Improved model for transmission probabilities of edge-welded bellows based on TPMC simulations

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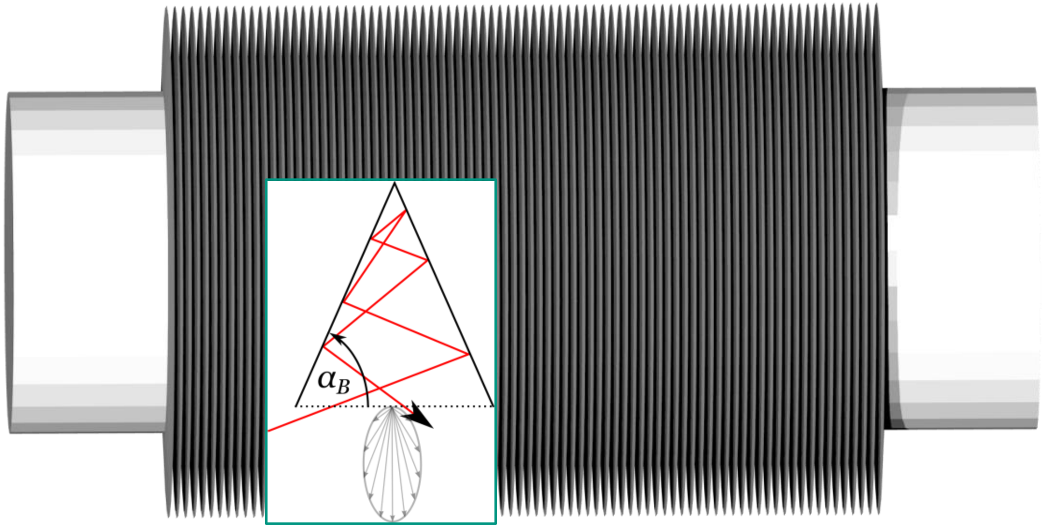
- Principle of vacuum simulations
- Simulation of edge-welded bellows
- Analysis of simulation results
- Improved model for edge-welded bellows

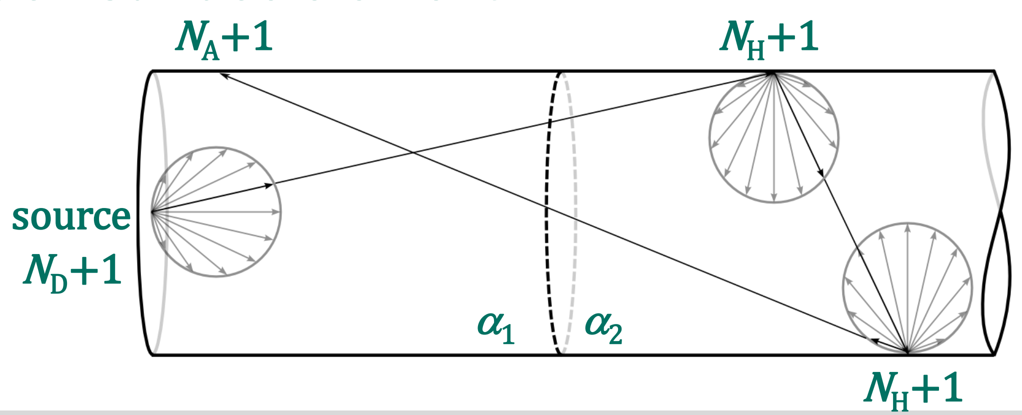


Principle of vacuum simulations

- **Test Particle Monte Carlo (TPMC)** simulation for **free molecular flow**
  - **Molflow+**

- **Surfaces** approximated by **mesh**
  - individual properties of each surface element:
    - sticking coefficient α_i
    - desorption probability and angular distribution $\cos^n(\Theta)$
    - diffuse (Lambertian) reflection

- **Particle tracking** counts for **each surface element**
  - number of **desorptions** N_D
  - number of **hits** N_H
  - number of **adsorptions** N_A

