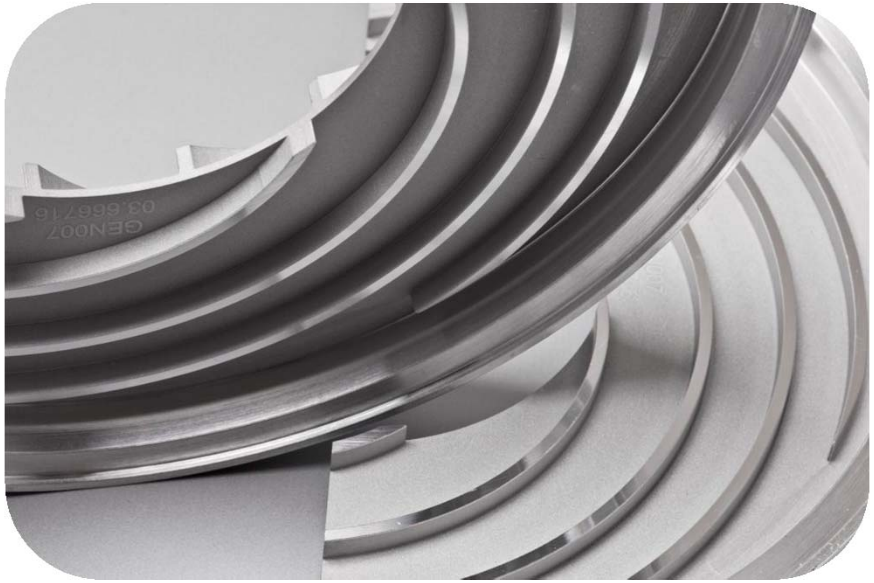
Solved and Unsolved Gas Dynamics Problems for Turbo-Molecular-Drag Pumps

an Industrial Overview

Silvio Giors,
Agilent Technologies
Vacuum Products Division, Italy
Turbomolecular Pumps R&D

