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INFLUENCE OF WALL FRICTION FACTOR AND LOCAL LOSS MODELS ON THE PREDICTION OF PRESSURE DROP IN A STEAM LINE

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Abstract. *The objective of the present work is to provide a comprehensive study of the most used friction factor correlations and local loss models applied to the calculation of pressure drop along a steam line indicating the most suitable models for this application. A comparative study was performed where each model was evaluated against a 3D simulation, using CFD techniques. The expected result was to determine which of three most used friction factors – Colebrook, Churchill and Blasius – provided the best prediction of distributed pressure loss and which local loss model – K, 2K or 3-K – performed better in the prediction of local losses.*

Keywords: *Nuclear Energy, Pressure Drop, CFD, Industrial Installations*

1. INTRODUCTION

This work was motivated from an actual demand related to a steam line in the Nuclear Station of Angra dos Reis, in Rio de Janeiro, between units 2 and 3. The nuclear station has three power plants: Angra 1, a Westinghouse design, operating since 1982 with power output of 650 MW; Angra 2, KWU/Siemens design, operating since 2001 with power output of 1350 MW; and Angra 3, a KWU/Siemens/Framatome design, which is under construction. During refueling outages and under certain treatment system functions, auxiliary steam is necessary for heating in several processes. Angra 2 and 3 designs counts with an integrated auxiliary steam system, where steam can be produced at both units and, in case of demand in any of the units, one acts as the provider of the other. In this way, a steam line which transports the steam from one plant to another is required, parallel to a condensate return line. This integrated system also counts with an auxiliary boiler, which produces steam when both power plants (Angra 2 and 3) are unavailable[1]. Figure 1 shows a schematic drawing of the auxiliary steam system arrangement.

The distance between Angra 2 and Angra 3 is approximately one kilometer, in such a way that it is of great relevance to know the magnitude of the pressure losses along the interconnecting lines between both plants.

As in this case, and in any other industrial installation project, it is necessary to know the magnitude of the pressure losses along the piping systems for its sizing, as well as the losses due to the mechanical components (pumps, control valves, compressors, heat exchangers etc.)

1.1 The challenges in the calculation of Δp: distributed losses

The pressure losses along a line can be determined by three main forms: (i) a reduced model is constructed and instrumented, and the pressure losses are obtained directly from the measures at inlet and outlet, employing the proper scaling parameters; (ii) a three-dimensional computational model is implemented, using CFD[2] techniques, in which the head loss is obtained from the solution of the pressure field, through the selected numerical method (Finite Elements, Finite Volumes or Finite Differences); (iii) a correlation for the friction factor and local losses is employed in an algebraic calculation procedure. This method is the most commonly used, for its low cost and for providing fairly accurate results.

Nevertheless, there are tens of correlations for friction factor, for different fluids and flow regimes – laminar flow,

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[1]Currently, wich Angra 3 still under construction, all auxiliary steam consumed during Angra 2 refueling outages is produced by the auxiliary boiler
[2]Computational Fluid Dynamics

turbulent flow, channel flow etc. The work of Fang *et al.* (2011) cites 11 correlations only for circular ducts. The high number of possibilities results in a difficulty at the moment of selecting the most adequate model. The domain of validity of each one may vary with the flow regime – usually expressed by the Reynolds number Re – or the roughness of the material. But usually there are multiple possible models for the same range.

In several applications, the selected correlation is the classical Blasius friction factor, for turbulent regime, expressed by

$$f \quad = \quad \frac{0.316}{\mathrm{Re}^{0.25}} \quad (\mathrm{Re} \le 2 \times 10^4) \tag{1a}$$

$$f \quad = \quad \frac{0.184}{\mathrm{Re}^{0.20}} \quad (2 \times 10^4 \le \mathrm{Re} \le 2 \times 10^6) \tag{1b}$$

For laminar regime, the Poiseuille correlation is employed (eq. 2)

$$f = \frac{64}{\mathrm{Re}} \tag{2}$$

The pair Poiseuille-Blasius provided reasonably accurate results for many applications, and is extremely simple. For this reason it is largely employed. Another correlation also very used is that of Colebrook and White (eq. 3)Colebrook and White (1937). But this one has the drawback of being an implicit relation between the friction factor f and the Reynolds number Re.

