow and the fluid velocity.
The laminar film created at the pipe wall is very thin. The maximum peak height of the profile of the pipe wall surface may, depending on its height, be able to protrude through the laminar film created. This protrusion results in disrupting the flow pattern of the laminar film and effectively creating a turbulent flow pattern adjacent to the pipe wall, increasing the pressure drop across the pipeline and reducing flow capacity, as reported by Fogg and al (2005).

3. The benefits of using a flow efficiency coating

There are a number of benefits in using a flow efficiency coating for a natural gas pipeline. Below are some of the different ways in which these benefits can be recognized :

- A reduction in the pressure drop in the pipeline and thus an increase in the flow rate of natural gas through the pipeline.
- A decrease in the pipeline outer diameter in the design phase of the project to achieve the same flow capacity as reported by Tobin and al (2005).

- A reduction in power consumption for compression of the gas to achieve the same flow capacity, with a subsequent reduction in greenhouse gas emissions for the transportation of natural gas as reported by Westcoat Energy (2003).

Other benefits that can be achieved during installation and operation of the pipeline include :

- Preventing the corrosion from reforming, eliminating the need for additional pre-commissioning work.
- Easier and faster commissioning of the pipeline thanks to the faster drying compared to the uncoated pipe after hydrostatic testing.
- Simplification of the testing and any robotic inspection procedures by the improved mobility of the equipment travelling down an internally coated pipe.
- The inhibition of Black Powder* formation within the gas pipeline – it leads to erosion failures and damages pipeline operating valves. Obviously, it can clog instruments and filters, lower the efficiency of compressors and contaminate the supplied product to customers. This is a world-wide problem that affects most gas pipeline operators.
- Short term corrosion protection during transport and storage.

*The term **"Black Powder"** is a color descriptive term used to describe a blackish material (very small, jagged & very hard particles). The material may be wet and have a tar-like appearance – see an example of the appearance from the picture below.

Picture 1 : appearance of the Black Powder

This powder can develop within gas pipelines due to a reaction of iron with condensed moisture, containing O_2, H_2S & CO_2), so the Black Powder could come from the following sources:

- Mill scale (iron oxides - Fe_3O_4), from the pipe manufacturing process through high temperature oxidation of steel.
- Flash rust ($Fe_2O_3$3, FeOOH) from hydrostatic testing water corrosion.
- Internal pipelines corrosion (MIC (Microbiological Influenced Corrosion) or H_2S reaction with steel.
- Carryover from gas gathering systems.

Black Powder may be mechanically mixed or chemically combined with any number of contaminants such as water, liquid hydrocarbons, salts, chlorides, sand, or dirt. Chemical analyses of the material have revealed that it consists mainly of a mixture of iron oxides and iron sulphides. See below an example of the chemical composition of Black Powder in table 1.

Table 1: Black Powder composition using the XRD technique

Main compound	**Approximate avg. weight, %**
Magnetite Fe3O4	60
Gamma- FeOOH	< 2
Alpha-FeOOH	25

Iron sulphides	Not detected
Siderite – $FeCO_3$	10
Elemental Sulfur	5

In 2012, the Abu Dhabi Gas Industries Company, known as Gasco took the decision to apply an internal epoxy coating for all new gas transmission pipelines (DGS1470-008), the application of an internal flow coating systems favouring two primary functions:

- Reduced gas friction by provision of a very smooth surface profile.
- Inhibiting Black Powder formation within the gas pipeline

This is being implemented for the HMT (Habshan – Maqta – Taweelah) pipeline currently under construction in the UAE, two 300-kilometres pipelines to supply the Taweelah industrial hub.

