ITERVAC - A semi-empirical code for calculations in the transitional flow regime

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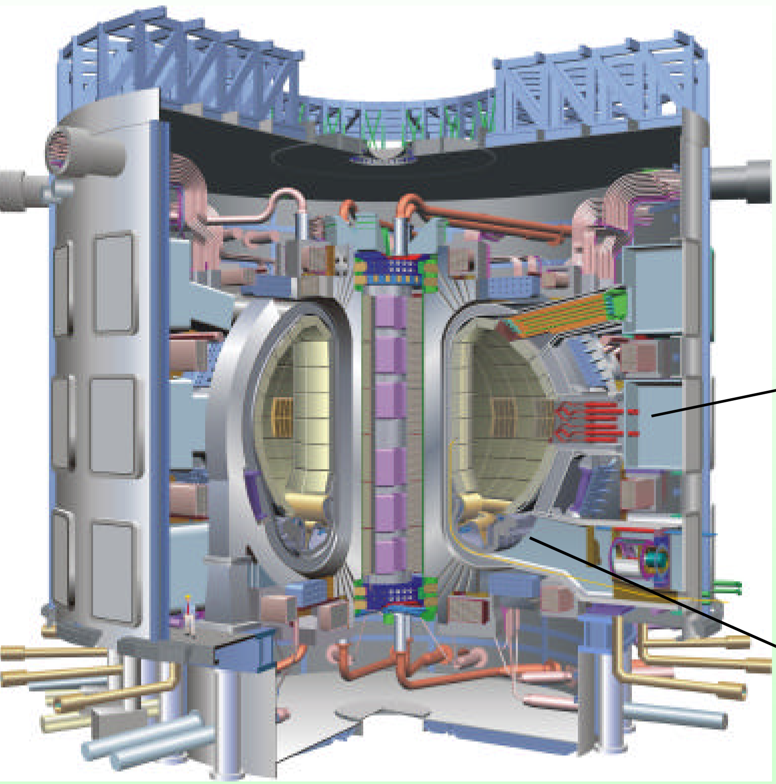
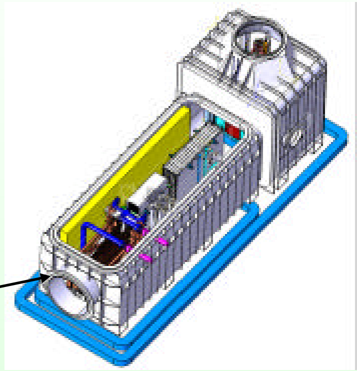
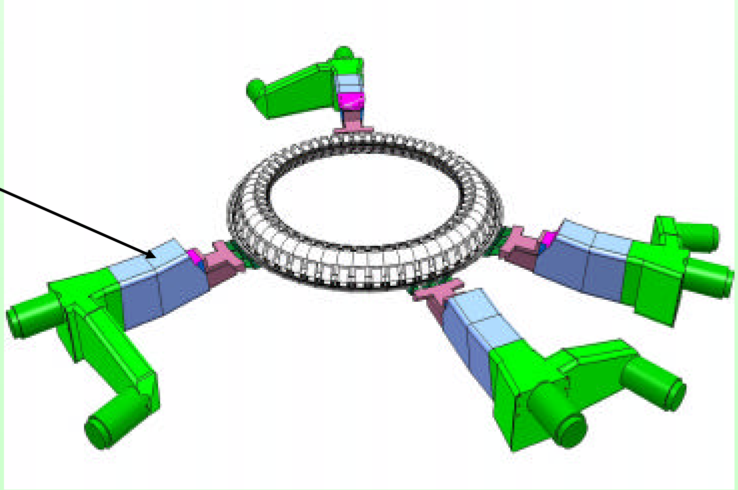
Large vacuum systems in ITER



NBI vacuum system



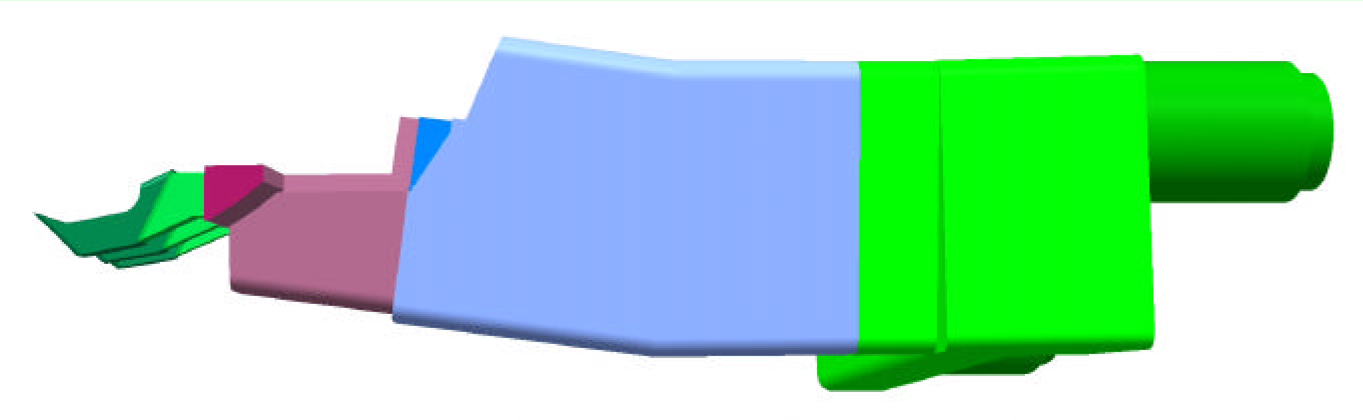
Torus vacuum system



Large vacuum systems in ITER (2)