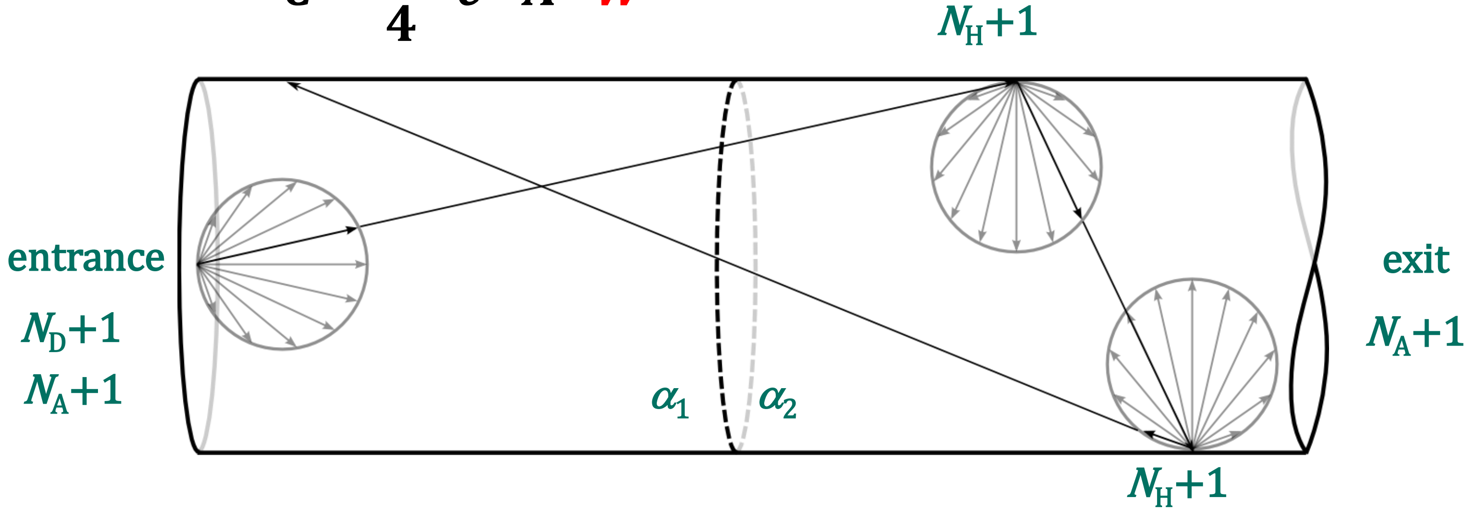


Principle of vacuum simulations: conductance

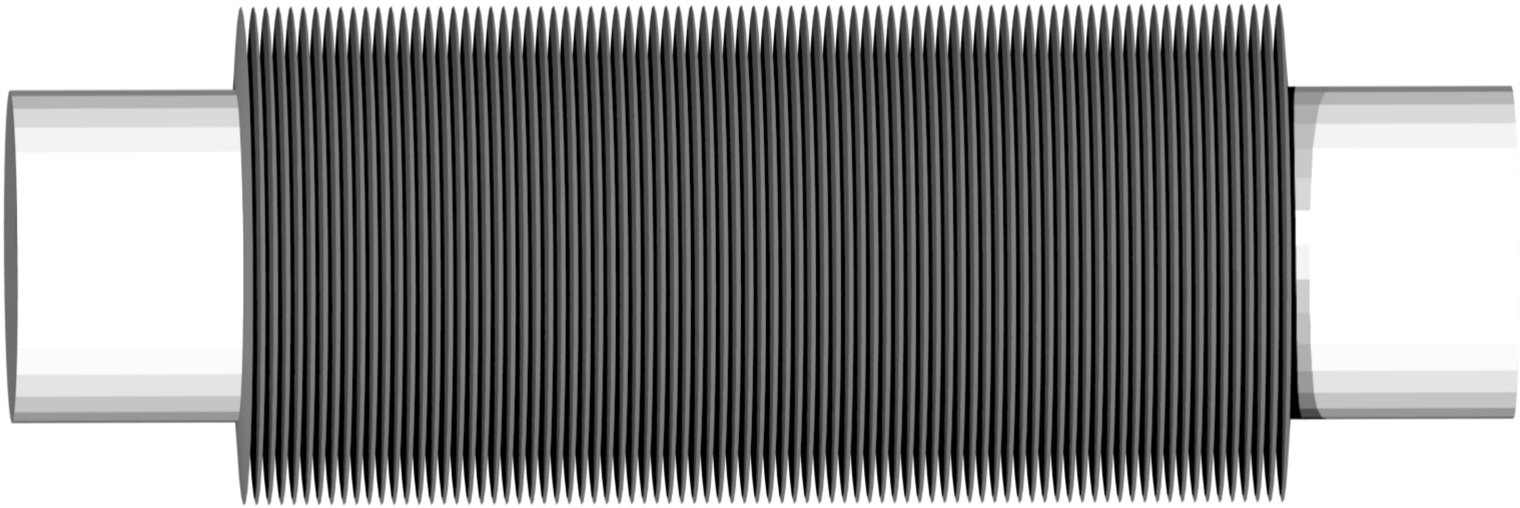
- **Conductance of a tube:** $Q = C \cdot \Delta p$
  - **Tube connects two large recipients**

- **Simulation of the conductance with TPMC code**
  - **Entrance:** desorbing and adsorbing surface (α_{in} = 100%) $N_{D,in}$, $N_{A,in}$
  - **Exit:** adsorbing surface (α_{out} = 100%) at exit $N_{A,out}$
  - **Conductance = inflow × transmission probability** $W = N_{A,out} / N_{D,in}$

$$C = \frac{1}{4} \cdot \bar{c} \cdot A \cdot W$$



Vacuum simulation of edge-welded bellows



- **implementation of edge-welded bellows:**
  - 2 straight tubes at each end
  - n bellow elements approximated by mesh

- **entrance and exit tube surfaces:** $\mathbf{30}$ surface elements per tube
- n **membrane elements:** $\mathbf{60} \times n$ surface elements

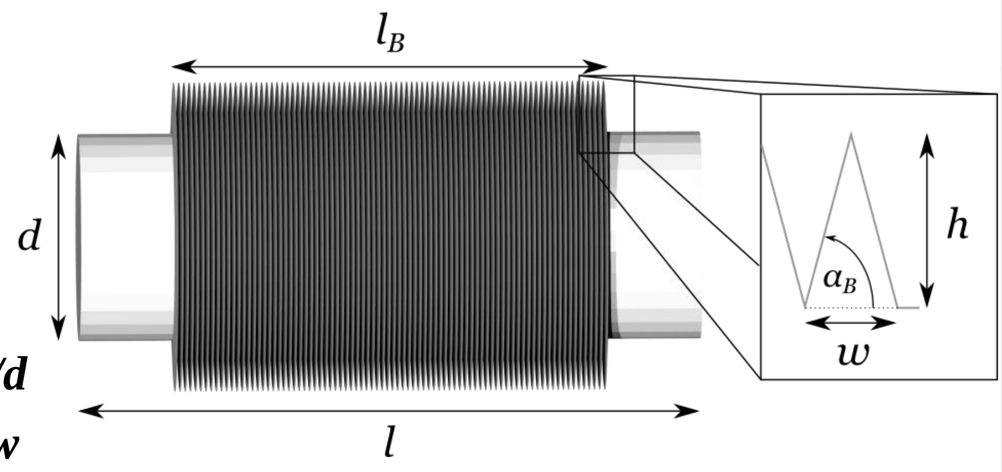
➔ large increase in number of surface elements

➔ increase in simulation time by **several orders of magnitude**

➔ is it possible to **replace the bellow** with a straight tube?

Bellow parameters

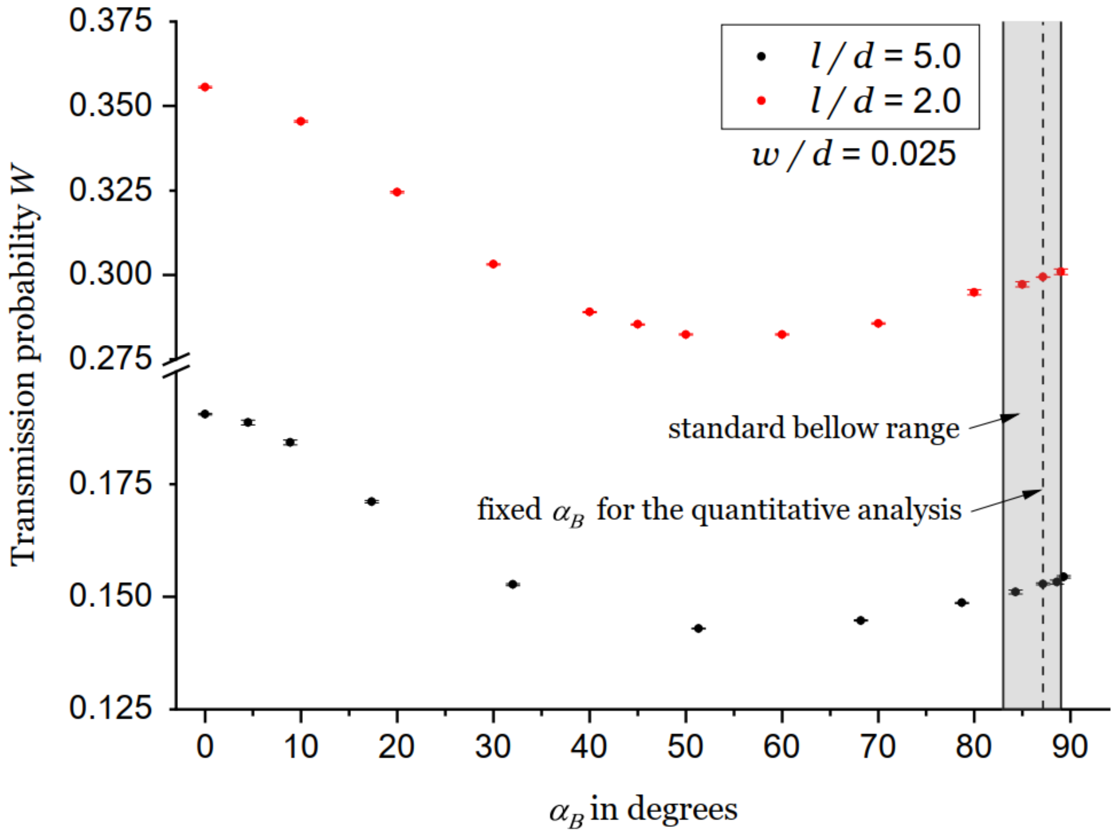
- **Model geometry parameters:**
  - tube diameter: d = **100 mm**
  - tube length / tube diameter l/d
  - bellow length / tube length l_B/l
  - bellow height / tube diameter h/d
  - width of single bellow element w