4. Economical analysis

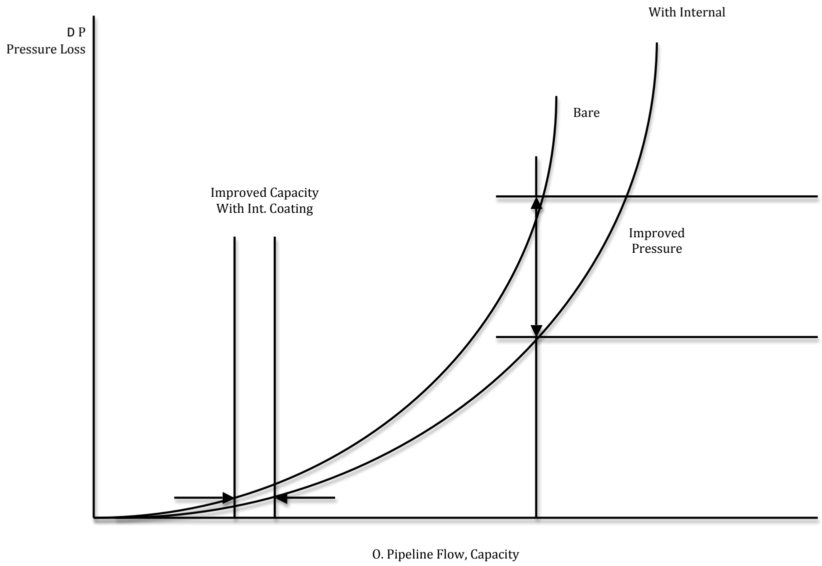
Steel pipe delivered to the coating yard has a relative roughness of the order of 20 µm. However, once in production,, this relative roughness may exceed 50 µm, depending upon the corrosion products formed on the surface due to the amount of time and conditions the pipe was stored in prior to installation, hydrostatic testing, and the corrosive nature of the fluid being transported. Using hydraulic pipe flow software, the pipe roughness versus maximum achievable flow rate can be plotted, for a constant discharge and arrival pressure.

From the late 1950s, US companies such as Tennessee Gas Pipeline Company and Transco conducted tests demonstrating the benefits of internal linings to increase the flow efficiency in gas pipelines by 5 to 10% with medium size diameters (24'', 30'', 36''). Several studies confirmed the magnitude of flow increase in the 1960s.

In 1998, a Norwegian university and Statoil, the state-owned Norwegian oil company confirmed the benefit of the internal flow coat by demonstrating a capacity increase of 21 %. In 2005, Statoil reported that it made the decision to apply an internal epoxy coating to the Langeled gas pipeline, in the North Sea, in order to increase transport capacity and reduce pig wear.

In 2002, the Zamorano study concluded that fuel gas costs for the compressor stations situated along the 1,200 km length of the Atacama Gas Pipeline, were 26.9 per cent lower on the coated section of pipeline than on the uncoated section. Indeed, the Argentinian pipeline section (530 km, 20'' OD) was coated with a solvent-based epoxy flow efficiency coating whilst the Chilean section was left bare because of the project CAPEX constraints. The economical analysis in this study was based upon the existing capacity of the pipeline and two capacity expansion scenarios. One conclusion of the study was that the economic benefits of using internal flow efficiency coatings were more substantial at higher gas flow rates – see figure 2

Figure 2 : Pipeline flow capacity for bare and internally coated pipe



An internal flow coating can also make a significant difference in reducing pumping and compression costs over the lifetime of the pipeline. These reduced energy costs can provide a financial payback within three to five years of service. It may also be possible to achieve further savings by reducing the number of compressor stations, or compressor size and capacity.

5. International flow coat standards and client requirements

Nowadays, two international standards are well recognized when technical requirements for Flow Efficiency Coatings are considered :

- API 5L2 : « Recommended Practice for Internal Coating of Line Pipe For Non-Corrosive Gas Transmission Service », by the American Petroleum Institute
- ISO 15741 : « Paints and varnishes — Friction-reduction coatings for the interior of on- and offshore steel pipelines for non-corrosive gases »

with the EN 10301 standard : ''Steel tubes and fittings for on and offshore pipelines - Internal coating for the reduction of friction for conveyance of non corrosive gas", which is pretty similar to the ISO 15741

A comparison between API 5L2 and ISO 15741 is presented in the following table. See table 2.