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

Also widely used is the correlation of Churchill, given by

$$f \quad = \quad 8\left[\left(\frac{8}{\mathrm{Re}}\right)^{12} + (A + B^{-1,5})\right]^{1/12} \tag{4}$$

$$A \quad = \quad \left\{-2,457\ln\left[\left(\frac{7}{\mathrm{Re}}\right)^{0,9} + \frac{0,27e}{D}\right]\right\}^{16}$$

$$B \quad = \quad \left(\frac{37530}{\mathrm{Re}}\right)^{16}$$

It can be noticed that f is explicitly determined. This correlation has the interesting characteristic of presenting a non-monotonic relation with Reynolds in the transition from laminar to turbulent regimes.

In summary, there is no consensus with respect to the selection of the most adequate friction factor correlation of each piping project, including inner flows in circular ducts, which is the case of the present work.
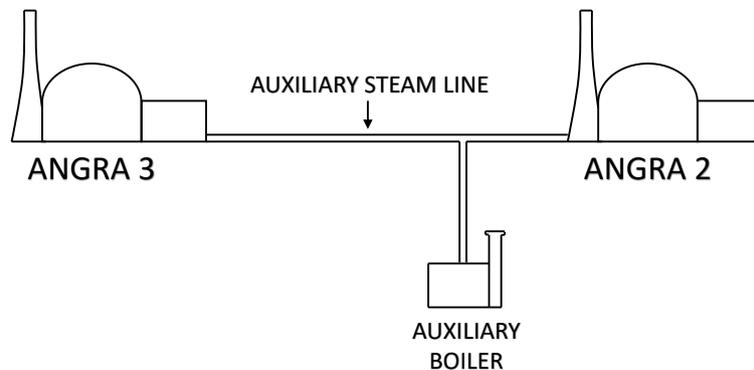

Figure 1. Sketch of the auxiliary steam system interconnected between Nuclear Power Plants Angra 2 and Angra 3 and the auxiliary boiler.

1.2 The challenges in the calculation of Δp: local losses

Another key point in the algebraic calculation of pressure losses is the selection of the model for local losses. In most cases, the so called "K" method, also known as Crane method (Crane, 2013), is adopted. This is the classical method where an empirical coefficient is provided for each type of fitting, in such a way that the pressure loss Δp along a pipe length L and diameter D com n fittings (elbows, valves etc.) is given by

$$\Delta p = \left(f\frac{L}{D} + \sum_{i=1}^{n} K_i \right) \frac{\rho v^2}{2} \tag{5}$$

where v is the mean velocity of the flow and ρ is the mean density of the fluid.

However, the so called "2K" and "3-K" methods are alternatives for introducing the effects of local losses in the calculation of the pressure drop in a pipe.

The 2K method was proposed by Hooper (1981) with the novelty of incorporating the effect of the Reynolds number in its coefficient. As explained by Hooper (1981), "K is independent of Re when Re is sufficiently high. However, K starts to rise as Re decreases toward 1,000, and becomes inversely proportional to Re when Re is below 100". So the 2K method was introduced as an improvement of the classical K method.

A further step in the sense of improvement was taken by the 3-K method (Darby, 2001). The 3-K method was proposed to strengthen the relations of the K and the 2K methods, exploring the best of both to create the most accurate model for local losses. As Darby (2001) said, "the 3K method was proposed as a correlation which would represent the best features of each of these methods over the widest range of Reynolds Number and fitting size".

However, the classical K method, which is doubtlessly the simplest of the three, is still largely used. Thus, as in the case of distributed pressure drop and the friction factors, it becomes necessary to know the cost-benefit relation of each local loss model at the moment of designing an industrial piping system.

2. OBJECTIVE

The objective of the present work is to provide a comprehensive study of the most used friction factor correlations and local loss models applied to the calculation of pressure drop along a steam line indicating the most suitable models for this application. A comparative study was performed where each model was evaluated against a 3D simulation, using CFD techniques.

The objective was to determine which friction factor correlation provided the best prediction of distributed pressure loss and which local loss model – K, 2K or 3-K – performed better in the prediction of local losses. So the main product of this work is to suggest the best combination of friction correlation / local loss model for the prediction of pressure loss in a circular duct.

In the following section, further details related to the research methodology is provided.