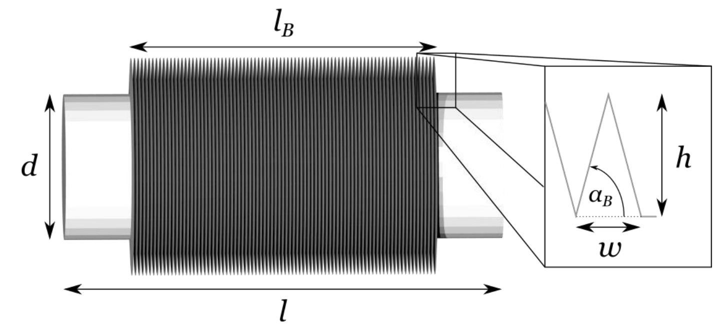


- **Monte Carlo data:**
  - number of desorptions N_D
  - number of adsorptions $N_A(E)$

- **Analysis of simulation data:**
  - transmission probability $$W(l/d, l_B/l) \equiv \frac{N_A(E)}{N_D}$$

Variation of opening angle α_B (h / d)

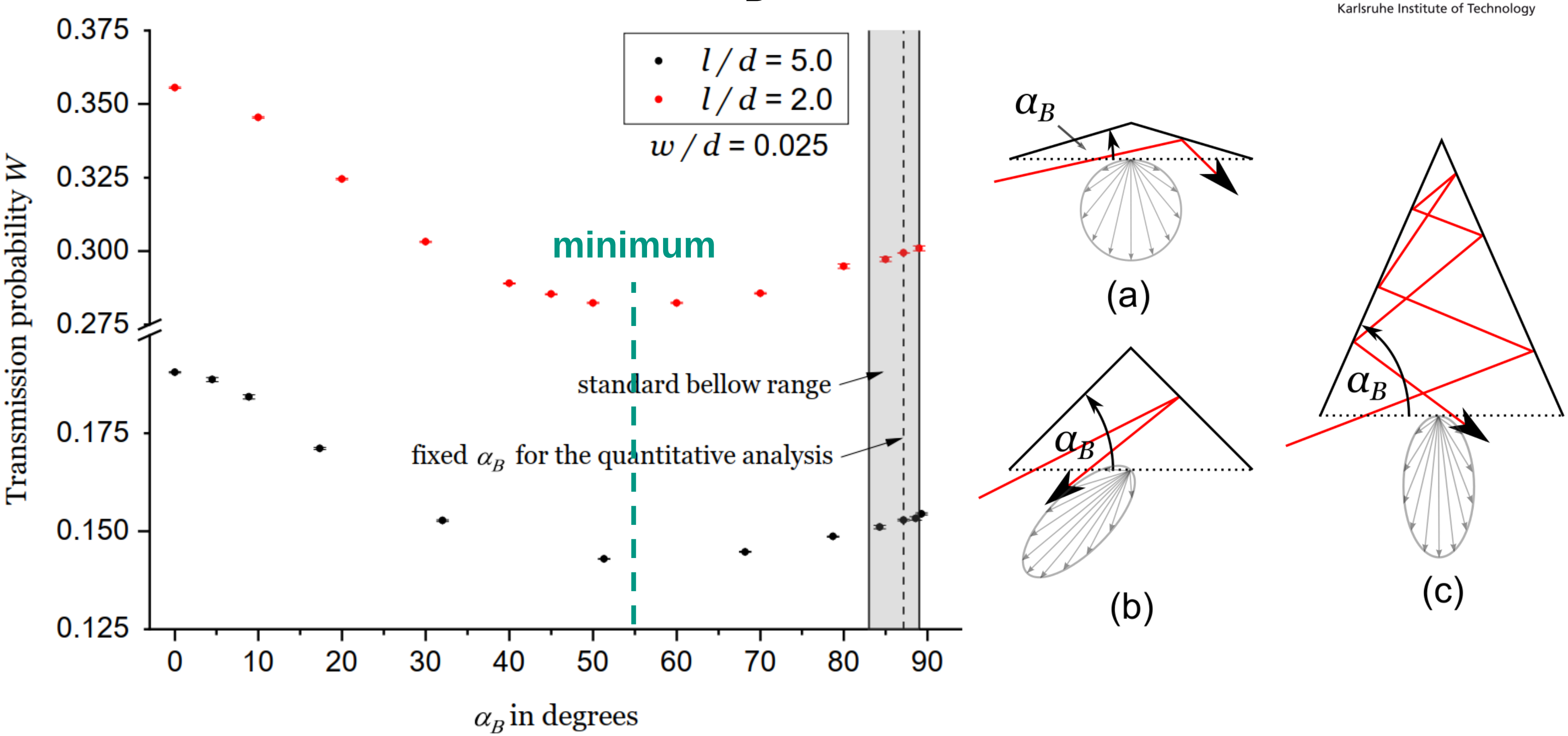




- tube diameter d
- tube length / tube diameter l/d
- bellow length / tube length l_B/l
- bellow height / tube diameter h/d
- width of single bellow element w

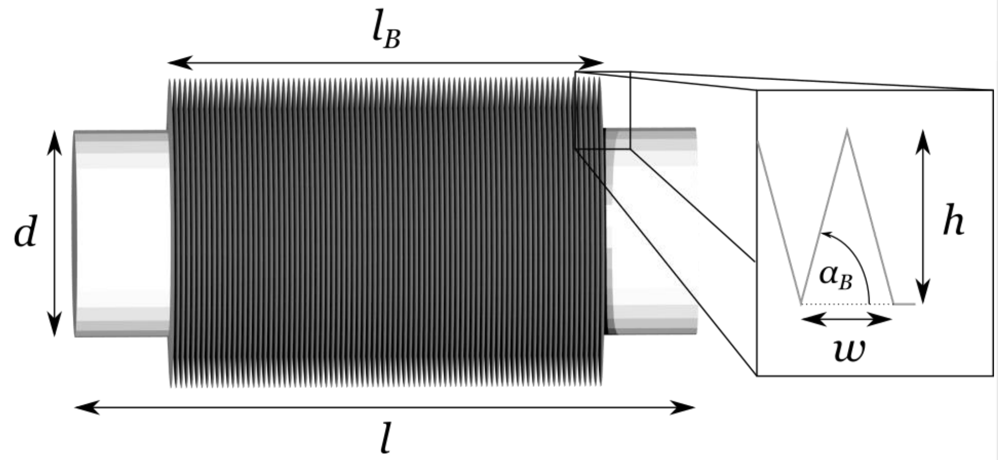
- **Variation of** h / d changes the transmission probability W **considerably**
- **Common bellow geometry**: W changes only **by a few percent**
  ➔ h / d **variance is acceptable** for common bellow geometries

