OPTIMUM DESIGN OF A MULTIPLE-PIPE ABOVE-GROUND PIPELINE

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Abstract: *The optimum sizes of the pipeline can be determined using different steel grades and different geometrical and loading conditions. The paper shows an initial parametric study on these conditions to find the lowest self mass. The number of tubes, diameter and thickness are variables. Spanlength, steel grade and loading are considered to be given parameters. Another constraint is transfer capacity. The mass per unit length difference between the smaller and larger diameters and thicknesses is significant, which emphasizes the necessity of optimization.*

Key words: *optimum design, multiple-pipe, stress, stability, slenderness*

1. INTRODUCTION

Over the last decades a new pipeline transportation appeared. In the past centuries, fossil fuels have increased green house gases concentration in the atmosphere, with effects on low layer heating and global climate condition changes.

Under Kyoto Protocol's directives, many methods for emissions reduction, with limited impact on the economies of the countries that have accepted this document [1], have been studying: particularly the reduction of CO_2 emission.

Carbon Capture and Storage (CCS) technologies consist in a series of procedures to capture CO_2 from industrial flue gases and to store it in appropriate sites to avoid its atmospheric dispersion.

After capture, carbon dioxide must be transported to the storage site. CO_2 is an inert gas and can be easily handled and transported in high pressure pipelines. Alternatively, it can be transported in industrial tanks by ship, rail and truck.

The risks of pipeline leakage are very small, as it is demonstrated by the long time utilization of oil and gas pipelines, but to minimize any risks, CO_2 pipelines could be routed away from large centers of population to avoid danger caused by CO_2 toxicity.

Pipelines can be considered the most suitable method for transporting CO_2, since the cost for this technology depends mainly on the distance, the quantity transported and whether the pipelines are onshore or offshore [2].

CO_2 is normally transported as a supercritical fluid. To maintain the product in its supercritical state, it is transported at pressures that range from 80 to 180 bars.

Booster stations along the pipeline route maintain the necessary pipeline pressure for CO_2 pipelines. The increased pressure in CO_2 pipelines is typically accommodated in thicker-walled pipes than those used for natural gas transportation [3].

There are short-distance segments in the pipeline system where above-ground pipelines are installed. There is a short distance near the power station where the underground pipeline is not necessary and near the storage equipment the pipeline emerges.

Fig.1. An above-ground pipeline [4]

In this paper above-ground pipelines are investigated which look similar to the structure in Figure 1, where a pipe-bridge is not installed. In this design process the spanlengths, the thickness and diameter of the tube, the number of pipes, the steel grade and loading can be parameters or unknowns.

The inner pressures are calculated for each inner diameter. In this study only the number of pipes, tube diameter and thickness are variables.

The spanlength, the steel grade and loading are considered to be given parameters in the design process. Changing these would result in another study. It should be noted that hydrodynamic investigation is not taken into account although it is important for the pipeline system and only straight pipeline is investigated.

2. DESIGN CONSTRAINTS

In this kind of design for above-ground high pressure pipeline transportation three kinds of constraints are to be used. These are the stress, deflection and stability constraints.

2.1 Stress constraint

The stress constraint can be calculated as follows.

The distributed load is

$$p = \left(1,2A\rho_a + 1,1A_t\rho_g\right)g \tag{1}$$

where ρ_a is the density of the steel, A_t is the area of transportation, ρ_g is the density of high pressure gas and the area of the pipe wall is

$$A = \frac{\left(D^2 - d^2\right)\pi}{4} \tag{2}$$

In structural analysis, Clapeyron`s theorem of three moments is a relationship between the bending moments at three consecutive supports of a horizontal beam. Let *A*, *B*, and *C* be the three consecutive points of support, and denote by *l* the length of *AB* and by *l*` the length of *BC*. Then the bending moments M_A, M_B, M_C at the three points are related by

$$M_A l + 2M_B(l + l') + M_C l = \frac{6a_1x_1}{l} + \frac{6a_2x_2}{l'} \tag{3}$$

where a_1 is the area on the bending moment diagram due to vertical loads on AB, a_2 is the area due to loads on BC, x_1 is the distance from A to the center of gravity for the bending moment diagram for AB, x_2 is the distance from C to the center of gravity for the bending moment diagram for BC.

So the bending moment at the middle support according to the Clapeyron formula is

$$M_2 = \frac{2,5pL^2}{4} \tag{4}$$

where *L* is the distance between the supporters.

The stress is

$$\sigma_1 = \frac{M_2}{K_x} \tag{5}$$

where

$$K_x = \frac{\left(D^4 - d^4\right)\pi}{32D} \tag{6}$$

where *D* is the outside diameter and *d* is the inside diameter.

Barlow’s formula can be calculated as

$$\sigma_2 = \frac{p_b d}{2t} \tag{7}$$

where *D* is the outside diameter and *d* is the inside diameter.