Typical Knudsen numbers inside the torus vacuum system of ITER:

- In the burn phase between 0.004 and 0.15
- After conditioning between 360 and 1400
- In the dwell phase between these values



Gas flow regimes

Range of Kn	**Flow regime**	**Governing eqs.**	**Numerical approach**
Kn → 0	Continuum	Euler	
$Kn < 10^{-3}$	Continuum (viscous)	Navier-Stokes	CFD, FEM
$10^{-3} < Kn < 10^{-1}$	Slip	Navier-Stokes with slip flow	CFD
$10^{-1} < Kn < 10$	Transition	Boltzmann and kinetic models	Analytical methods (1D), DSMC
10 < Kn	Free molecular	Boltzmann and kinetic models without collisions	Test Particle Monte Carlo

→ one (simplified) program for the complete range ? ITERVAC

Basic framework of the ITERVAC code

Dimensionless mass flow in a circular channel:

$$F = -\dot{m} \cdot \frac{8 \cdot \sqrt{2 \cdot k \cdot T / m_0}}{p \cdot d_h^3 \cdot (\partial p / \partial x)}$$

ITERVAC baseline equation with 4 fitting parameter:

$$F = \frac{c_1}{Kn} + c_2 + \frac{c_3 \cdot Kn}{c_4 + Kn}$$

Viscous flow limit:

$$\lim_{Kn \to 0} F = c_1 / Kn = F_{visc}$$

?

$$F_{visc} = \frac{4 \cdot \sqrt{p}}{Kn \cdot \mathrm{Re} \cdot x}$$

The friction factor is $\xi = 64/\mathrm{Re}$ at laminar flow conditions. ? $c_1 = (\sqrt{p} / 16)$.

More general approach:

$$c_1 = \frac{c_{lam} \cdot 16 \cdot A}{\sqrt{p} \cdot d_h^2 \cdot \mathrm{Re} \cdot x}$$

Basic framework of the ITERVAC code (2)

Free molecular flow limit:

$$\lim_{Kn \to \infty} F = c_2 + c_3 = F_{mol}$$

Assuming a isothermal, isotropic Maxwellian distribution inside a prismatic channel:

$$F_{mol} = \frac{w_{12} \cdot A \cdot 8 \cdot L}{p^{3/2} \cdot d_h^3}$$

For a circular channel:

$$F_{mol}^{circ} = \frac{2 \cdot w_{12} \cdot L}{d \cdot \sqrt{p}}$$

Interpretation of the factors c_i

c_1 ? viscous flow limit

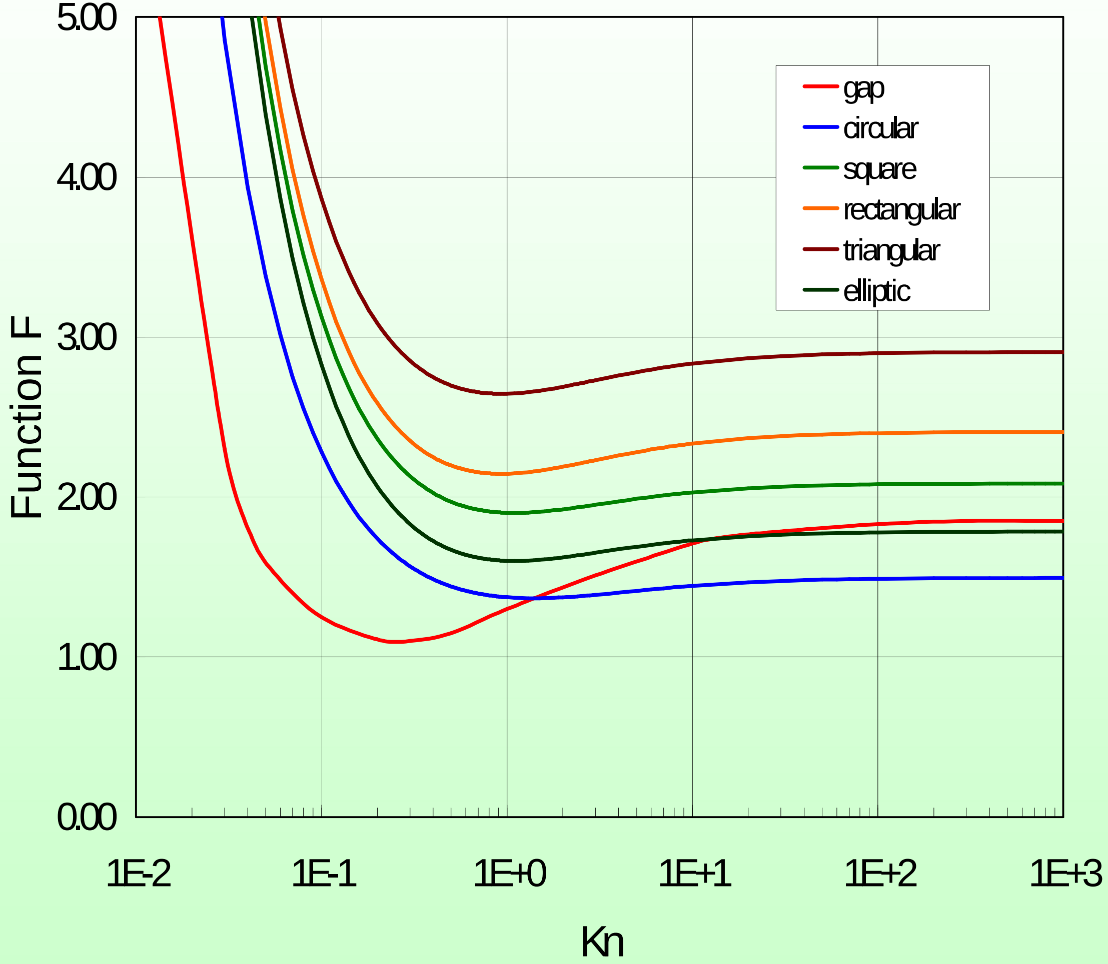
$c_2 + c_3$? free molecular flow limit

c_4 ? fixed parameter describing the influence of the beaming effect

Geometry	c_{lam}	c_2	c_3	c_4
Circular	1.0	1.1162	0.3291	1.4
Square	1.12462	1.4862	0.5735	1.4
Rectangular (2x1)	1.02907	1.6655	0.7318	1.4
Triangular	1.2	1.9706	0.9632	1.4
Elliptic (2x1)	0.95108	1.3404	0.5054	1.4
Infinite gap	2/3	0.7133	1.1918	1.4

For short channels ($L/d<80$) c_2 and c_3 are weighted by a correction function and c_1 is corrected for entrance effects.

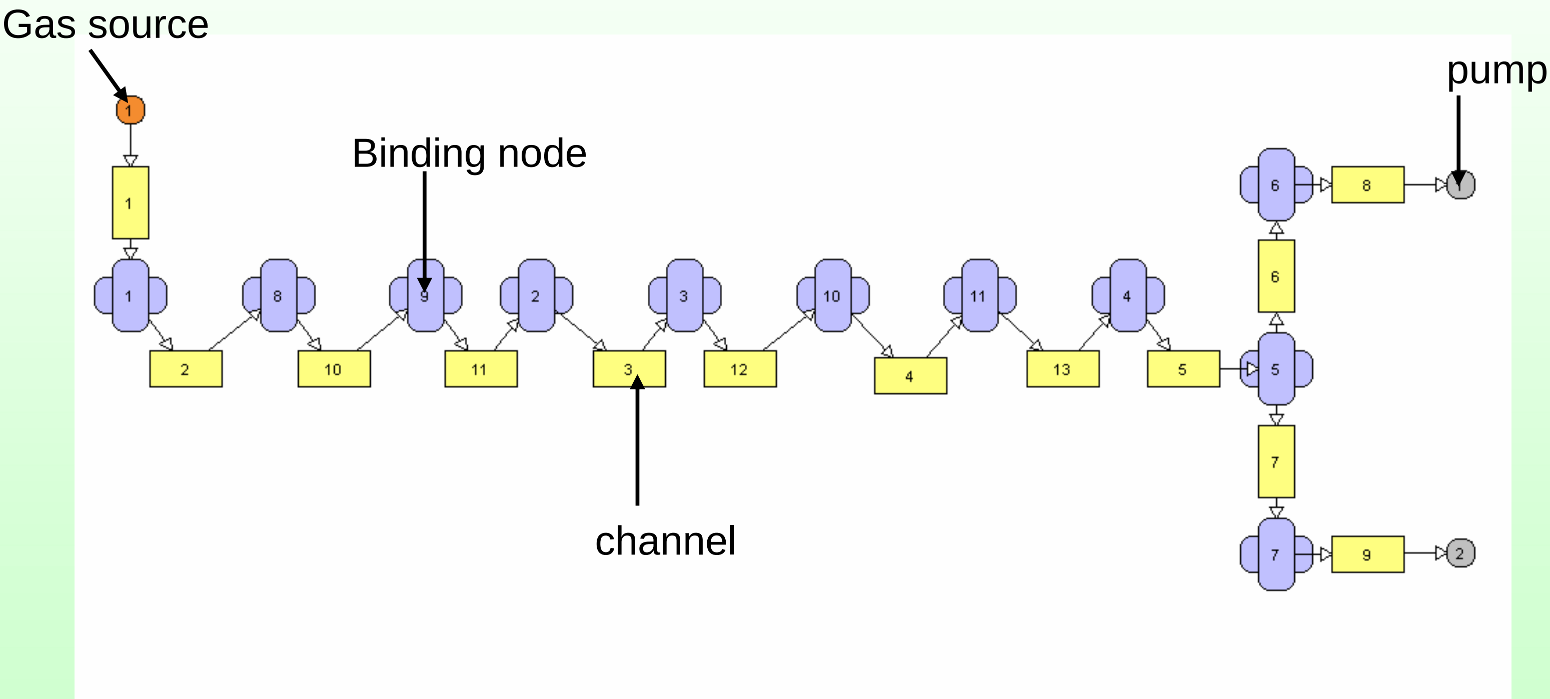
Influence of the channel shape



Non-dimensional mass flows at high L/d ratios as a function of the Knudsen number (Kn)