Variation of opening angle α_B (h / d)



- **small angles (a)**: bellow converging towards **straight tube**
- **large angles (c):** multiple reflections in one bellow element; **forward reflection reduced**
- **Minimum for angles around 55°:** bellow surfaces have perfect angle for **backward reflection**

Variation of bellow length l_B/l and tube length l/d



- **Model geometry parameters:**
  - tube diameter: d = **100 mm**
  - tube length / tube diameter l/d
  - bellow length / tube length l_B/l
- **Fixed parameters:**
  - bellow height / tube diameter $h/d = 0.25$
  - width of single bellow element $w/d = 0.025$
- **Analysis of simulation data:**
  - transmission probability $W(l/d, l_B/l) \equiv \frac{N_A(E)}{N_D}$

Variation of bellow length l_B/l and tube length l/d

- **Transmission probabilties** for **straight circular tubes** from literature (no bellows, **empirical**):

$$W\left(l/d,0\right)=\frac{14+4\frac{l}{d}}{14+18\frac{l}{d}+3\left(\frac{l}{d}\right)^2}$$

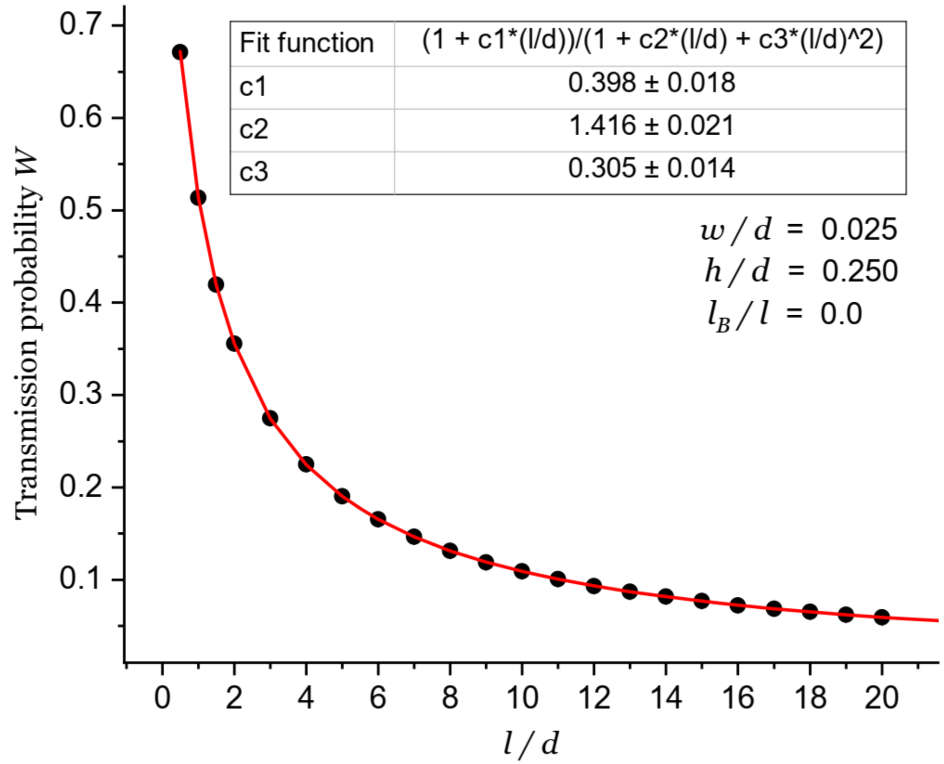
(K. Jousten et al, Handbook of Vacuum Technology, p. 136)

- **Plot** of **TPMC** transmission probabilities ***W*** *versus* ***l*/*d***

- **Ansatz** for *W* of the tube:

$$W\left(l/d,0\right)=\frac{1+c_1\frac{l}{d}}{1+c_2\frac{l}{d}+c_3\left(\frac{l}{d}\right)^2}$$

- The c_i **parameters** were fitted with the TPMC results

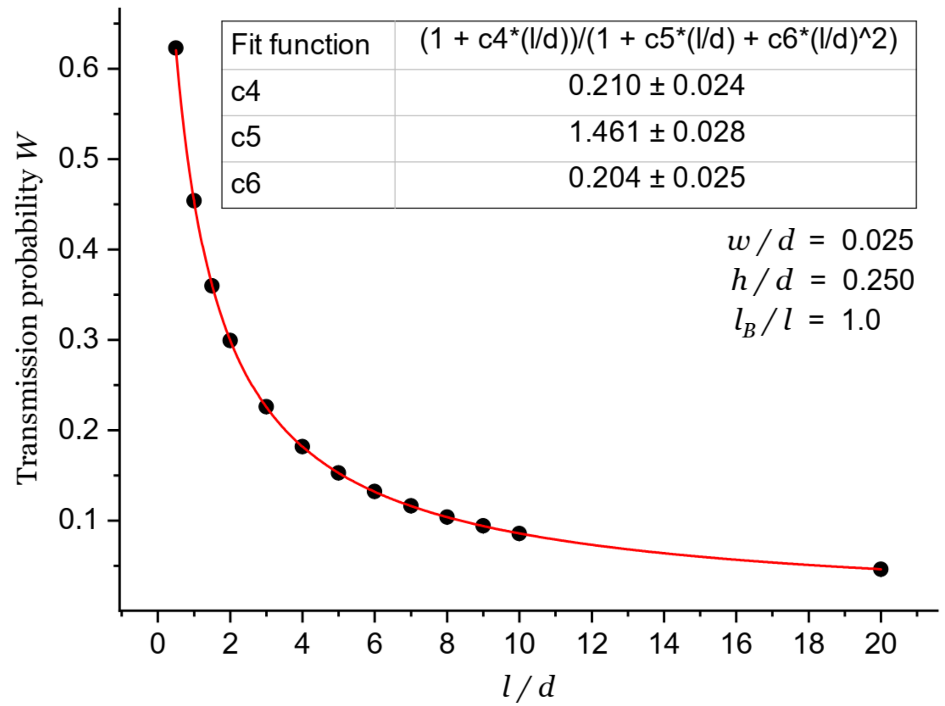


Variation of bellow length l_B/l and tube length l/d

- **Transmission probabilties** of **pure bellows** (no straight tube elements), *i.e.* $l_B/l = 1$
- **Plot** of the **TPMC** transmission probabilities W versus l/d
- l/d dependence follows the **same functional form** as before, but with **different** fit parameters
- **Ansatz** for W of a pure bellow:

$$W\,(l/d, 1) = \frac{1+c_4\,\frac{l}{d}}{1+c_5\,\frac{l}{d}+c_6\left(\frac{l}{d}\right)^2}$$