Norm	API 5L2		ISO 15741 : 2001	
Date of issue	July, 2002		December, 2001	
DFT in microns	51 ± 5		60 < X < 100	
	Test conditions	Requirement	Test conditions	Requirement
Adhesion	adhesion with cross lines (16 x 16 at 90° spaced over 26mm). Used clear plastic tape	No lifting of any material other than cuttings	Cross cut test 4.3.4 ISO 2409	≤ 1
Stripping test	A sharp blade at 60° to the surface have to be pushed = blade has a tendency to lift the coating	no coating removing from strips but shall flake off. The flakes when rolled shall produce powdery particules		
Buchholz Hardness	Buchholz hardness at 25°C DIN 53 153	≥ 94	Buchholz hardness ISO 2815	≥ 94
Abrasion	ASTM D968, Method A	≥ 23 (abrasion coef)		
Bend test (conical mandrel)	Bend a coated panel 180° around a mandrel with 13 mm diameter. ASTM D522	No flaking, loss of adhesion or cracking with a mandrel with a maximum diameter of 13 mm. Visual checking	Conical mandrel (d1=38mm, d2=3,2mm and L=203mm) ISO 6860	maximum extent of cracking from the small end of the mandrel ≤ 13 mm and no loss of adhesion
Resistance to Neutral Salt spray	500h with X cut ASTM B117	No blistering ≤ 3,2 mm of coating can be removed in any dircetion with clear plastic tape.	480h with X cut ISO 7253	No blistering, no paint removal and corrosion (see 4.3.6)
Resistance to Artificial Ageing			Condition 1 = Cycle C Condition 2 = after coating : 10 days at 18-25°C and 24h at 50°C + 4 days at 80°C and 24h at 18-25°C Bend test in agreement with ISO 6860 for condition 1 and 2	maximum extent of cracking from the small end of the mandrel ≤ 13 mm
Resistance to Gas Pressure variations	In suitable pressure equipment. Dry Nitrogen at 83 bars at 19-31°C and during 24 hours.	No blistering	Dry Nitrogen at 100 bars for 10 tests cycles ISO 15741 Annex C	adhesion ≤ 1 no blistering and good appearance
Resistance to hydraulic blistering	In suitable hydraulic pressurizing equipment. Distilled water saturated with CaCO3. 165 bars at 25°C during 24 hours	No blistering	Conditionning cycle B 23°C until no more tack free + 30 min at 150°C In suitable hydraulic pressurizing equipment. Distilled water saturated with CaCO3. 100 bars at 23°C during 24 hours	adhesion ≤ 1 no blistering and good appearance
Resistance to water immersion	21 days at room temperature Satured CaCO3 solution in distilled water (100% immersion)	No blistering over 6,3 mm from edges (slight softening is permited)	480h at 40°C in water quality 3 in agreement with ISO 3696 36 ISO 2812-2	No blistering or appreciable softening
Resistance to Water / Methanol immersion	5 days at room temperature in mixture, equal parts by volume, water methanol (100% immersion)	No blistering over 6,3 mm from edges (slight softening is permited)		
Resistance to Chemicals			-Cyclohexane - 95% by volume diethylene glycol in water - Hexane - Methanol - Toluene - Lubricating oil 168h ISO 2812-1 method 1 procedure A	Adhesion (rating ≤ 1)
Curing Test	After 4h immersion in the paint's thinner	No softening, wrinkling or blistering shall be observed after 30 min at room temperature		

Additional requirements by clients are sometimes specified and increasingly observed, especially concerning the roughness, such as in the DG1470 Part 008 from Gasco and the specification 10-00050-10-MX-SPC-0110-0003 for the South Stream offshore pipeline project, respectively Rz ≤ 10 µm and Rz ≤ 5 µm according to the ISO 4287.

The South Stream consortium also has some additional requirements in terms of appearance (glossy appearance) and chemical resistance (adhesion after 168 hours' immersion in 100 % methanol and immersion in 100 % triethylene glycol).

6. Available technologies and application conditions

From the late 1950's, epoxy chemistry has been the predominant coating technology worldwide thanks to its commercial availability in North America, where the flow coats were first used and the very good compromise offered by the epoxy chemistry in terms of mechanical properties, corrosion protection and chemical resistance, even though Novolac epoxy coatings are the prefered choice of a few operators, such as Petrobras in Brazil.

The challenge has been, in the intervening years, to also develop formulations by reducing the solvent content in the formulation, even though the API 5L2 is not very demanding in this respect. The API 5L2 is intended for low solids coating materials, so the material specification requirements did not directly apply to the solvent free epoxy formulations, the challenges over the last several years have been to develop low VOC or VOC free formulations to cope with the stringent HSE requirements and the compliance with the API 5L2 and ISO 15741 international standards. Furthermore, low VOC or VOC free formulations have been to be developed to comply with the application conditions in terms of :

- Application equipment : multi component
- Spray characteristics : consistent
- Pot life : more than 1 hour at 20°C
- Applied film thickness : 50 – 100 µm
- Curing time : hard dry in less than 18 hours at 20°C
- Coating roughness : < 10 µm with a smooth even appearance
- Air entrapment : none

7. Roughness testing

Laboratory scale tests at Axson Coatings

At the laboratory scale level, two versions of Flow Efficiency Coatings were tested : a medium solids version (66 % by volume), called HES version and a solvent free version (100 % volume solids), called SF version, both of them currently commercialized under the Eurokote® 436.20 trademark.
The main objective was to evaluate the roughness profile of both versions once applied in a conventional manner and to compare the roughness profile between a solvent based coating and a solvent free coating.
The HES version is designed to be applied with a single component airless spray system, whilst the SF version is designed to be applied by twin feed hot airless spray equipment.