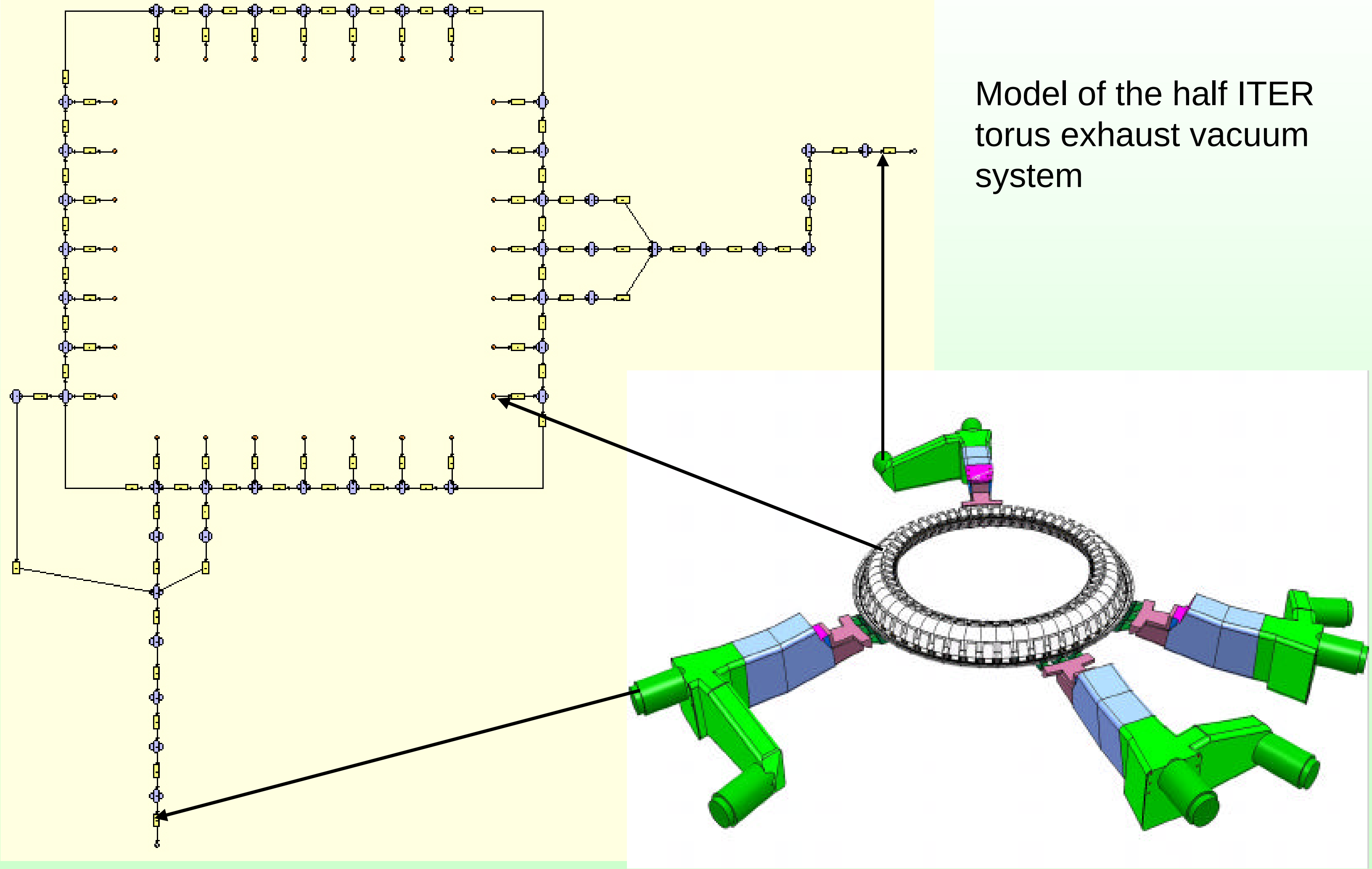
ITERVAC networking

ITERVAC provides the user with all tools to build up 2D networks.



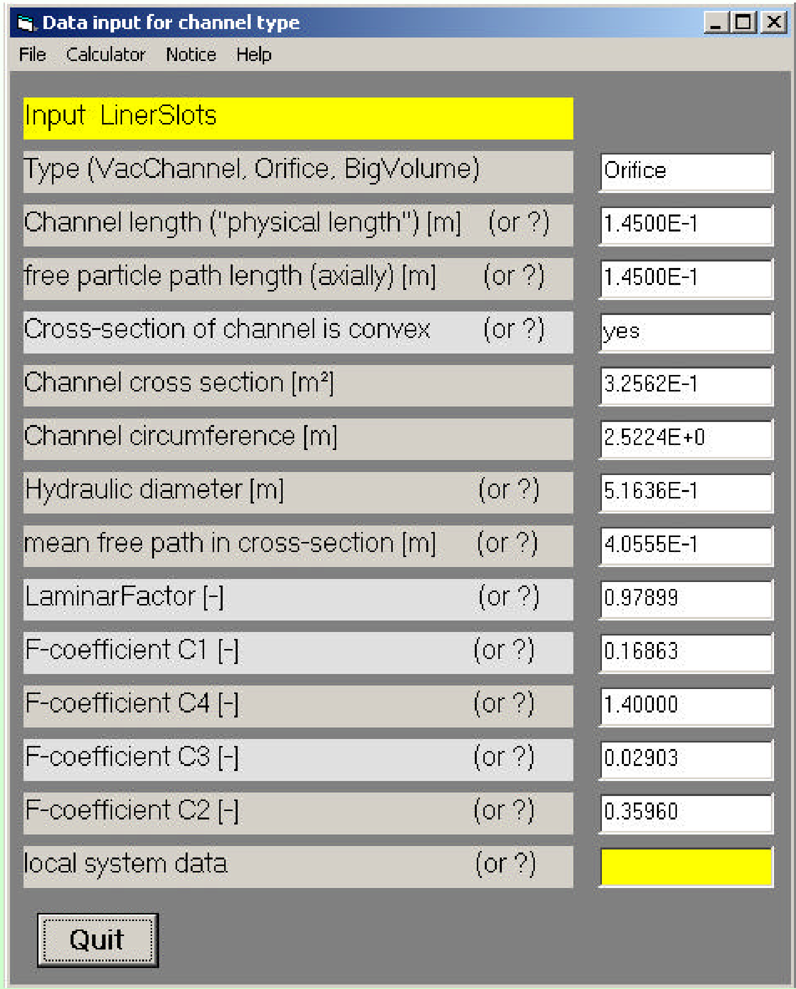
ITERVAC calculates the mass flow through every channel depending from the pressure of the gas source and inside the pumps.