- The c_i **parameters** were fitted with the TPMC results



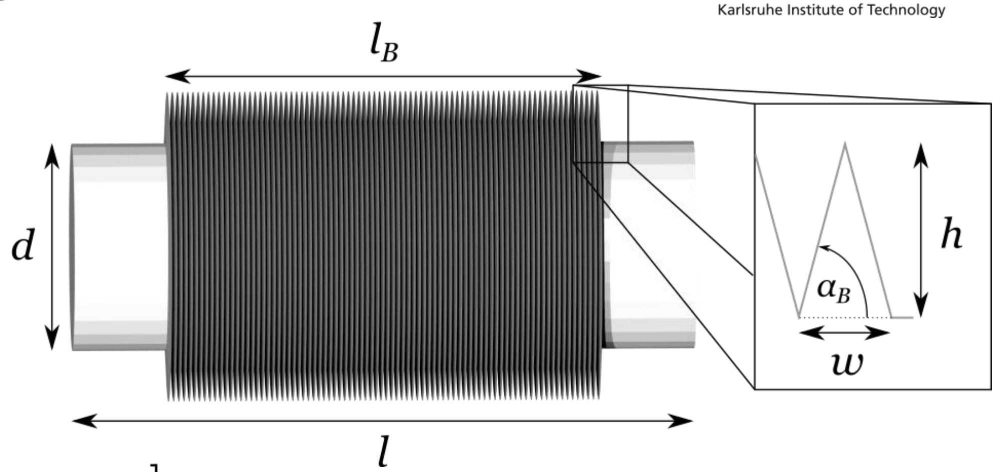
Fit function	(1 + c4*(l/d))/(1 + c5*(l/d) + c6*(l/d)^2)
c4	0.210 ± 0.024
c5	1.461 ± 0.028
c6	0.204 ± 0.025

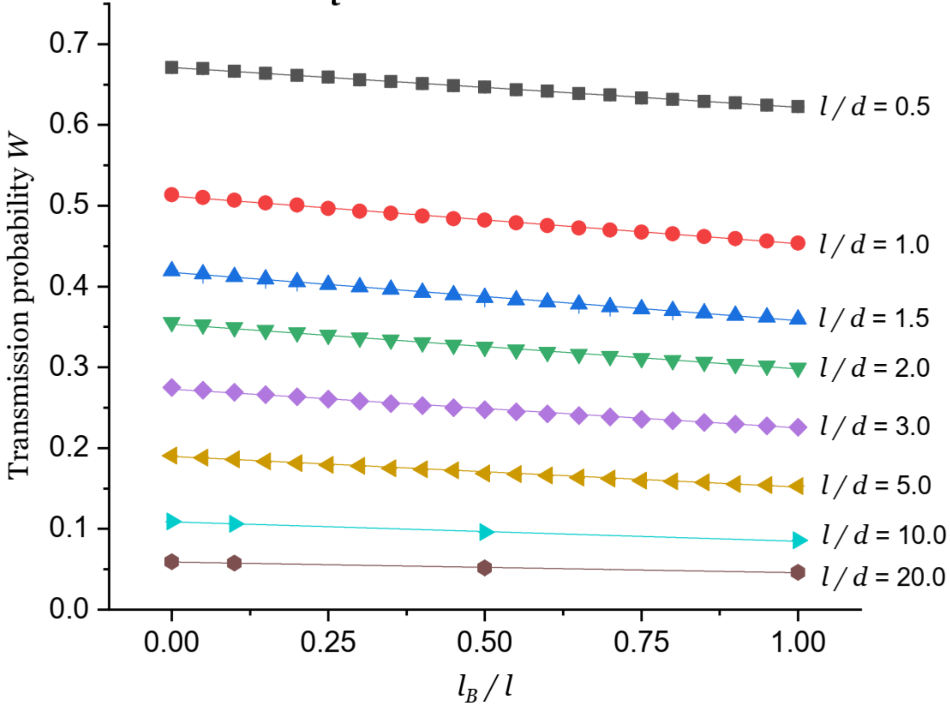
Variation of bellow length l_B/l and tube length l/d

- **What is W in general** ?
  - Bellow length: $0 \le l_B/l \le 1$
  - 2 tubes, central bellow
- Simulation shows **linear dependence** of W on l_B/l
- **New ansatz** for W:

$$W\left(\frac{l}{d},\frac{l_B}{l}\right) =$$

$$W_T\left(\frac{l}{d}\right) + \frac{l_B}{l}\cdot\left[W_B\left(\frac{l}{d}\right) - W_T\left(\frac{l}{d}\right)\right]$$





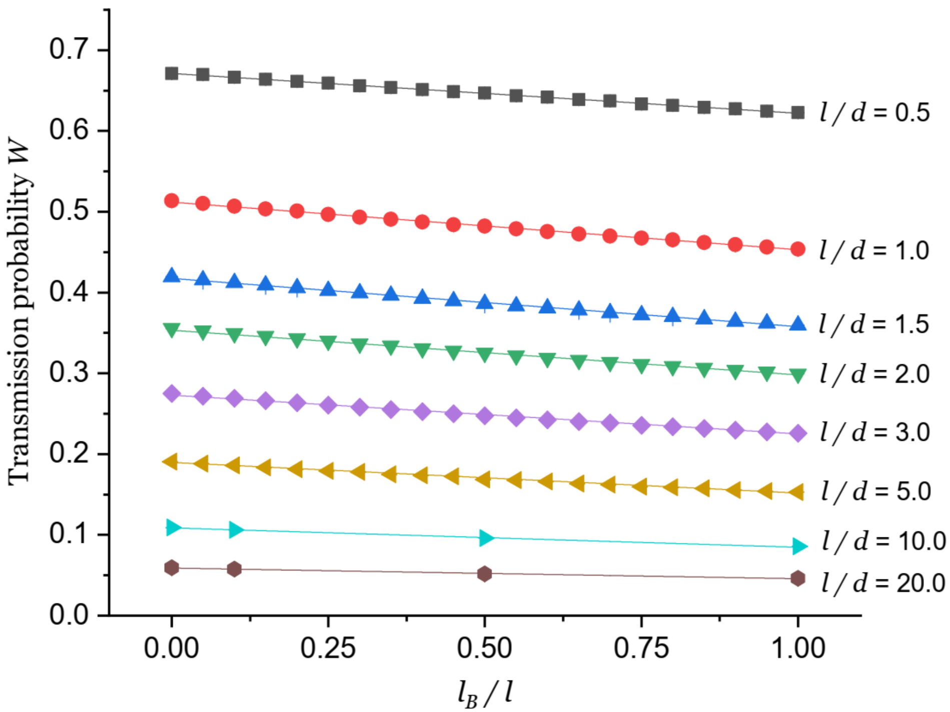
Variation of bellow length l_B/l and tube length l/d