silvio.giors@agilent.com



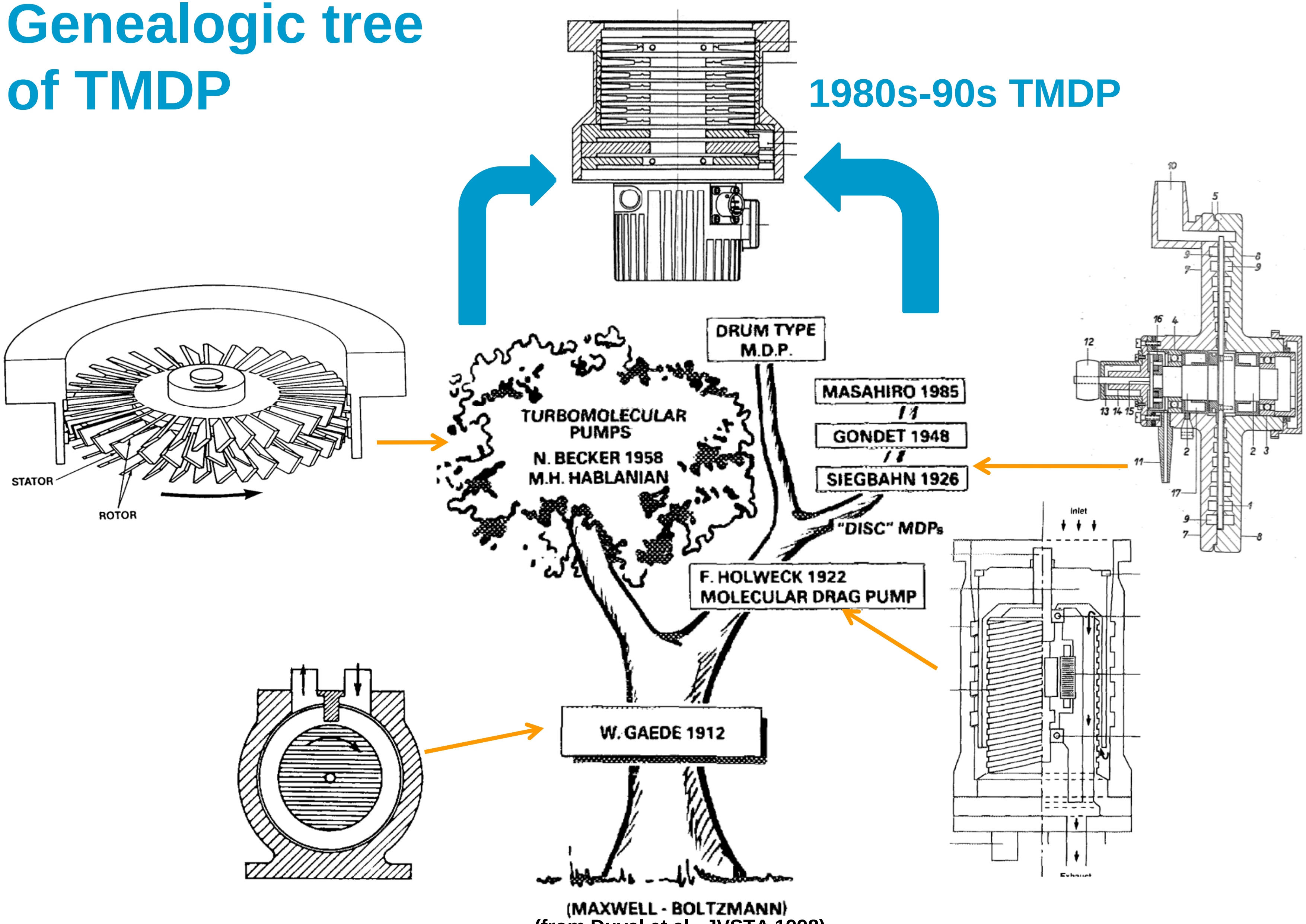
64th IUVSTA workshop on Practical Applications and Methods of Gas Dynamics for Vacuum Science and Technology
May 16-19, 2011 - Leinsweiler, Germany

