Prediction of silica carry-over and solubility in steam of boilers using simple correlation

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1. Introduction

Silicon is the second most abundant element on the surface of the Earth. Many of its compounds are found in natural waters, and some occur quite often as either minor or major constituents of scale [1]. Silica in natural waters occurs both as colloidal particles and as a highly reactive soluble silica. The soluble silica can react and form an almost infinite series of complex silicates that vary in form with environmental conditions. The Earth’s crust is almost entirely (80–90%) silicon compound. The percolation of water through minerals causes silica to dissolve, and under the right temperature and pressure, the soluble silica is transported, redeposited, or reacted and then redeposited as scale in equipment [1].

In the past decade several turbines were diagnosed and analyzed during maintenance and operation to identify and quantify the losses [2]. After classifying the results obtained from the analysis of several turbines, it was concluded that the most common faults that occurred in the steam turbines were increase in roughness and deposits on the blade surface [2].

Erosion, roughness, steam path damage, etc., are factors that reduce power capacity in a steam turbine. Any power loss occurring locally in intermediate stages of a steam turbine results in more available energy in the downstream stages, this effect is well known as the Loss Factor [3].

The presence of silica in boiler water can rise to formation of hard silicate scales. It can also interact with calcium and magnesium salts, forming calcium and magnesium silicates of very low thermal conductivity. Silica can give rise to deposits on steam turbine blades, after being carried over either in droplets of water in steam, or in a volatile form in steam at higher pressures [4].

Majority of the boilers generating steam for turbines rarely have excessive carry-over of boiler water in the steam. Efficient operational practices, optimised steam separator systems and appropriate chemical control will ensure minimal carry-over. However, silica deposits in turbines can occur even when boiler water carry-over is negligible [4]. This is mainly due to the pick up of silica from the boiler water, which dissolves silica and carried over to the turbine sections, where redeposition occurs. Investigations carried out by researchers indicate that the key to minimizing silica carry-over is to maintain the boiler water silica content below certain levels, wherein the concentrations largely depend on operating pressures [4].

Silica can carry over into the steam in two ways. It can be present in the steam as the result of general boiler water carry-over or it can go into steam in a volatile form. In the latter case, silica acts
2. Methodology to develop new correlation

The required data to develop this correlation includes the reported data [4] for solubility in steam of boilers as a function of pressure and water silica (SiO₂) content. The following methodology has been applied to develop this correlation.

Firstly, solubility of silica in steam of boilers is correlated as a function of pressure for different boiler ware silica, then, the calculated coefficients for these polynomials are correlated as a function of boiler ware silica. The derived polynomials are applied to calculate new coefficients for Eq. (1) to predict the solubility of silica in steam of boilers. Table 1 shows the tuned coefficients for Eqs. (2)–(5).

In brief, the following steps are repeated to tune the correlation's coefficients.

1. Correlate the solubility of silica in steam of boilers as a function of pressure (P) for a given boiler water silica content (C_w).
2. Repeat step 1 for other boiler water silica content.
3. Correlate corresponding polynomial coefficients, which were obtained for different pressures versus boiler ware silica, a = f(C_w), b = f(C_w), c = f(C_w), d = f(C_w) [see Eq. (2)–(5)].

Table 1 shows the tuned coefficients used in Eqs. (2)–(5).

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Coefficients for boiler water silica less than 50 mg/kg</th>
<th>Coefficients for boiler Water silica between 50 mg/kg and 500 mg/kg</th>
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</thead>
<tbody>
<tr>
<td>A_1</td>
<td>-9.91036274604</td>
<td>-7.29715827822</td>
</tr>
<tr>
<td>B_1</td>
<td>3.6035324119</td>
<td>3.3618512456</td>
</tr>
<tr>
<td>C_1</td>
<td>-1.308523907</td>
<td>-1.2035405971</td>
</tr>
<tr>
<td>D_1</td>
<td>1.5017551061</td>
<td>1.2824562436</td>
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<tr>
<td>A_2</td>
<td>4.0978329389</td>
<td>4.1843241026</td>
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<td>C_2</td>
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<tr>
<td>D_4</td>
<td>2.2667148187</td>
<td>2.010057934</td>
</tr>
</tbody>
</table>
the correlation, because these functions are smooth and well-behaved (i.e. smooth and non-oscillatory) equations which should allow for more accurate predictions.