Reduced stress is

$$\sigma_R = \sqrt{\sigma_1^2 + \sigma_2^2 - \sigma_2\sigma_2} \tag{8}$$

The permissible stress is

$$R_{adm} = \frac{f_y}{n_e} \tag{9}$$

where safety factor n_e is 1,2 and f_y is the yield stress.

The stress constraint is

$$\sigma_R \le R_{adm} \tag{10}$$

2.2 Deflection constraint

The deflection of the pipe between the supports can be calculated as follows

$$w = \frac{pL^4}{284EI_x} \tag{11}$$

where *E* is the elastic modulus and the moment of inertia is

$$I_x = \frac{\left(D^4 - d^4\right)\pi}{64} \tag{12}$$

The limitation of the deflection is

$$w \le \frac{L}{300} \tag{13}$$

2.3 Stability constraint

This constraint depends on the ratio between the outer diameter and the wall thickness. The limit is given by Eurocode to avoid local buckling in the tube walls:

$$\frac{D}{t} \le 90\varepsilon^2 \tag{14}$$

where

$$\varepsilon = \sqrt{\frac{235\text{MPa}}{f_y}} \tag{15}$$

3. NUMERICAL RESULTS

The aim of this investigation is to find the lowest mass per unit length pipe for a given transporting CO_2 volume flow rate. To obtain this optimum, the best number of pipes, outside diameter and wall thickness combination has to be found under the European Standard [5] which meets the three design constraints and although hydrodynamic investigation is not taken into account the velocity of flow is limited by 20 m/s.

In this numerical example the mass flow rate is 5000 tons per day, what is about 29,2 m^3/s. The distance between the supports is L = 25 m and the yield stress of the material of the tube is f_y = 448 MPa.

The optimum results for different diameters calculated by a MathCad code where the unknowns were the number of pipes, outside diameter and wall thickness. The results are shown in Table 1. The optimum results are given in bold italics.

Table 1. ***Optimum results for different numbers of pipes***

Number of pipes	Outside diameter [mm]	Wall thickness [mm]	Mass per unit lenght [kg/m]	Total mass per unit lenght [kg/m]
1	1524	36	1321	1321
2	1016	22,2	544	1088
3	864	20	416	1249
4	762	17,5	321	1285
5	660	14,2	226	1131
6	610	14,2	209	1252
7	559	12,5	168	1179
8	***508***	***11***	***135***	***1080***
9	508	11	135	1213
10	457	10	110	1102
11	457	10	110	1213
12	457	10	110	1323
13	406,4	8,8	86	1122

Mass per unit length comparisons of structural versions obtained for a given numerical example by minimum mass design show the following. There are optimum number and sizes for diameter and thickness and choosing these, the total mass per unit length of the structure can be reduced to 1080 kg/m as a global optimum, which can be a 18,2% decrease compared to the one pipe system. Because of the high number of pipes the second cheapest result (1088 kg/m) with two pipes can be a good result because of the maintenance. The limitation of the velocity of flow and the European Standard give same geometrical results for high pipe numbers.

Another study would cover changing the spanlength and steel grade, which is a more complex optimization with five unknowns.

4. CONCLUSIONS

The optimization of above-ground steel pipelines for high pressure CO_2 transport is a small part of large CO_2 pipeline systems. But the optimum number and sizes of the pipe (diameter and thickness) can be determined to reduce the weight and the cost of the transport system. In this optimization no special optimization technique is needed because there are only three unknowns and there is a limitation in the Standard [5].

Diameter and thickness combinations have to meet stress, deflection and stability constraints. If the outside diameter is large, one cannot reduce the wall thickness because the stability constraint will be the active constraint. But if it is small, the stress constraint will be the active constraint.

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REFERENCES

[1]. Kovacs, I., Andraș, I., Andraș, A., Tomuș, O.B. *Tapasztalatok es kilatasok a szen szereperol a romaniai energetikaban,* 46. Bányagépészeti és Bányavillamossági Konferencia, 2013, Balatongyörök, ISBN 978-963-87684-2-1., pp.125-128.

[2]. Bumb P, Desideri U, Quattrocchi F, Arcioni L.: *Cost Optimized CO_2 Pipeline Transportation Grid: A Case Study from Italian Industries,* World Academy of Science, Engineering and Technology 58, 2009, pp. 138-145.

[3]. Amann, R. et al.: *A Policy, Legal, and Regulatory Evaluation of the Feasibility of a National

Pipeline Infrastructure for the Transport and Storage of Carbon Dioxide, Topical Report, 2010, 102 p.

[4]. Saundry, P. (Contributing Author), **Congressional Research Service** (Content Source), **Hassenzahl, D.** (Topic Editor): *Pipelines for Carbon Dioxide Control in the United States*. In: Encyclopedia of Earth. Eds. Cutler J. Cleveland (Washington, D.C.: Environmental Information Coalition, National Council for Science and the Environment) 2013. http://www.eoearth.org/article/Pipelines_for_Carbon_Dioxide_Control_in_the_United_States?topic=54490

[5]. European Standard EN 10220:2002. *Seamless and welded steel tubes – Dimensions and masses per unit length*, 9p.