Outline

- Genealogic tree of TurboMolecular-Drag Pumps (TMDP)
- TMDP technology and modelling challenge
- Operating conditions of TMDP applications
- TMDP modelling request from industry
- TMP stages modelling
- MDP stages modelling
- Heat exchange modelling
- Conclusions and industry requirements to VGD

Genealogic tree of TMDP

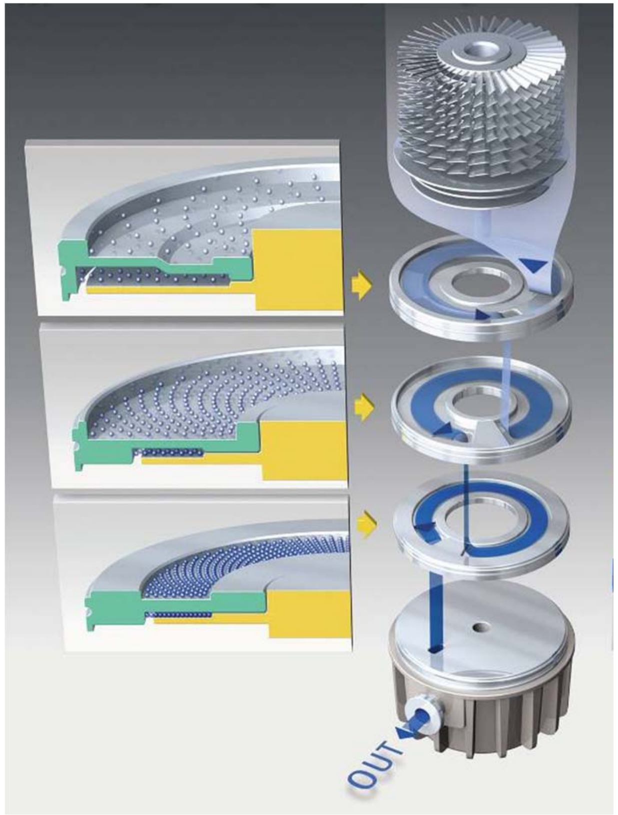
1980s-90s TMDP



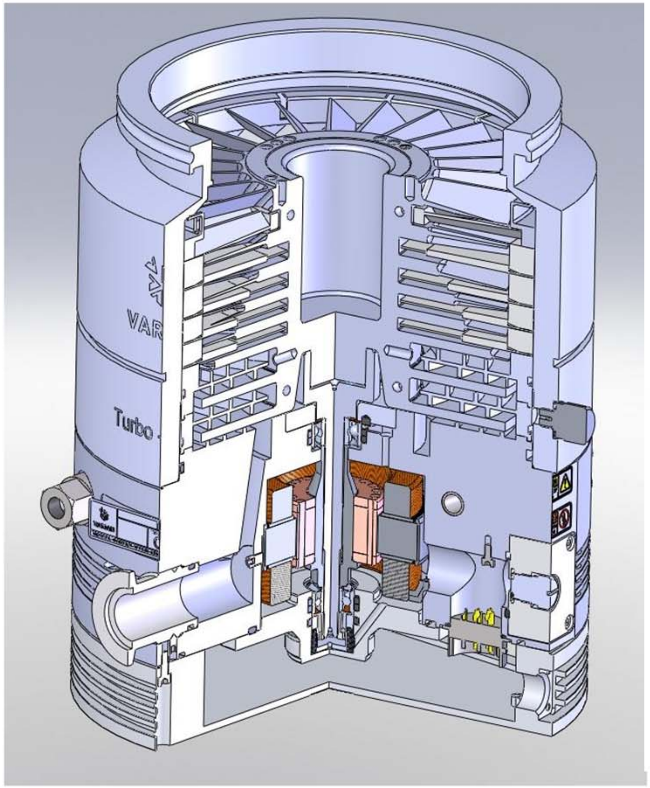
(from Duval et al., JVSTA 1998)

TMDP technology and modelling challenge (1)

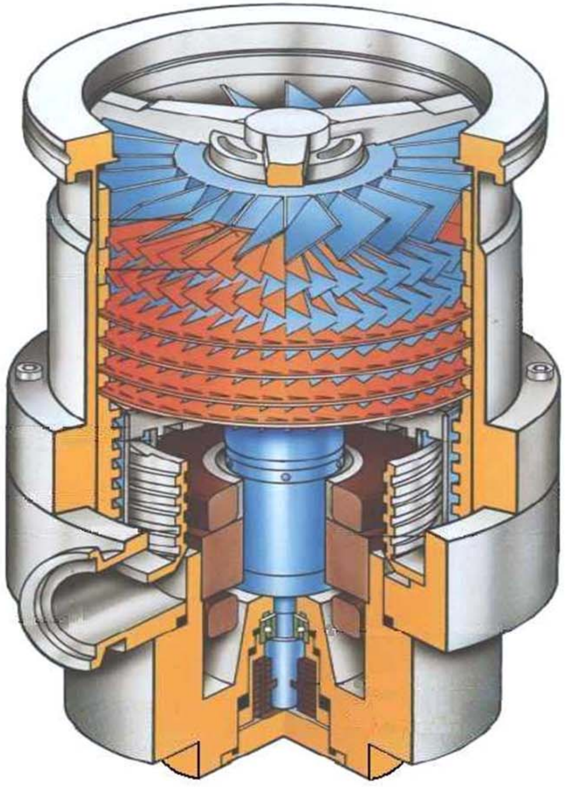
Molecular drag stages are used downstream turbo stages in TMDPs to handle high foreline pressures (10 mbar range) and improve light gases compression→ allow smaller backing pumps and lower power consumption, unloading turbo stages



Macrotorr® (Gaede pump redesigned) was Varian TMDP design, with stages axially in series