3. METHODOLOGY

This work consists on a comparative study, where a 3D RANS[3] simulation, using the Finite Volumes Method, is performed to provide the steady state regime of a steam/condensate flow along a pipeline based on the auxiliary steam system of the Angra dos Reis Nuclear Power Station. The following figure shows some details of the numerical simulation (CFD). Two flow conditions were taken into account:

- saturated steam flow in a 341.4 mm diameter pipe; 6 bar at the inlet

- subcooled condensate flow in a 150.0 mm diameter pipe; 30 ^{o}C and 6 bar at the inlet

For each flow condition, the study was performed in two steps. In the first one, a straight pipe (no fittings), with a reduced length of 400 m, is simulated and the resulting pressure drop is compared to those predicted by means of a set friction factors based on those evaluated by Fang *et al.* (2011) (cf. 2). The objective is to select the most accurate correlation without the influence of accidents.

In the second step of the study, after selecting the friction factor correlation, the three methods for local losses are compared against the 3D simulation of steam flow along a 550 m long pipe containing two 45° elbows and thirty two 90° elbows, all with curvature of 1.5.

This procedure was employed for the steam flow and then repeated for the condensate flow. The objective was to evaluate the applicability of the friction correlations and local loss models for different Re numbers.

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[3]Reynolds Averaged Navier-Stokes

Table 1. Flow conditions and geometry variants employed in the study.

	pipe diameter	pipe length	fluid
case 1	341.4 mm	400 m	saturated steam at 6 bar
case 2	150.0 mm	400 m	condensate at 6 bar / 30 ^{o}C
case 3	341.4 mm	550 m	saturated steam at 6 bar
case 4	150.0 mm	550 m	condensate at 6 bar / 30 ^{o}C

4. RESULTS

The first test (case 1) consisted on the comparison between the 3D simulation in a straight line (no fittings) with 400 m of length and the friction correlations of Fang *et al.* (2011) for steam flow. Sixteen friction factor correlations were analyzed against the 3D simulation. Table 2 summarizes the results, showing the Δp obtained with each one and the error related to the CFD result. The error ϵ was calculated as

$$\epsilon = \frac{\mid \Delta p - \Delta p_{\text{CFD}} \mid}{\Delta p_{\text{CFD}}} \qquad (6)$$

Table 2. Comparison of pressure drop calculated with friction factor correlations in a straight pipeline for steam flow (case 1).

rank	Δp [bar]		error
-	3D simulation	0.166797	-
1	Serghides (1984)	0.169059	1.3561%
2	Haaland (1983)	0.171874	3.0438%
3	Zigrang and Sylvester (1982)	0.172530	3.4370%
4	Colebrook (1937)	0.172531	3.4379%
5	Barr (1981)	0.172582	3.4681%
6	Sonnad and Goudar (2006)	0.172639	3.5026%
7	Chen (1979)	0.172854	3.6314%
8	Romeo et al. (2002)	0.173035	3.7398%
9	Jain (1976)	0.173394	3.9553%
10	Churchill (1977)	0.173501	4.0191%
11	Swamee and Jain (1976)	0.173532	4.0378%
12	Manadilli (1997)	0.173623	4.0922%
13	Moody (1947)	0.175817	5.4079%
14	Wood (1966)	0.182583	9.4640%
15	Round (1980)	0.182887	9.6467%
16	Blasius (1913)	0.129014	22.6521%

In the following test (case 2) the friction correlations were tested for condensate flow. Results were compiled in table 3.
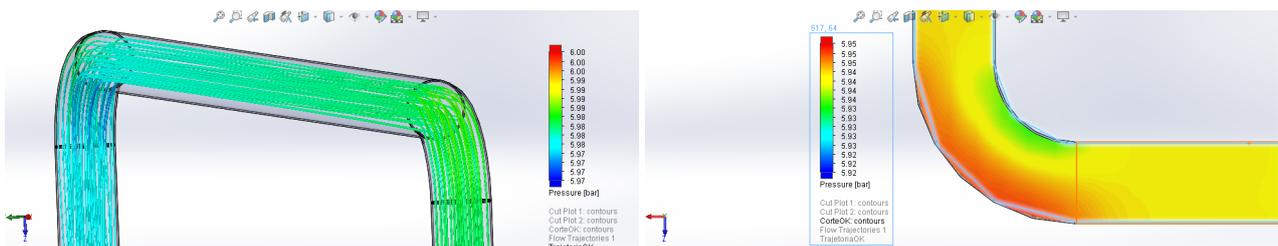

Figure 2. Details of the 3D simulation. On the left: streamlines colored according to pressure field; on the right: cut plot of the pressure field in a 90° elbow.