- **New ansatz** for the transmission probability of bellows:

$$W\left(l/d, l_B/l\right) = \left(1 - \frac{l_B}{l}\right) \frac{1 + c_1 \frac{l}{d}}{1 + c_2 \frac{l}{d} + c_3 \left(\frac{l}{d}\right)^2} + \frac{l_B}{l} \frac{1 + c_4 \frac{l}{d}}{1 + c_5 \frac{l}{d} + c_6 \left(\frac{l}{d}\right)^2}$$

- **Fit results for parameters c_i :**

parameter	fit value	standard error σ
c1	0.2915	0.0020
c2	1.3018	0.0026
c3	0.2225	0.0015
c4	0.2707	0.0069
c5	1.5267	0.0077
c6	0.2777	0.0077



*(M. Krause, J. Wolf, Vacuum **160** (2019), 402)*

Comparison of straight tube results with literature

- Case without bellows, i.e. **straight tubes**:

$$W\,(l/d,0) = \frac{1+c_1\frac{l}{d}}{1+c_2\frac{l}{d}+c_3\left(\frac{l}{d}\right)^2}$$

- For **very long tubes**, this becomes:

$$W\,(l/d,0)\Big|_{(l/d)\to\infty} \longrightarrow (1.322 \pm 0.013)\cdot\left(\frac{l}{d}\right)^{-1}$$

- This is **in accordance** with literature for a **straight circular tube**:

$$W\,(l/d)\Big|_{(l/d)\to\infty} \longrightarrow \frac{4}{3}\cdot\left(\frac{l}{d}\right)^{-1}$$

(K. Jousten et al, Handbook of Vacuum Technology, p. 136)

- For **very long bellow** (**$l_B/l = 1$**), the model converges to:

$$\boldsymbol{W(l/d)} \to \frac{c_4}{c_6}\cdot\frac{d}{l} = (0.97 \pm 0.04)\cdot\frac{d}{l} \approx \boldsymbol{\frac{d}{l}}$$

Comparison of straight tube results with literature

- Case without bellows, i.e. **straight tubes**:

$$W\left(l/d,0\right)=\frac{1+c_1\frac{l}{d}}{1+c_2\frac{l}{d}+c_3\left(\frac{l}{d}\right)^2}$$

- For **very short tubes**, this becomes:

$$W\left(l/d,0\right)\Big|_{(l/d)\to 0} \longrightarrow\ 1-(1.0103\pm 0.0025)\,\frac{l}{d}$$

- This is **in accordance** with literature for a **straight circular tube**:

$$W\left(l/d\right)\Big|_{(l/d)\to 0} \longrightarrow\ 1-\frac{l}{d}$$

(K. Jousten et al, Handbook of Vacuum Technology)

Comparison of straight tube results with literature

- **TPMC simulation:**

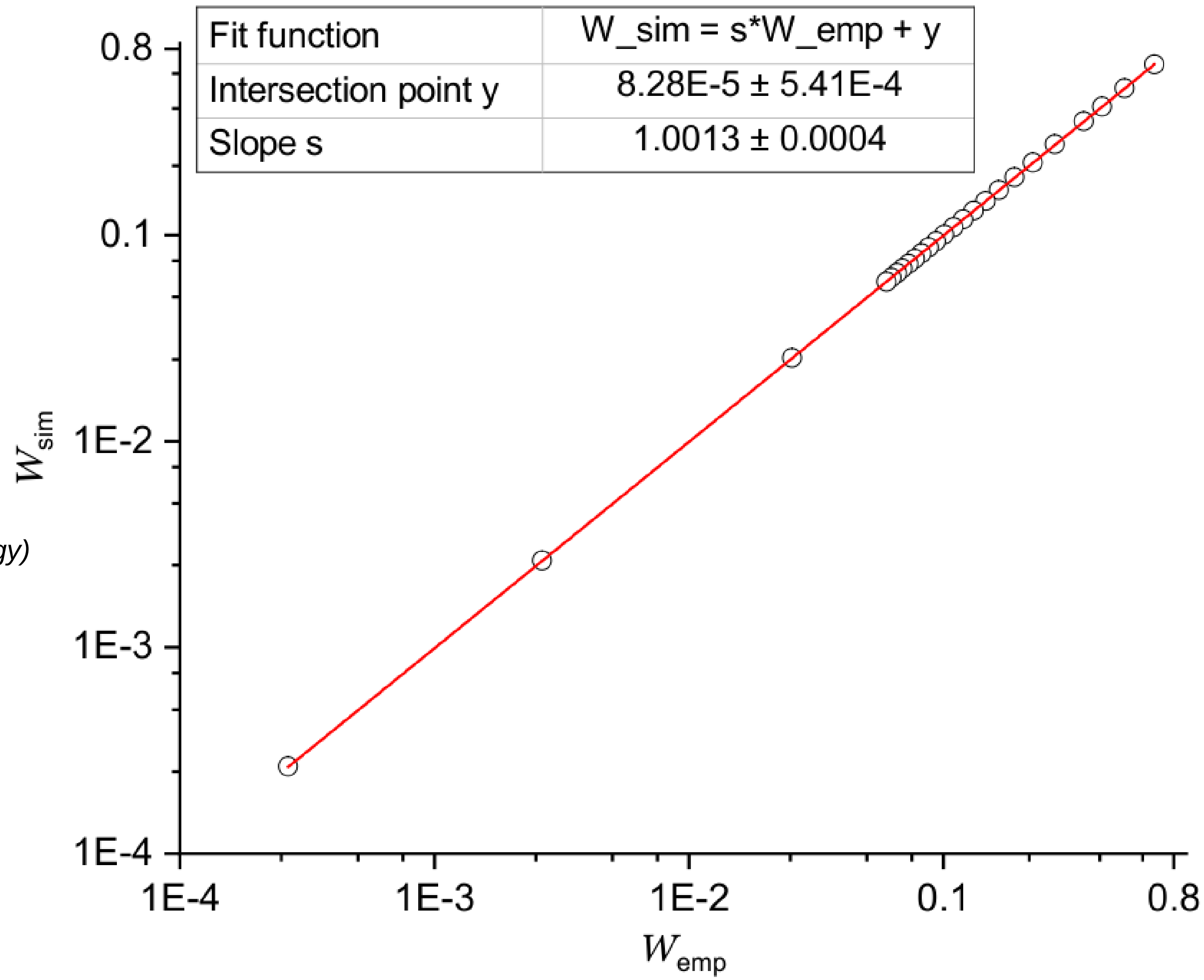
$$W\left(l/d,0\right)=\frac{1+c_1\frac{l}{d}}{1+c_2\frac{l}{d}+c_3\left(\frac{l}{d}\right)^2}$$

- **Literature:**

$$W\left(l/d,0\right)=\frac{14+4\frac{l}{d}}{14+18\frac{l}{d}+3\left(\frac{l}{d}\right)^2}$$