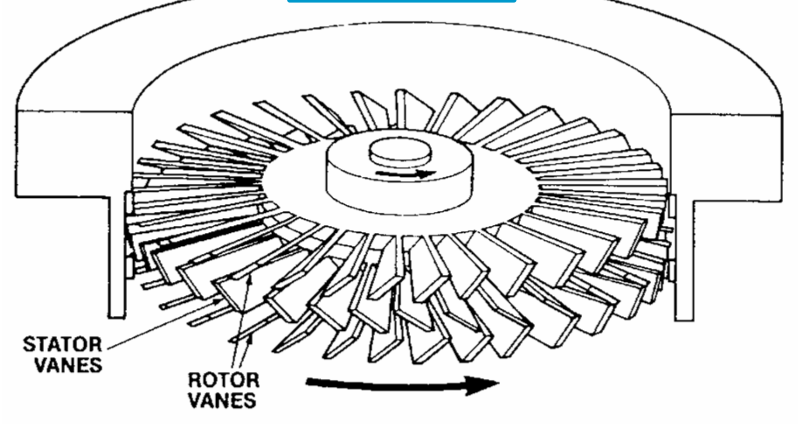
TwisTorr® (Siegbhan pump redesigned) is Agilent molecular drag TMDP design on new products (from 2010), with stages axially in series.



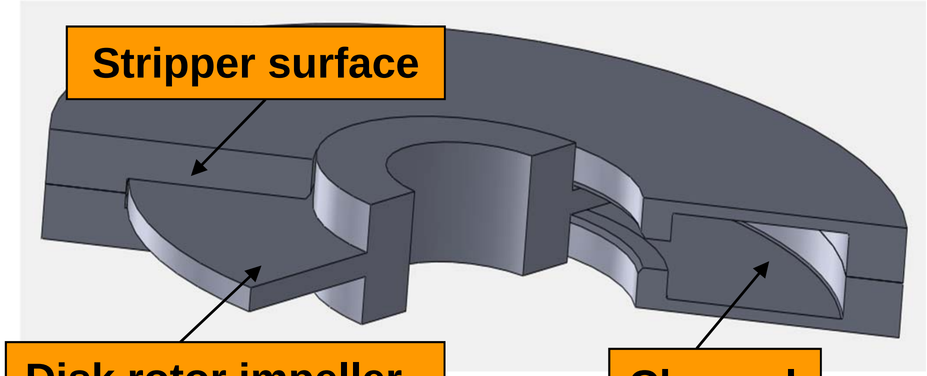
Holweck TMDP design (courtesy of Pfeiffer Vacuum), with stages in series nested radially

TMDP technology and modelling challenge (2)