Firstly, steel plates (dimension : 150*100*1 mm) were shot-blasted and de-dusted in order to achieve a Sa 2.5 level of cleanliness (according to ISO 8501-1) and a surface roughness profile Rz of about 45 µm profile. The surface roughness was measured with a Marsurf PS1 device and, as an example, the following measurements were taken on of the steel plates - see Table 3.

Table 3 : Example of the surface roughness of the shot-blasted steel plates

Rz Min	Rz Average	Rz Max	standard deviation	Number of measurements
33.6	**39.79**	55.2	4.58	26

Measurements conditions :

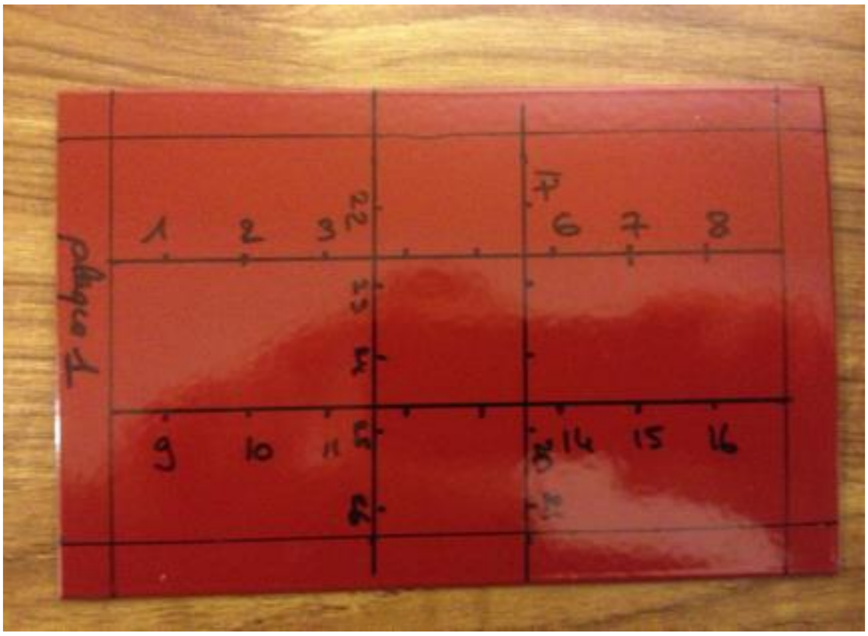
- Marsurf PS1 device with a PHT 6-350 sensor
- Cut-off : 2.5 mm
- Gaussian filter

The steel plates were applied in our laboratory by using an airless spray equipment in the following conditions as per the instructions for using Eurokote 436.20

- Temperature of the substrate : Minimum +10°C (+20°C for the SF version) and maintained at least 3°C above the dew point / Maximum +40°C
- Air temperature / RH : Min. +10°C / Min RH 5% - Max. +40°C / Max RH 85%
- Temperature of the product : Min +10°C / Max +30°C in the case of the solvent based HES version. In the case of the solvent free SF version, the resin part should be pre-heated to around 50°C and the hardener part to around 30°C.

As an example, the SF version of Eurokote® 436.20 was applied after preheating of part R and part D to respectively 55°C and 35°C (metering unit, hosels) and applied by airless spray (nozzle 17 to 24/1000 inches) with a 160 bars minimum pressure.

See below a picture showing a coated plate with marks illustrating the different locations used for the roughness measurements – Picture 2



26 locations were selected to conduct measurements on a representative surface of each coated panel for both the HES and SF versions. The measurements were taken 15 days after curing at room temperature (20°C).

Hereafter are summarized the test results of the Ra, Rz roughnesses on coated plates applied with around 100 µm DFT, the values being obtained from measurements of the 26 locations – Tables 4-1 and 4-2

Table 4-1 : test results for Eurokote® 436.20 HES

zone	maxi	aver.	mini	std deviation
Ra	0.65	0.41	0.27	0.10
Rz	3.53	2.30	1.41	0.58
DFT	88	100	116	

Table 4-2 : test results for Eurokote® 436.20 SF

zone	Max	Aver.	Min	std deviation
Ra	0.64	0.47	0.33	0.08
Rz	3.37	2.33	1.53	0.38
DFT	98	107	125	

Comments :

- A very similar roughness profile is observed between the HES and SF versions, respectively 2.30 and 2.33 in Rz, a non-significant difference considering the standard deviation.
- a low roughness profile is observed, complying with the stringent specifications observed nowadays, such as Gasco DGS1470-008 spec or the South Stream specifications.