3. Results and discussion

Figs. 1 and 2 show the results of the proposed correlation for predicting the silica solubility in steam of boilers as a function of pressure and water silica content in comparison with the reported data. It is evident from the above figures that there is a good agreement between predicted values (for wide range of pressure and water silica contents) and the reported data in literature [4]. The solubility of silica in steam directly depends on both the density and temperature of steam. With decreasing temperature and density, solubility of silica reduces. As the pressure affects steam density which has a strong bearing on steam temperature, it has an important effect on the solubility of silica in steam. These figures show the solubility of silica in steam increases at high pressures and high boiler water silica. Table 2 shows the accuracy of proposed correlation in terms of average absolute deviation percent with some typical reported data. It shows the proposed correlation has an average absolute deviation percent about 4.2%, which is very small deviation from reported data. Sample calculations shown here clearly demonstrate the simplicity of the proposed method and the benefits associated with such estimations. If the proposed approach is adopted in utilities on a periodic basis, significant savings can be assured with reduced maintenance issues in terms of failure of boiler surfaces and scaling problems associated with the carry-over of silica in steam of boilers. Current efforts in

![Figure 1](image1.png)

**Fig. 1.** Comparison of predicted solubility of silica against literature reported data [12] for low concentration of boiler water silica (1–50 mg/kg).

![Figure 2](image2.png)

**Fig. 2.** Comparison of predicted solubility of silica against literature reported data [12] for high concentration of boiler water silica (20–500 mg/kg).
this investigation pave the way for alleviating the problems associated with the overheating and failure of boiler sections due to scale formation and turbine inefficiencies by arriving at an accurate measure of silica solubility in steam which can be used by the utility personnel for monitoring the operational parameters.

3.1. Sample calculation for the practice engineers

The calculations shown here are for a typical boiler operating with 500 mg/kg silica in the water at 2760 kPa. An estimation of silica which comes out of the system when the steam is expanded through a turbine to 690 kPa is given below.

3.2. Solution

As the boiler water silica is more than 50 mg/kg, use 2nd column of Table 1:

\[ a = -4.42055397 \quad (\text{from Eq. (2)}) \]
\[ b = 6.9594653 \times 10^{-4} \quad (\text{from Eq. (3)}) \]
\[ c = -2.1723342 \times 10^{-8} \quad (\text{from Eq. (4)}) \]
\[ d = 5.6549925 \times 10^{-13} \quad (\text{from Eq. (5)}) \]
\[ S = 0.0746 \text{ mg/kg} \quad (\text{from Eq. (6)}) \]

when the steam is expanded through a turbine to 690 kPa. Because “a”, “b”, “c” and “d” are as a function of boiler water silica so we have the same coefficients, however for new pressure \((P = 690 \text{ kPa})\) we will have:

\[ S = 0.0205 \text{ mg/kg} \quad (\text{from Eq. (1)}) \]

So for a 2760 kPa (ga) boiler operating with 500 mg/kg SiO\(_2\) in the water within the boiler could generate steam containing 0.0746 mg/kg of SiO\(_2\). When this steam is expanded through a turbine to 690 kPa (ga), the solubility of SiO\(_2\) decreases to about 0.0205 mg/kg. The silica coming out of solution (0.0746 – 0.0205 = 0.054 mg/kg) could coat turbine blades and eventually result in extensive turbine maintenance. This is classic example showing how the information evolving out of this correlation can be used to understand and predict the potential maintenance issues which could damage the utility components. The results of this example (0.054 mg/kg) have good agreement with calculated results based on literature based data of 0.06 mg/kg \([4]\).

4. Conclusions

High boiler water silica content can result in silica (SiO\(_2\)) vaporization with the steam, and under certain circumstances, siliceous scale. A novel and robust correlation was developed to predict the silica solubility in steam of boilers as a function of pressure and water silica content. The obtained results are compared with the reliable data and show good agreement with the data with absolute deviations being within 4.2%. The proposed correlation appears to be superior owing to its accuracy and simple background, wherein the relevant coefficients can be retuned if new and more accurate data are available in the future. Example shown clearly demonstrates the usefulness of the proposed model for the practice engineers. Current efforts in this investigation will pave the way by arriving at an accurate measure of silica solubility in steam which can be used by the utility personnel for monitoring the operational parameters periodically.

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References