ITERVAC networking (2)



Model of the half ITER torus exhaust vacuum system

ITERVAC input



Global input parameter are:

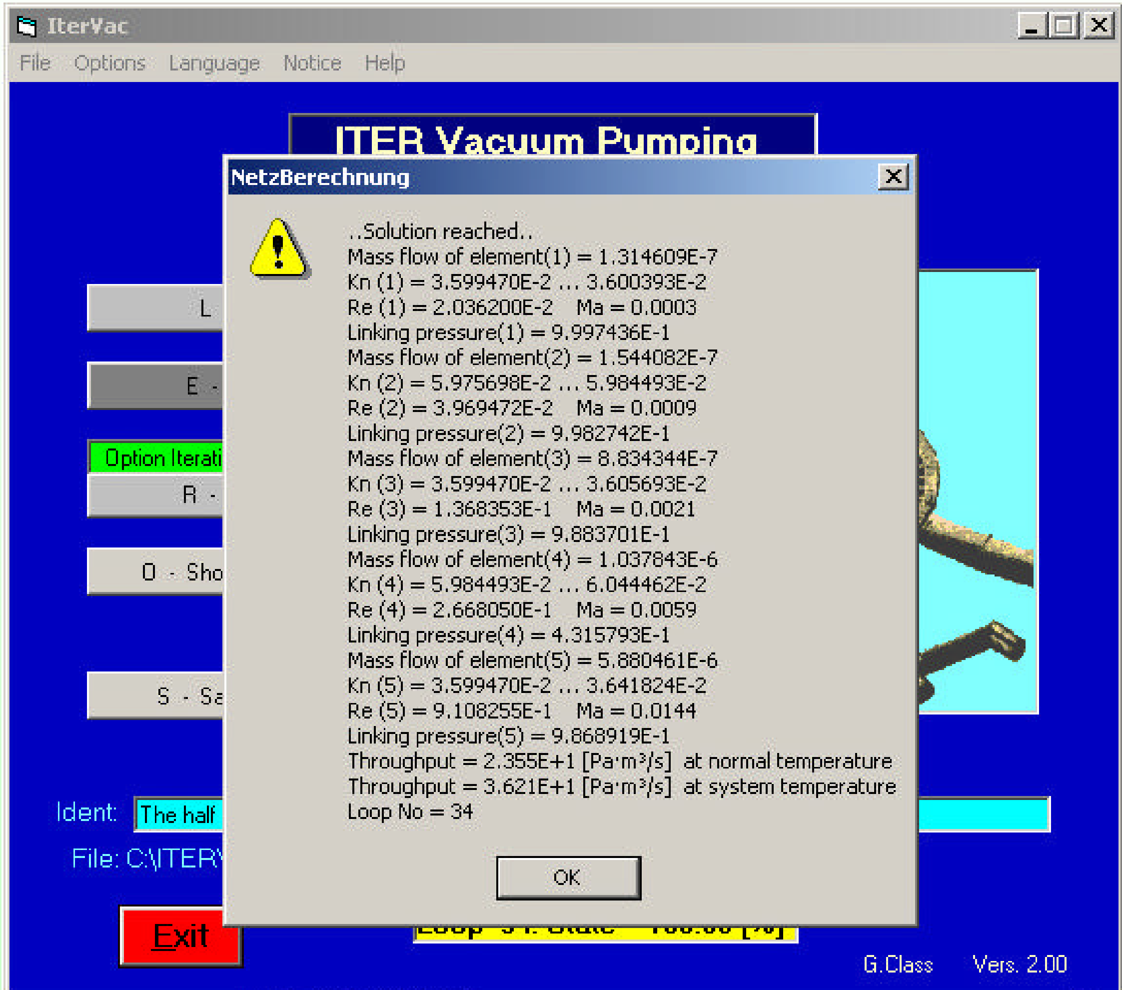
- temperature
- gas viscosity

For every channel the input of:

- channel type
- length
- free particle path length
- cross section dimensions

is needed.

ITERVAC calculation



ITERVAC calculates the mass flow in all channels at isothermal conditions for one gas species.

At the end of calculation the results are summarised in one window and can be saved in a text file.

ITERVAC output

erg_D2_55_1.0Pa.txt - Editor

Datei Bearbeiten Format ?

```
Bauelement: LinerSlots
****************************************
Element Nr. 1;  Symbol Nr. 1
*******************************************
Typ: Orifice    Temperatur: 420.000 [K]
P1: 1.0000E+0 [Pa]    P2: 9.9974E-1 [Pa]
Kn: 3.5995E-2 [-]...3.6004E-2 [-]
Re: 2.0362E-2 [-]    Ma: 0.00032 [-]
Leitwert C: 2.8931E+2 [m³/s], bei 273.15 [K]
mPkt: 1.3146E-7 [kg/s]    Q_norm: 7.4191E-2 [Pa·m³/s]

Element Nr. 3;  Symbol Nr. 3
*******************************************
Typ: Orifice    Temperatur: 420.000 [K]
P1: 1.0000E+0 [Pa]    P2: 9.9827E-1 [Pa]
Kn: 3.5995E-2 [-]...3.6057E-2 [-]
Re: 1.3684E-1 [-]    Ma: 0.00214 [-]
Leitwert C: 2.8889E+2 [m³/s], bei 273.15 [K]
mPkt: 8.8343E-7 [kg/s]    Q_norm: 4.9857E-1 [Pa·m³/s]

Element Nr. 5;  Symbol Nr. 5
*******************************************
Typ: Orifice    Temperatur: 420.000 [K]
P1: 1.0000E+0 [Pa]    P2: 9.8837E-1 [Pa]
Kn: 3.5995E-2 [-]...3.6418E-2 [-]
Re: 9.1083E-1 [-]    Ma: 0.01439 [-]
```