(K. Jousten et al, Handbook of Vacuum Technology)

- **On average only 0.13% deviation**



Replacement of bellows in TPMC simulations

- **Objective:** replace a **bellow** with a **straight tube**
  - **same transmission probability**
  - **same diameter**
  - **modified length *l´***

- Transmission probability of the **bellow**:

$$W\left(l/d, l_B/l\right) = \left(1 - \frac{l_B}{l}\right) \frac{1 + c_1 \frac{l}{d}}{1 + c_2 \frac{l}{d} + c_3 \left(\frac{l}{d}\right)^2} + \frac{l_B}{l} \frac{1 + c_4 \frac{l}{d}}{1 + c_5 \frac{l}{d} + c_6 \left(\frac{l}{d}\right)^2}$$

- **Straight tube** with **modified length *l'*** and same transmission probability:

$$W\left(l'/d, 0\right) = 1 \frac{1 + c_1 \frac{l'}{d}}{1 + c_2 \frac{l'}{d} + c_3 \left(\frac{l'}{d}\right)^2}$$

Replacement of bellows in TPMC simulations

- **Ansatz**: $W \equiv W\left(l/d, l_B/l\right) = W\left(l'/d, 0\right)$

$$\Rightarrow \quad \boxed{\frac{l'}{d} = \frac{c_1 - c_2 W + \sqrt{(c_1 - c_2 W)^2 + 4 c_3 W (1 - W)}}{2 c_3 W}}$$

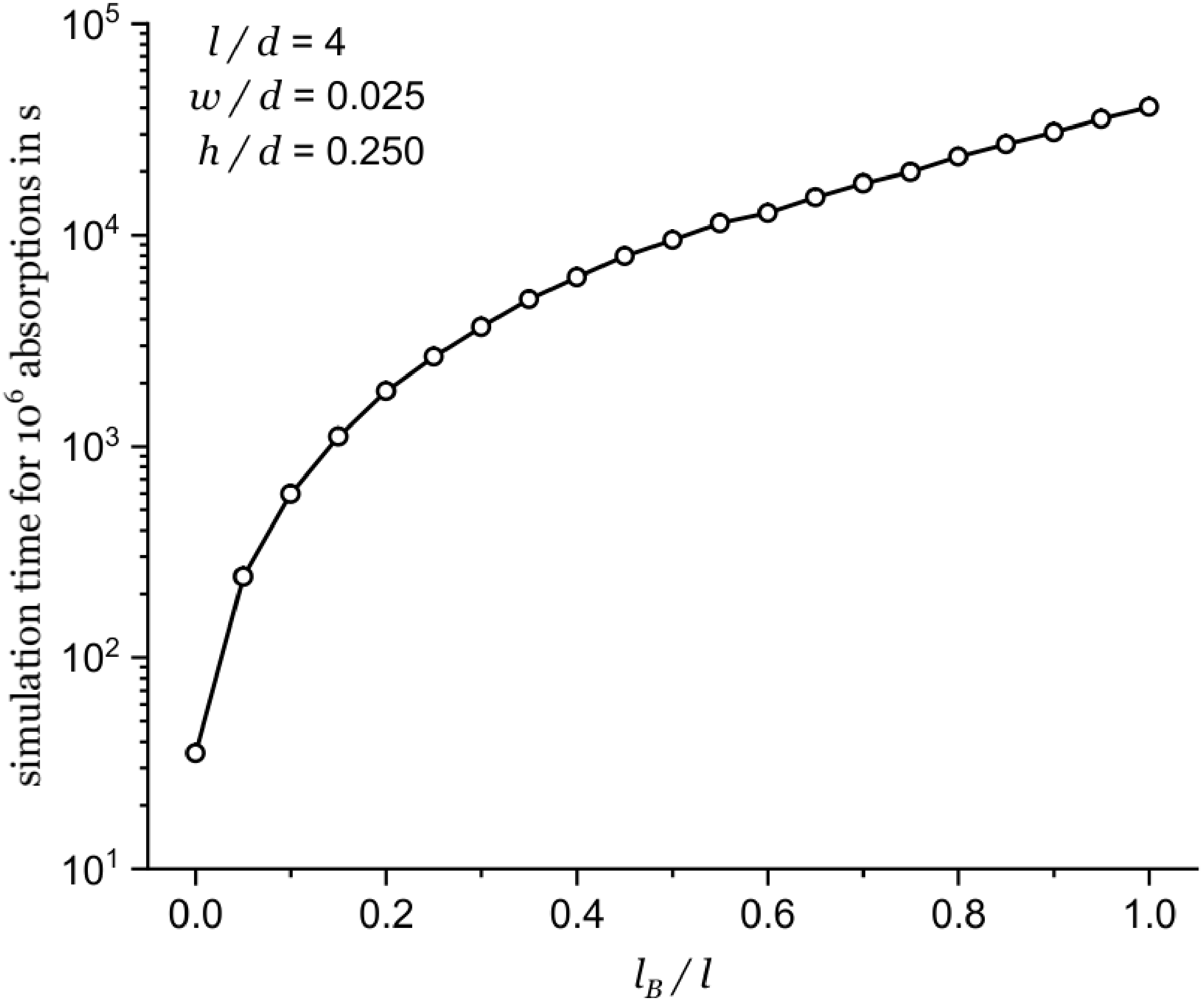
- **Proposed procedure for replacing bellows in TPMC simulations**:
  - calculate ***W*** with the model introduced here
  - calculate the effective length *l'/d*
  - **replace the bellow** in the simulation **with a straight tube** with length ***l'/d***
- this procedure **has been tested** for a few bellows with different design parameters

