Robust Design of a Butterfly Valve

OptiY GmbH - Germany
Butterfly Valve

Adjustable Valve Angel

Valve Surface Radius

Inlet
Water + Sand

Outlet

Butterfly Valve
Design Specifications

Design Parameter Space:

- Valve Angle = [30, 60] deg
- Valve Radius = [1, 7] mm
- Angle Tolerance = 2 deg
- Radius Tolerance = 0.1 mm

Process or Environment Parameters:

- Inflow Rate = 5 ± 0.125 m s⁻¹
- Sand Grain Roughness = 20 ± 0.5 μm
- Water Density = 997 ± 25 kg m⁻³
- Water Molar Mass = 18.02 ± 0.45 kg kmol⁻¹

Functional Requirements:

- Outlet Mass Flow Rate = [-0.06, -0.054] m s⁻¹
- Outlet pressure = minimal as possible
- Valve Erosion = minimal as possible
- Wall Erosion = minimal as possible

Initial Nominal Parameters

<table>
<thead>
<tr>
<th>Name</th>
<th>Nominal</th>
<th>Tolerance</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Valve Angle</td>
<td>45</td>
<td>30</td>
<td>deg</td>
</tr>
<tr>
<td>Valve Radius</td>
<td>4</td>
<td>6</td>
<td>mm</td>
</tr>
<tr>
<td>Inflow rate</td>
<td>5</td>
<td>0.25</td>
<td>m s⁻¹</td>
</tr>
<tr>
<td>Sand Grain Roughness</td>
<td>2e-005</td>
<td>1e-006</td>
<td>m</td>
</tr>
<tr>
<td>Water Density</td>
<td>997</td>
<td>50</td>
<td>kg m⁻³</td>
</tr>
<tr>
<td>Water Molar Mass</td>
<td>18.02</td>
<td>0.9</td>
<td>kg kmol⁻¹</td>
</tr>
</tbody>
</table>
Nominal CFD-Simulation

Flow Velocity

Wall Total Pressure
Nominal CFD-Simulation

Erosion Density Rate

Outlet Pressure
Design Space: 2D Section Diagrams
Design Space: 3D Graphics

Outlet Mass Flow

Valve Erosion Density Rate
Global Sensitivity: Parameter Importance [%]
### Global Sensitivity: Parameter Interaction [%]

**Outlet Mass Flow**
- Valve Angle*Valve Radius: 32.682
- Valve Radius*Water Molar Mass: 6.974
- Valve Angle*Sand Grain Roughness: 5.167
- Valve Angle*Inflow rate: 4.64
- Valve Angle*Water Molar Mass: 4.622
- Valve Angle*Water Density: 4.206
- Valve Radius*Water Density: 1.785
- Valve Radius*Inflow rate: 1.783
- Valve Radius*Sand Grain Roughness: 1.198
- Water Density*Water Molar Mass: 0.712
- Inflow rate*Water Density: 0.368
- Sand Grain Roughness*Water Molar Mass: 0.318
- Inflow rate*Water Molar Mass: 0.142

**Outlet Pressure**
- Valve Angle*Valve Radius: 21.745
- Valve Angle*Water Molar Mass: 14.974
- Valve Angle*Water Molar Mass: 14.529
- Valve Angle*Inflow rate: 11.494
- Valve Radius*Inflow rate: 8.756
- Valve Radius*Sand Grain Roughness: 4.582
- Inflow rate*Water Molar Mass: 1.45
- Valve Angle*Sand Grain Roughness: 0.814
- Inflow rate*Sand Grain Roughness: 0.29
- Valve Radius*Water Density: 0.207
- Sand Grain Roughness*Water Molar Mass: 0.179
- Valve Angle*Water Density: 0.169
- Inflow rate*Water Density: 0.004

**Wall Erosion**
- Valve Angle*Water Density: 46.468
- Valve Angle*Sand Grain Roughness: 12.288
- Sand Grain Roughness*Water Density: 4.853
- Valve Angle*Water Molar Mass: 1.199
- Water Density*Water Molar Mass: 0.836
- Valve Angle*Inflow rate: 0.58
- Inflow rate*Water Density: 0.33
- Valve Radius*Water Density: 0.018
- Valve Angle*Valve Radius: 0.009
- Inflow rate*Sand Grain Roughness: 0
- Valve Radius*Sand Grain Roughness: 0
- Inflow rate*Water Molar Mass: 0
- Valve Radius*Inflow rate: 0