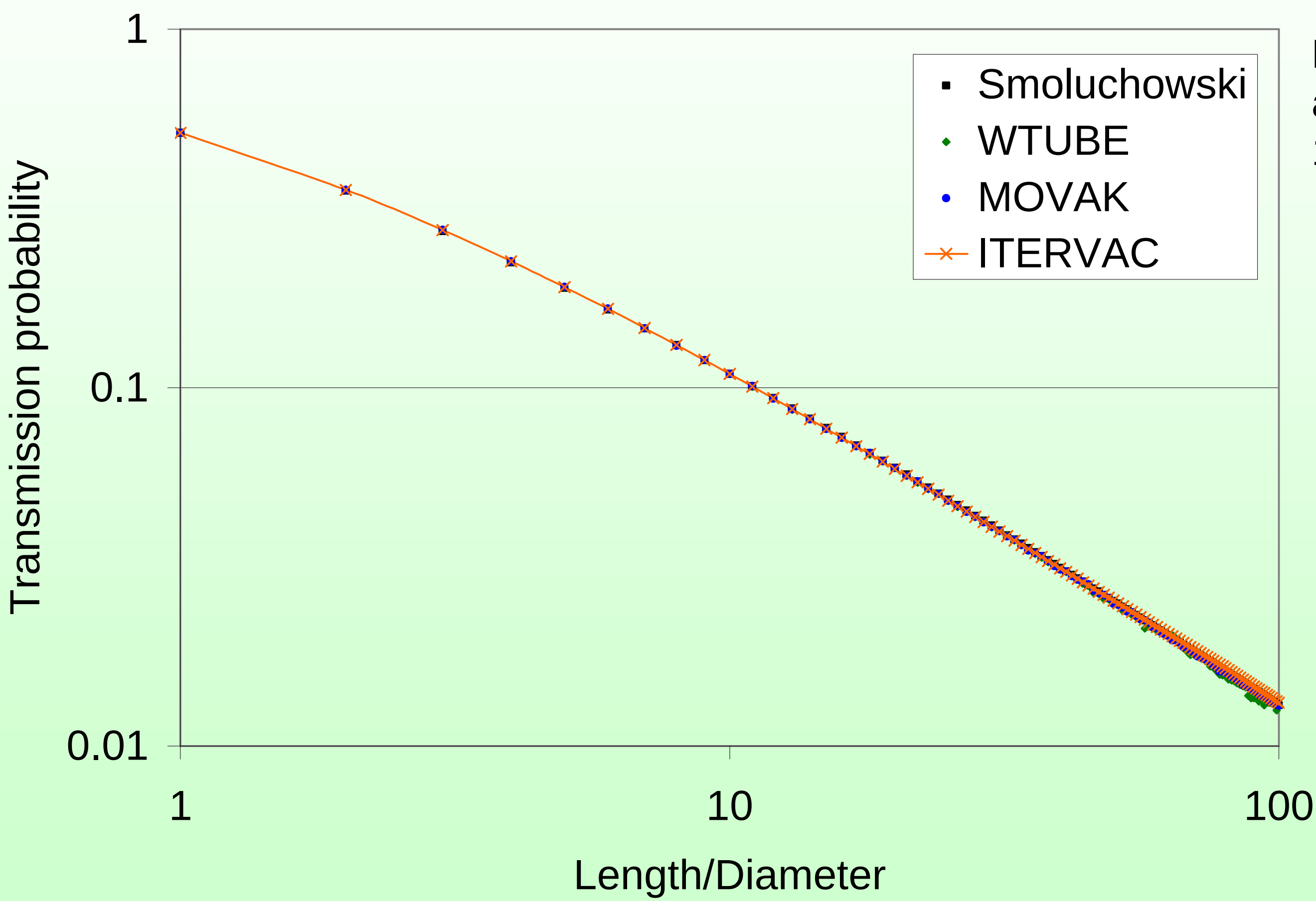
For every channel the output consists of:

- channel type
- pressure at in- and outlet
- Knudsen number at in- and outlet
- Mach number
- Reynolds number
- conductance at 273 K
- mass flow
- throughput at 273 K.