  ➔ **error of a few percent**

  ➔ **significant reduction in simulation time**

Replacement of bellows in TPMC simulations

- Reduction in simulation time by several orders of magnitude



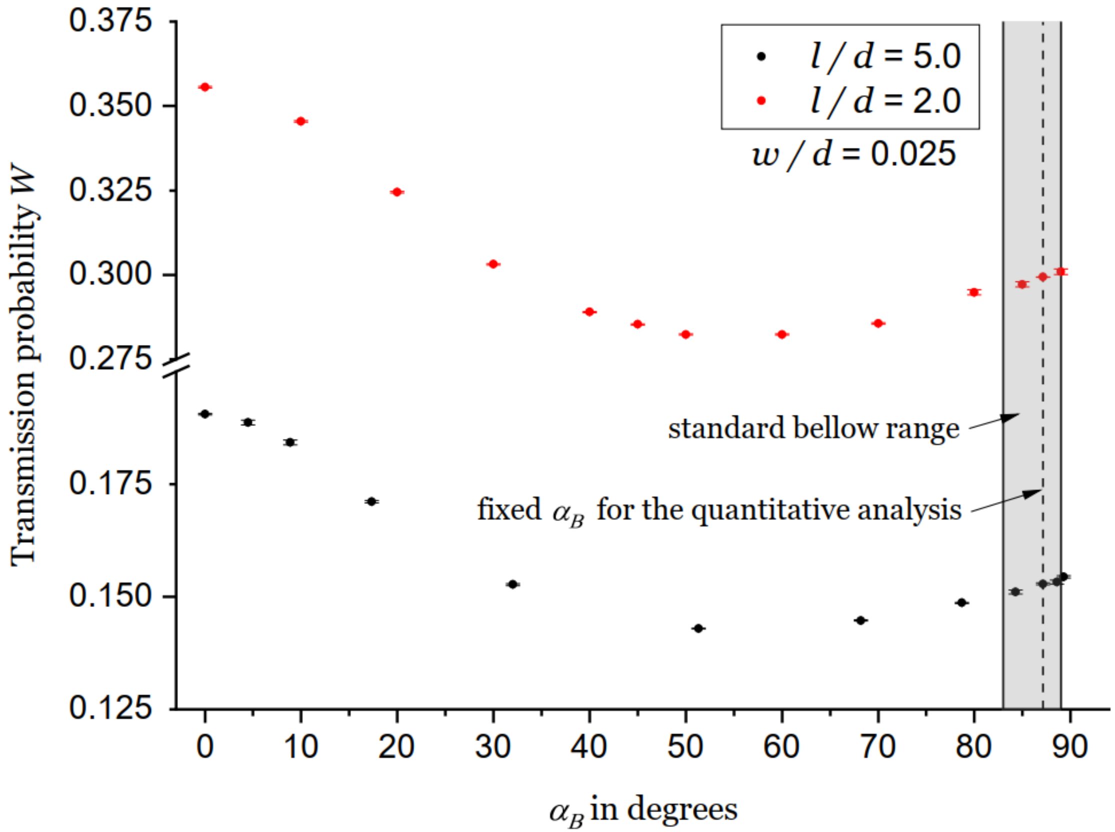
Conclusion

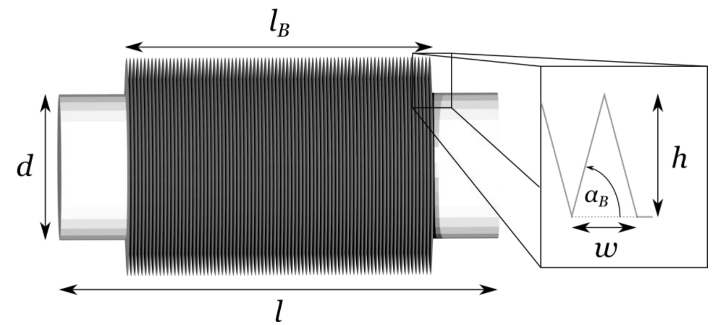
- A **wide range of bellow** design parameters have been **simulated**
- **Variations** in bellow widths and heights have **no significant effect** (for standard bellow parameters)
- A **numerical model for transmission probabilities** has been found, based on TPMC simulations
- A simple **approximation** for the transmission probability of **very long bellows** is $W \approx d/l$
- A procedure for **replacing bellows by straight tubes** in molecular flow simulations has been proposed
- **Details and results:**

*(M. Krause, J. Wolf, Vacuum **160** (2019), 402; doi:10.1016/j.vacuum.2018.11.049; arxiv:1810.00768)*

Backup slides

Variation of opening angle α_B (h / d)





- tube diameter d
- tube length / tube diameter l/d
- bellow length / tube length l_B/l
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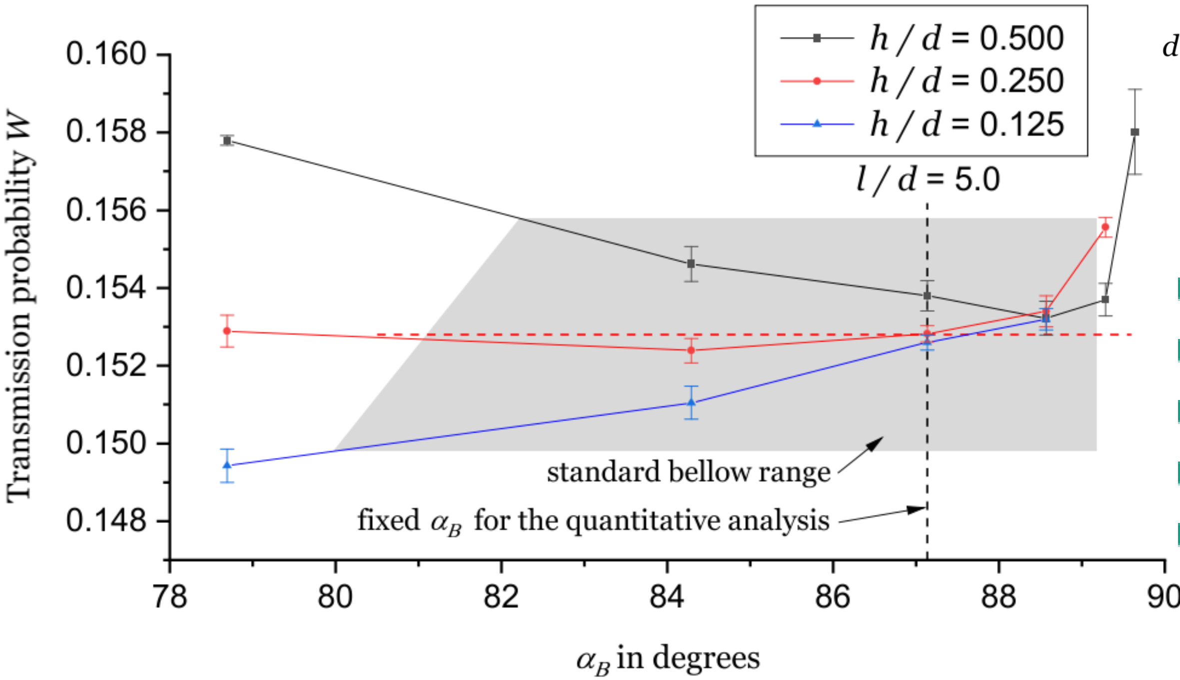
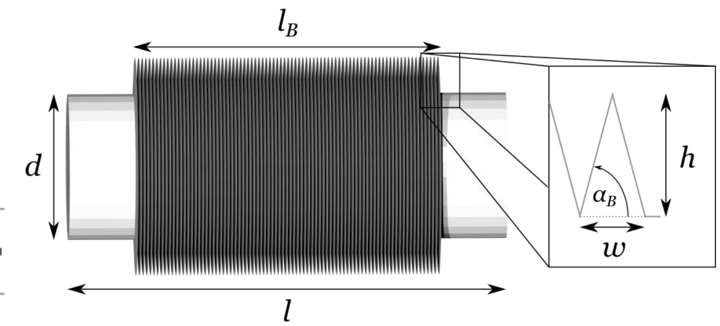
  ➔ **h / d variance is acceptable** for common bellow geometries

Variation of opening angle α_B (w / d)





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  ➔ w / d **variance is acceptable** for common bellow geometries