Based on different application conditions between our laboratory conditions and industrial applications, such as the pipe rotating when the material is applied, the curved surface of the internal pipe, the heat inertia of the pipe due its pipe wall thickness, differences in coating roughness profile could be observed.

Several industrial tests have been conducted on both the medium solids (HES) and solvent free (SF) versions by pipe coaters for product qualification and / or project purposes. Hereafter, the industrial test results achieved with the SF verision of Eurokote® 436.20 are presented.

Industrial scale tests in a pipe mill

At an industrial level, coating characteristics were compared on test pieces, coated during the application process of internally coated pipes production. Test pieces (160*80*1 mm metal panels) were manufactured from low-carbon steel and shot-blasted in a shot blasting unit Schlick 151 from Airblast by using steel grit reference WGP050 manufactured by W Abrasives (France). Once shot blasted, the test pieces had a roughness between 43 and 47 µm.
Before coating, the panels were acid and acetone washed in accordance with the requirements of API 5L2.
The metal test panels were fixed on pipes before coating in order to coat the panels together with the pipes.
After coating, the panels were removed from the pipe and cured according to the following programme : 15 minutes in the air with a 40 % relative humidity and then 30 minutes in the oven with air circulation at a temperature of 150°C.
Test panel coatings were made from the following liquid epoxy materials :

- Eurokote 436.20 SF, the solvent free version of the Eurokote 436.20 serie of Flow Efficiency Coatings provided by Axson France SAS
- Competition A, a solvent free liquid epoxy
- Competition B, a high solids (81 %) solvent based liquid epoxy.

The performance was compared by assessing the roughness profile, using a SJ-301 Surflet equipment according to ISO 8503-4. Ra and Rz were measured o a 4 mm length with a 0.8 mm cut-off by using a Gaussian filter.

The coating thicknesses were measured with a Konstanta K-5 gauge by making 10 measurements on each sample – see Table 5

Table 5 : test results of the coated surface roughness profile

Flow Efficiency Coating	Ra in µm (Average value on 5 samples)	Rz in µm (Average value on 5 samples)	Coating thickness Magnitude in µm – values on 5 samples	Coating thickness Average in µm – from the 5 samples
Eurokote 436.20SF	0.42	1.98	74 - 121	95
Competition A	0.14	0.77	84 - 110	98
Competition B	0.45	3 .20	59 - 92	74

Comments :

- The low roughness profile of Eurokote® 436.20 is confirmed at the industrial scale, even with a lower roughness data compared to the data observed from the laboratory application.

- Beyond the technical requirements, expressed in the API 5L2 and ISO 15741 standards, this roughness profile shows how modern coating materials can comply with stringent requirements (lower than 10 µm and even lower (≤ 5 µm)) in terms of roughness profile.

7. Perspectives & Conclusions

Internal liquid epoxy coatings have demonstrated their interest as a flow efficiency coating of gas transmission pipelines in terms of operations and maintenance since the 1960s. Furthermore, it helps to solve technical solutions, such as the formation of Black Powder. From a performance point of view, the API and ISO standards have been benchmarks for the selection of liquid epoxy coating materials.

Recently, clients or operators have expressed new requirements, especially in terms of surface profile roughness to guarantee the flow efficiency.

Existing modern coating materials have been designed to cope with the technical requirements, as listed in the API 5L2 and ISO15741 international standards and by taking account specific requirements, such as the surface profile roughness. Beside those performance requirements, the development of new epoxy coating materials has been conducted without any compromise on the health, hygiene and environmental regulations, as demonstrated by the performance of the solvent free version of Eurokote® 436.20, this material being also benzyl alcohol and VOC free.

The benefits of the flow efficiency provided by the internal lining can be considered for carbon capture and storage projects (CCS). For instance, for the project associated with the pipeline transportation, an internal coating was selected by Shell and considered by applying a 100 µm dry thickness of a solvent-based epoxy coating to comply with the requirements, especially when the CO2 is depressurized down to 1 bar involving a fluid temperature as low as -70°C. Of course, dry CO2 water specification is mandatory (≤ 50 ppm in volume (20 ppm by mass)) to avoid any damage due to corrosion.

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