Benchmarking

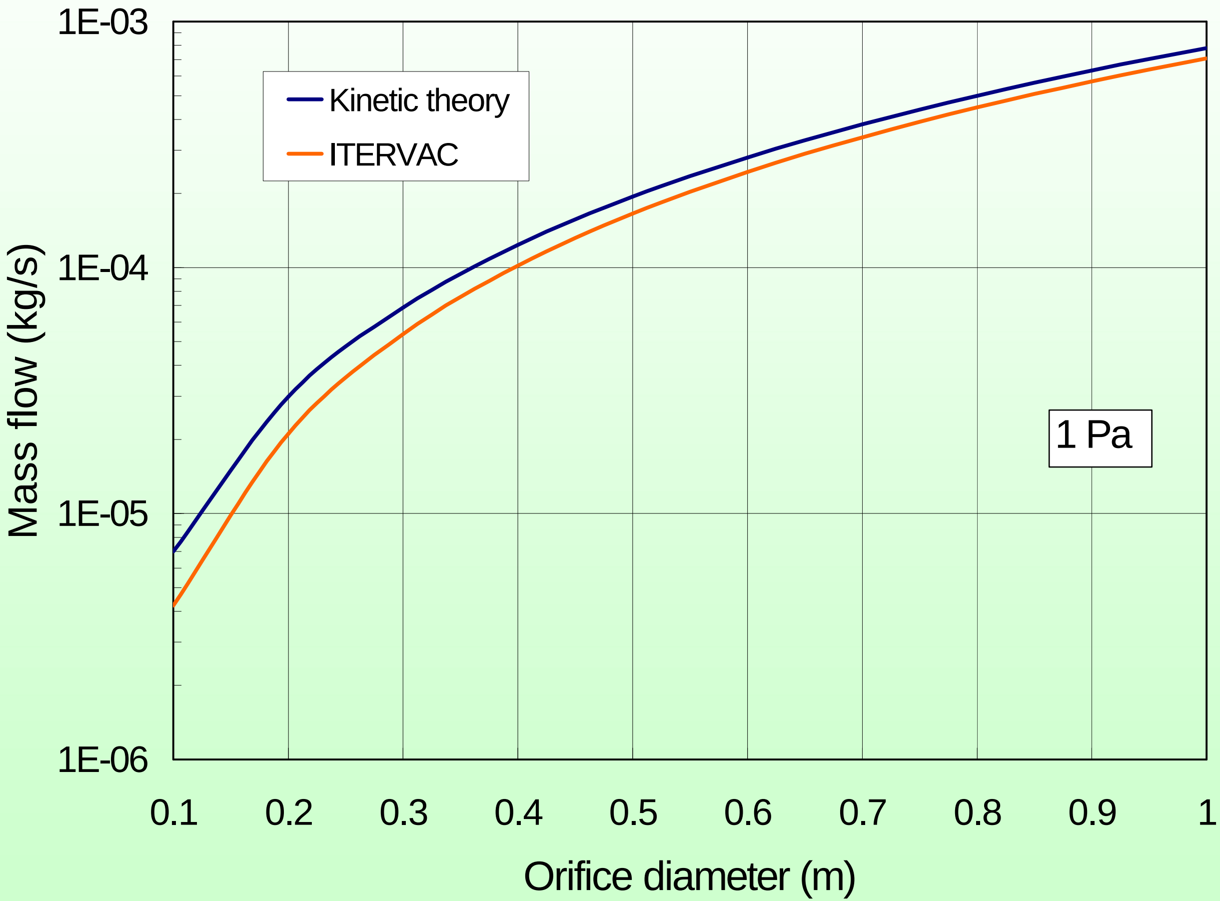
- Viscous flow through long and short circular and triangular equilateral channel: The maximum deviation found was 3%.
- Molecular flow through circular (L/d 1-100), square shaped (L/d 10, 80), triangular channels (L/d 80) and gap (L/d 80): The maximum error found here was 3%.
- Transitional flow through a circular tube L/d 10, orifice at different upstream pressures: The ITERVAC results were compared with kinetic theory solutions. For the tube the deviation of calculation against simulation found was about 20 % in some cases, only 5% in other cases. For a thin orifice a deviation of about 8 % was found at 10 Pa upstream pressure, increasing up to 40%, especially in the low diameter region, at an upstream pressure of 1 Pa.

Benchmarking (2)



Molecular flow through a circular channel (L/d 1-100)

Benchmarking (3)



Flow through an orifice at upstream pressure of 1 Pa.