TURBO



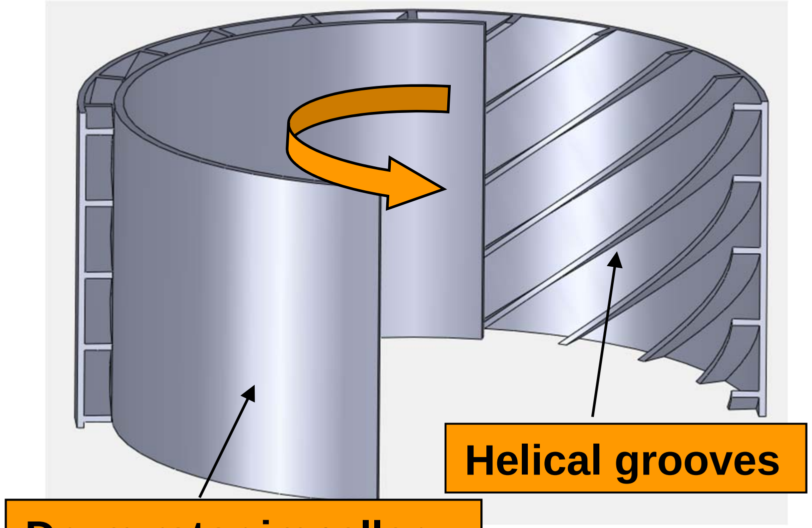
GAEDE



Stripper surface

Disk rotor impeller

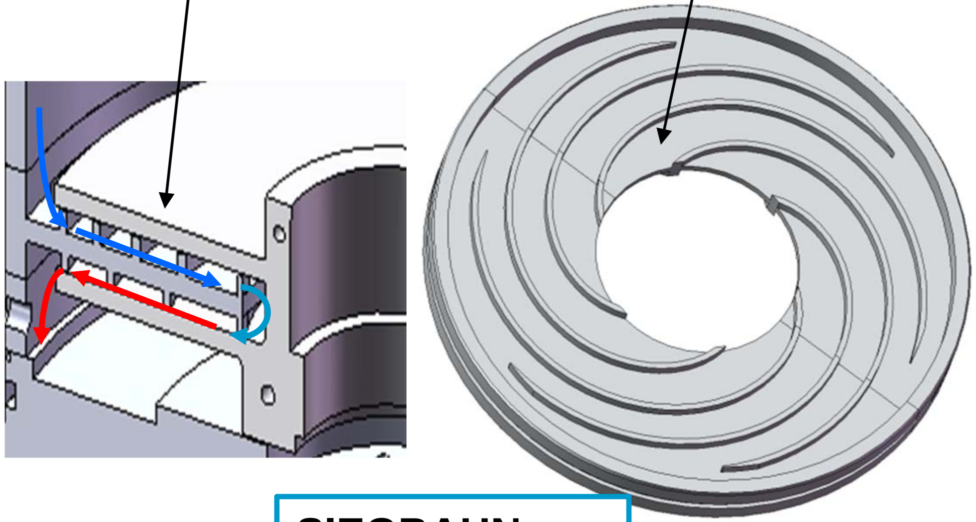
Channel



Helical grooves

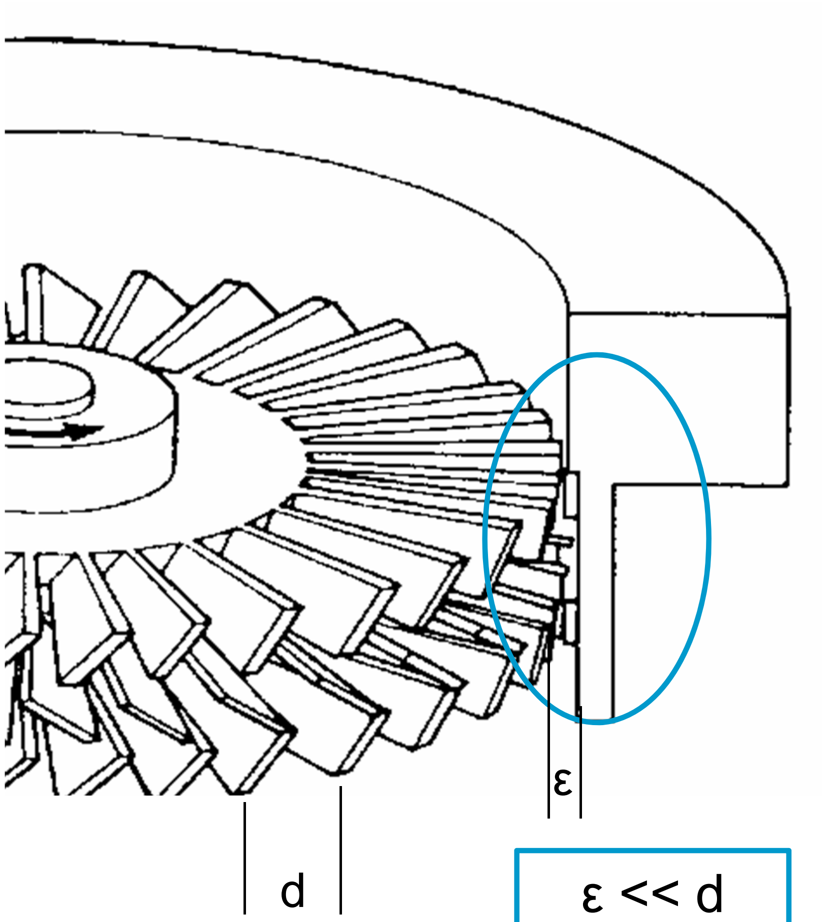
Drum rotor impeller

HOLWECK



SIEGBAHN

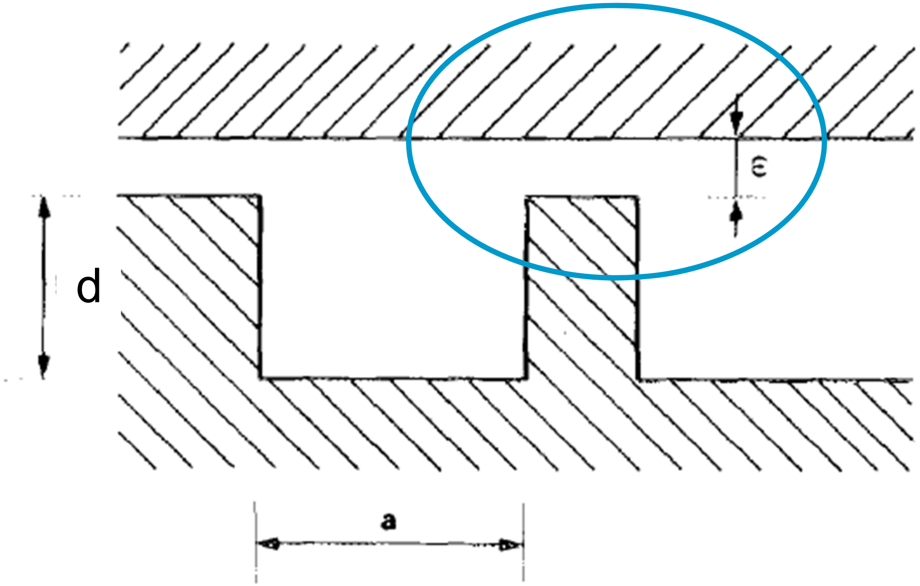
TMDP technology and modelling challenge (3)



$\varepsilon \ll d$

$Kn_{\varepsilon} \gg Kn_{d}$

- Leakage modelling is foundamental for compression prediction
- Different length scales → **different flow regimes, possible mesh issues and stiff problems**



Operating conditions of TMDP applications (1)

* Typical value

Application	Pump size (l/s)	Inlet pressure* (mbar)	Foreline pressure* (mbar)	Main pumped gases*	Power absorption* (W)
UHV systems	80 – 2000	$<10^{-9}$	$<10^{-2}$	H2, N2	< 50
GC-MS	80 – 300	10^{-6}	10^{-1}	H2, He	< 20
LC-MS	300 – 700 (multi flow)	10^{-7} - 10^{-2}	2 – 5	Air, N2	100 – 180
ICP-MS	200 – 400 (multi flow)	10^{-7} - 10^{-3}	1 – 7	Ar	50 – 180
Glass/DVD coaters	700 – 2000	10^{-4} - 10^{-3}	$< 10^{-1}$	Ar	200-500
Thin film solar process	2000 – 3000	10^{-5} - 10^{-3}	$< 10^{-1}$	Many heavy molecules	400-1000