Table 3. Comparison of pressure drop calculated with friction factor correlations in a straight pipeline for steam flow (case 2).

rank	Δp [bar]		error
-	3D simulation	0.044900	-
1	Serghides (1984)	0.047116	4.9360%
2	Blasius (1913)	0.047537	5.8728%
3	Haaland (1983)	0.049498	10.2404%
4	Moody (1947)	0.049980	11.3145%
5	Barr (1981)	0.050174	11.7464%
6	Zigrang and Sylvester (1982)	0.050188	11.7771%
7	Round (1980)	0.050201	11.8061%
8	Colebrook (1937)	0.050207	11.8203%
9	Jain (1976)	0.050233	11.8778%
10	Swamee and Jain (1976)	0.050279	11.9790%
11	Churchill (1977)	0.050298	12.0232%
12	Chen (1979)	0.050357	12.1545%
13	Sonnad and Goudar (2006)	0.050410	12.2717%
14	Manadilli (1997)	0.050541	12.5628%
15	Wood (1966)	0.051132	13.8787%
16	Romeo et al. (2002)	0.051103	15.6213%

Based on these results, the Serghides correlation was adopted for the comparative analysis of local loss models. A line 550 m long with two 45° elbows and thirty two 90° elbows, both with $R/D = 1.5$ (R is the radius of the fitting curvature), was simulated with the CFD model according to cases 3 and 4 (cf. table 1). Tables 4 and 5 show the results.

The Serghides correlation is expressed by

$$
\begin{aligned}
f &= A - \frac{(B-A)^2}{(C-2B-A)^{-2}} \\
A &= -2\log_{10}\left(\frac{\varepsilon/D}{3.7} + \frac{12}{Re}\right) \\
B &= -2\log_{10}\left(\frac{\varepsilon/D}{3.7} + \frac{2.51A}{Re}\right) \\
C &= -2\log_{10}\left(\frac{\varepsilon/D}{3.7} + \frac{2.51B}{Re}\right)
\end{aligned}
\tag{7}
$$

Table 4. Comparison of pressure drop calculated with three different local loss models for steam flow (case 3).

	Δp [bar]	error
3D simulation	0.247708	-
K (Crane)	0.293179	18.3543%
2K	0.301458	21.6989%
3-K	0.303968	22.7121%

Table 5. Comparison of pressure drop calculated with three different local loss models for condensate flow (case 4).

	Δp [bar]	error
3D simulation	0.089070	-
K (Crane)	0.070175	21.2141%
2K	0.070176	21.2129%
3-K	0.071555	19.6639%

Results show that the accuracy of the local loss model depends on the flow regime (Re number). For steam flow case (case 3), the best result was obtained with the K (Crane) method, and for the condensate case (case 4), it was the 3-K method that performed better.

5. CONCLUSIONS

The study presented in this work produced interesting results related to different models for distributed and local pressure losses. The obtained results showed that the friction factor of Serghides provided the most accurate pressure losses for both steam and condensate flows (cases 1 and 2 according to 1).

Interesting results were obtained regarding the performance of the classical Blasius correlation. It greatly underestimated the pressure loss for the steam flow case, but had the second best prediction in the condensate case. It shows how dependent the Blasius correlation is of the flow regime, performing better when it approaches the experimental conditions for which the correlation was derived. From this point of view, the Serghides was the one with the best capacity to adapt to different flow condition.

It should be mentioned that both flow conditions (steam and condensate) were in the turbulent regime. An interesting assessment would be to evaluate the friction correlations in the laminar regime. Of course, not all correlations applied in this study would be applicable, starting from the Blasius equation, which would be replaced by the Poiseuille equation.

Regarding the local losses, in the steam flow condition, it can be said that the models performed in the exactly opposite way with respect to the expected results. The 3-K method, which was developed to combine the qualities of the classical K (Crane) method and the 2K method, had the greatest error, while the K (Crane) method had the best result.

When the fluid changes to condensate (also decreasing pipe diameter), the 3-K method does have the best performance, with the K (Crane) and the 2K methods almost tied with the second best approach.

It is interesting to note that all the local loss models overestimate the losses, being conservative from the point of view of transport efficiency.

A certain conclusion is that most methods are highly flow regime dependent, and the best correlation would be the one with the highest capacity to adapt to the flow regime under prediction.

This work can be continued in order to include more friction correlations, other geometries and other flow regimes, so that the results can be generalized and serve as a useful guide for engineers in the selection of the adequate algebraic model.

6. REFERENCES

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7. RESPONSIBILITY NOTICE

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