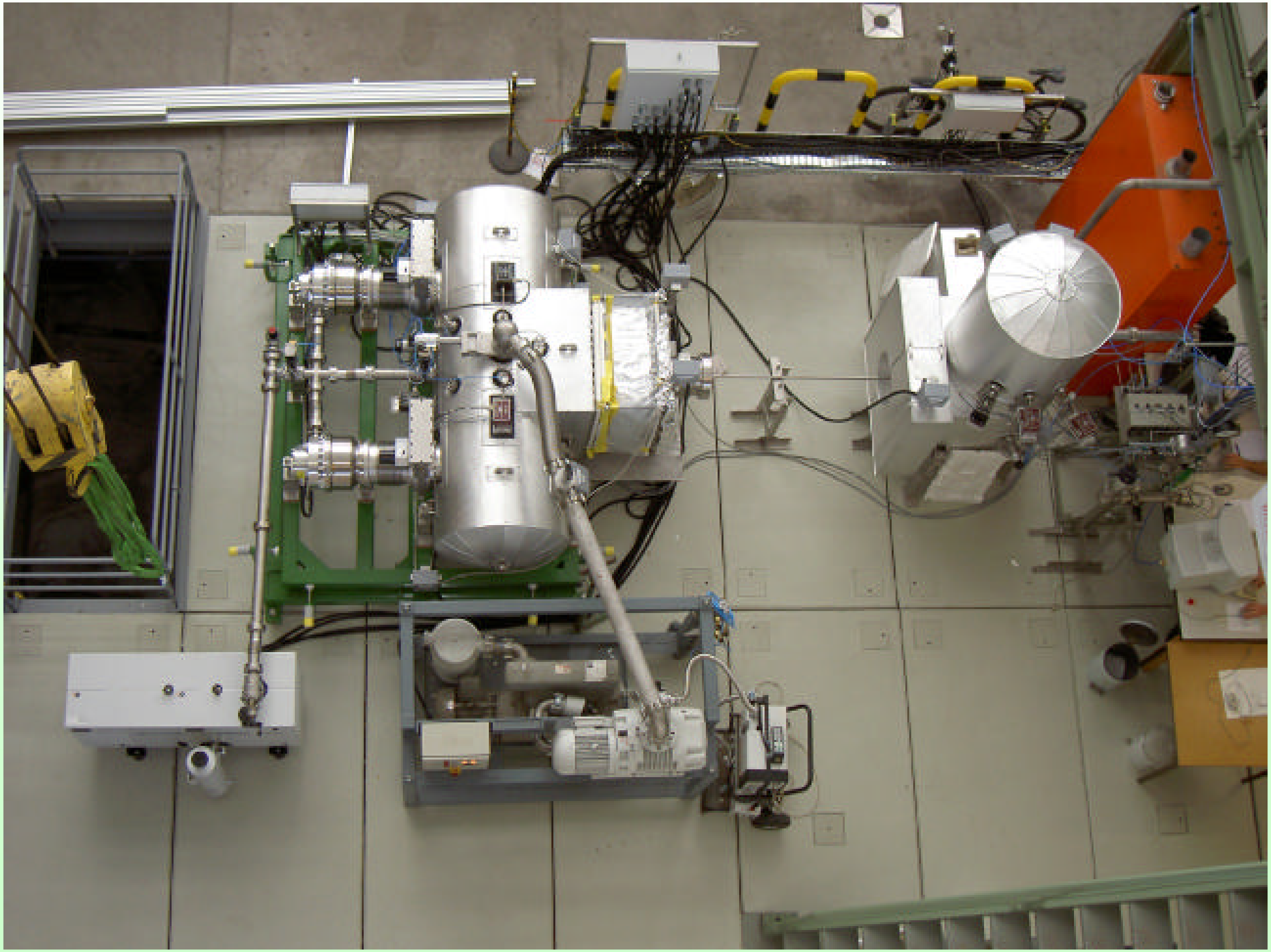
Experimental validation

At Forschungszentrum Karlsruhe a test rig for measurement of the pressure difference at given mass flow for different channels was built up:

- Mass flows between 0.1 and 30000 sccm
- Pressure reading between 10^3 and 10^{-10} mbar
- Pumping speeds up to 5 m^3/s (N_2)
- Channels with cross section dimensions up to 0.6 m and length up to 2 m.

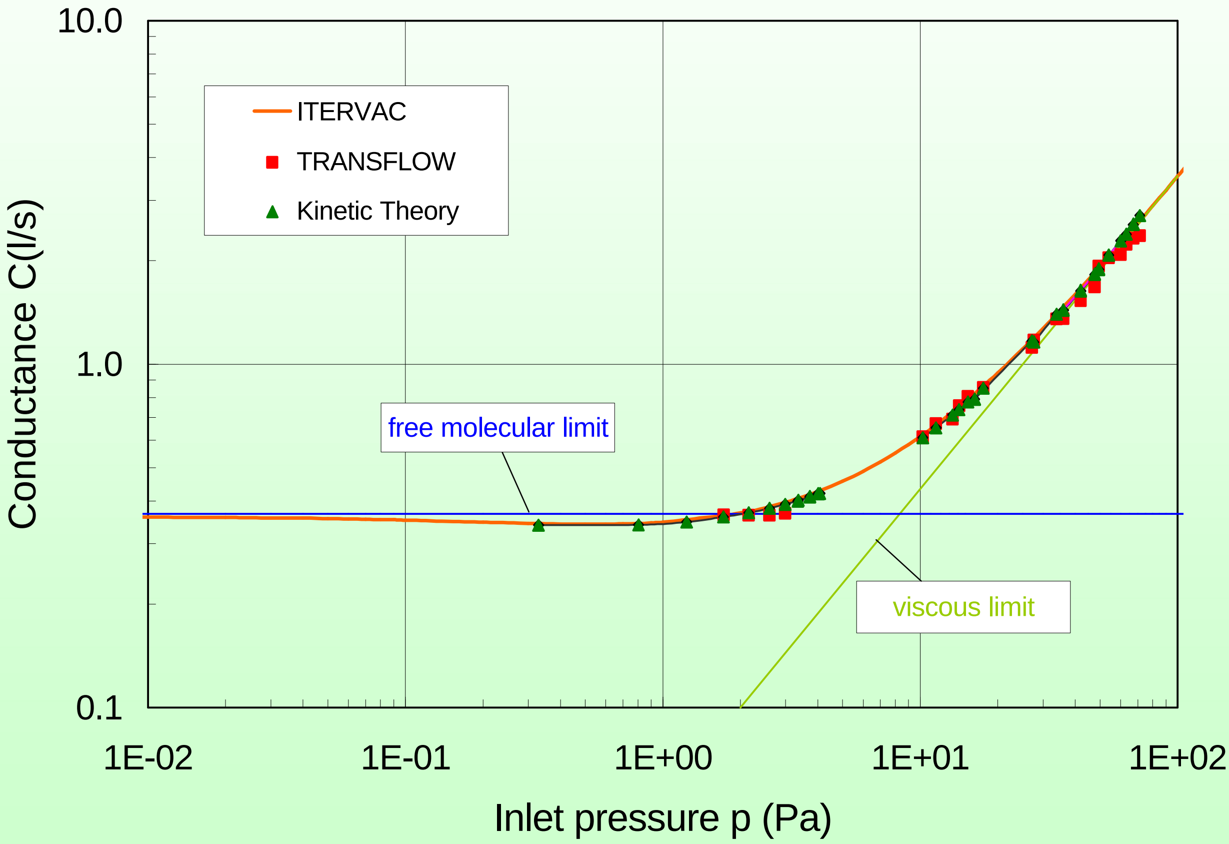
The first 4 channels are long channel with L/d about 80 and circular, square shaped, equilateral triangular and trapezoidal cross sections.

Experimental validation (2)



Bird's view onto the TRANSFLOW test rig

First results for the circular tube



1277 mm long,

15.95 mm diameter (average)

Nitrogen

Room temperature (average)

Outlook

- ✓ Finishing the measurements with the long channels
- ✓ Short channel measurements (L/d about 10)
- ✓ Simulation of all measurements with ITERVAC and comparison with the experiments

Thanks for your attention !