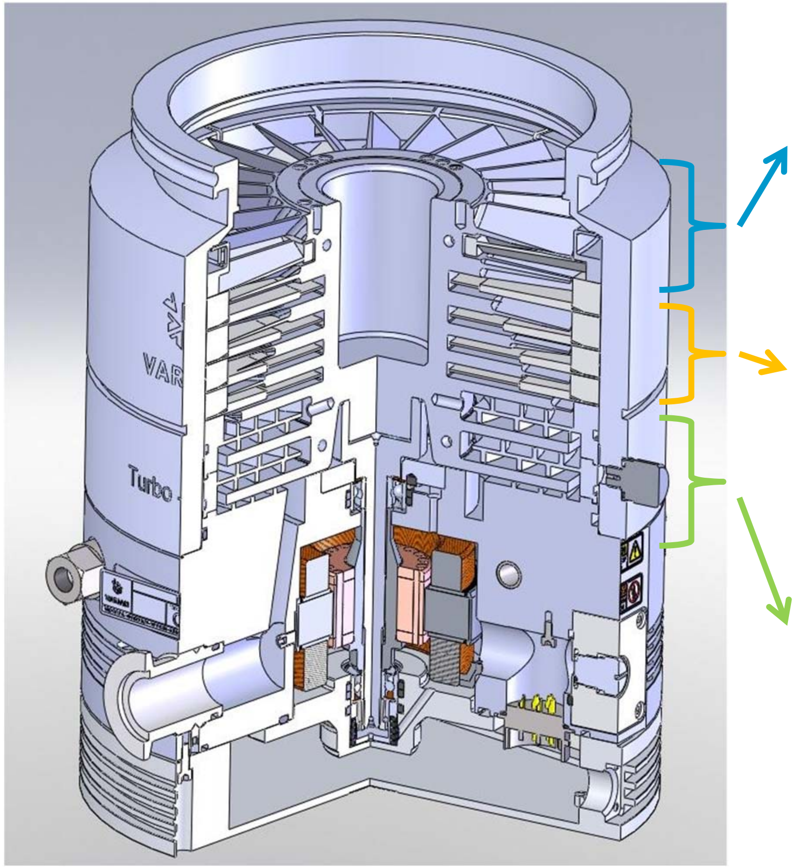
Many applications use the TMDP at relatively high pressures and power!

Operating conditions of TMDP applications (2)

Typical operating parameter range for a 10^3 l/s TMDP:

- p_{inlet}: $10^{-10} \div 10^{-2}$ mbar; p_{outlet}: $10^{-3} \div 20$ mbar
- Mass flow rate (@ $p_{inlet} = 10^{-3}$ mbar) $\approx 10^{-6}$ kg/s
- Rotor peripheral speed $\approx 300 \div 350$ m/s

$$\mathrm{Kn} = \frac{\lambda}{d}$$



INLET TMP STAGES

d=10-20 mm

$10^{-10} < p[\mathrm{mbar}] < 10^{-2}$

$10^{7} > \mathrm{Kn} > 10^{-1}$

Molecular to transition regime

INTERM. TMP/MDP STAGES

d=5-10 mm

$10^{-5} < p[\mathrm{mbar}] < 10^{-1}$

$10^{3} > \mathrm{Kn} > 10^{-1}$

Molecular to transition regime

OUTLET MDP STAGES

d=1-5 mm

$10^{-3} < p[\mathrm{mbar}] < 10^{1}$

$10^{1} > \mathrm{Kn} > 10^{-3}$

Transition to viscous regime

TMDP modelling request from industry

TMDP industry would like to have:

- **Analitycal or simple numerical models, predictive within +/- 15% precision**
  - For single stages: useful for first design step
  - For complete pump, to optimize stages coupling and sequence
- **Sophisticated numerical models (DSMC or other Boltzman model solvers) :**are useful for optimization of each single stage at next step design phases in numerical experiments, **provided that the computation time is 10 times lower than making a real experiment**
- **Heat exchange models are the most important missing one**
- **ALL validated on wide range of geometrical and operating parameters, in molecular and transition regime**

TMP stages modelling (1):
test particle Monte Carlo and analytic

1960 – Kruger applied the test-particle Monte Carlo method to single and multiple blade rows, and successfully compared these results to experiments.

1963 – Mublesh and Shapiro develop the integral equation that describes the 2D TMP balde row in molecular regime → first analytic model of a TMP, successfully compared to experiments in molecular regime.

2004 – Amoli et al.: Monte Carlo 3D, with good comparison with data in molecular regime

Missing good clearance model and missing transition behavior

TMP stages modelling (2): DSMC

J-S. Heo and Y-K. Huang, Vacuum 56, 133 (2000)