**Valve Erosion**
- Valve Angle*Valve Radius: 13.524
- Valve Angle*Inflow rate: 3.863
- Valve Angle*Water Density: 2.78
- Valve Angle*Sand Grain Roughness: 2.707
- Valve Radius*Water Density: 1.389
- Valve Radius*Inflow rate: 1.145
- Valve Radius*Sand Grain Roughness: 0.981
- Inflow rate*Water Density: 0.931
- Valve Angle*Water Molar Mass: 0.76
- Valve Radius*Water Molar Mass: 0.271
- Sand Grain Roughness*Water Density: 0.117
- Water Density*Water Molar Mass: 0.024
- Inflow rate*Sand Grain Roughness: 0.007
Nominal Design Optimization

Optimization Goal:
- Constraint: Outlet Mass Flow [-0.06, 0.054]
- Criteria: Maximize Outlet Pressure, Valve Erosion and Wall Erosion

Nominal Design:
- Outlet Mass Flow = -0.05404 kg s^{-1}
- Outlet Pressure = 244 Pa
- Valve Erosion = 668 kg m^{-2} s^{-1}
- Wall Erosion = 9212 kg m^{-2} s^{-1}
Uncertainty Parameters and Tolerances

- Valve Angle
  - Mean: 44.999
  - Sigma: 0.333529
  - Variance: 0.111242

- Valve Radius
  - Mean: 4.67499
  - Sigma: 0.01666
  - Variance: 0.00027751

- Inflow rate
  - Mean: 4.99999
  - Sigma: 0.0417008
  - Variance: 0.00173896

- Sand Grain Roughness
  - Mean: 1.99999e-05
  - Sigma: 1.66861e-05
  - Variance: 2.78427e-05

- Water Density
  - Mean: 997.059
  - Sigma: 8.33317
  - Variance: 6.94417

- Water Molar Mass
  - Mean: 18.0205
  - Sigma: 0.150005
  - Variance: 0.0225016
Nominal Design: Reliability Analysis

-0.06 ≤ X ≤ -0.054
Failure Probability = 56.12%
Robust Design Optimization

Optimization Goal for Outlet Flow Rate:
Minimize Taguchi Quality Loss Function
\[ L = \text{Cost} \times (\text{Variance} + (\text{Mean} - \text{Target})^2) \]
- Cost = 1 Unit
- Target = -0.057 \(\Rightarrow\) [-0.06, -0.054]
Robust Design: Reliability Analysis

-0.06 \leq X \leq -0.054
Failure Probability = 0.36\%
Robust Design: Design Sensitivity

### Outlet Mass Flow

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Total Effect</th>
<th>Main Effect</th>
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</thead>
<tbody>
<tr>
<td>Sand Grain Roughness</td>
<td>53.6</td>
<td>49.43</td>
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<tr>
<td>Inflow rate</td>
<td>31.64</td>
<td>26.1</td>
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<tr>
<td>Water Molar Mass</td>
<td>11.76</td>
<td>1.96</td>
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<td>Water Density</td>
<td>9.91</td>
<td>0.73</td>
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<tr>
<td>Valve Angle</td>
<td>7.59</td>
<td>6.02</td>
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<td>Valve Radius</td>
<td>0.65</td>
<td>0.55</td>
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### Wall Erosion

<table>
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<tr>
<td>Water Density</td>
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<td>65.4</td>
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<td>Sand Grain Roughness</td>
<td>29.48</td>
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<tr>
<td>Water Molar Mass</td>
<td>3.05</td>
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<td>Valve Angle</td>
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<td>0.52</td>
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<tr>
<td>Inflow rate</td>
<td>0.82</td>
<td>0.31</td>
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<tr>
<td>Valve Radius</td>
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### Outlet Pressure

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Total Effect</th>
<th>Main Effect</th>
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<tr>
<td>Water Molar Mass</td>
<td>89.93</td>
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<td>Inflow rate</td>
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<td>Sand Grain Roughness</td>
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<td>Water Density</td>
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<td>Valve Radius</td>
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<td>0.09</td>
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### Valve Erosion

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Total Effect</th>
<th>Main Effect</th>
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<td>Sand Grain Roughness</td>
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<td>Inflow rate</td>
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<tr>
<td>Water Molar Mass</td>
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<tr>
<td>Valve Radius</td>
<td>0.01</td>
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Conclusion

Nominal design using classical nominal simulation cannot warranty the reliability and quality of the products, because the nominal parameters are only one fix value.

Robust design is a power-full tool for design of reliable and quality product in the early design stage without any cost. It considers the uncertainty parameters as stochastic distributions.

In the case of the butterfly valve, we have got a robust design with 0.36% failure probability for the manufacturing.

OptiY® is the leading software platform for robust design of all engineering fields using different commercial CAD/CAE-software or in-house codes.