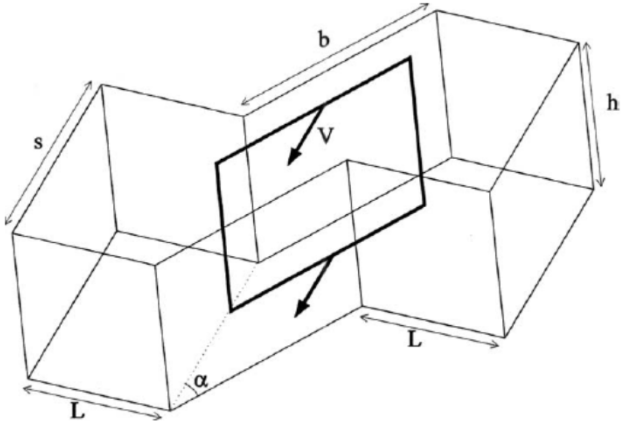
- DSMC 2D

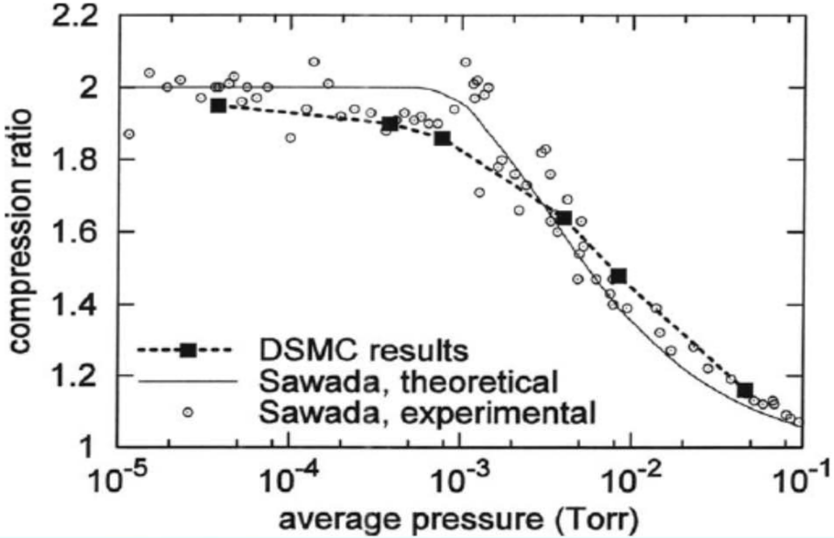
S. Wang and H. Ninokata, Prog. Nucl. Energy, 47, 664 (2005).

- DSMC full 3D
- Single stage only

•**R. Versluis, R. Dorsman, L. Thielen, and M.E. Roos**, J. Vac. Sci. and Technol. A, 27, 543 (2009).

- Plane 3D (no radial effect), with moving blades effect, single stage simulation
- No radial clearances included
- Compares well with Sawada experiments

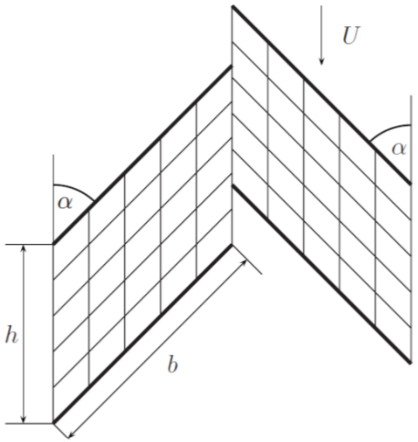


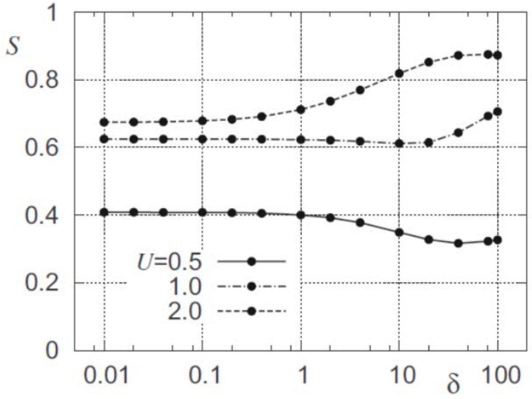


TMP stages modelling (3): DSMC

F. Shapirov, Numerical simulation of turbomolecular pump over a wide range of gas rarefaction**,** *JVST A Nov/Dic 2010*

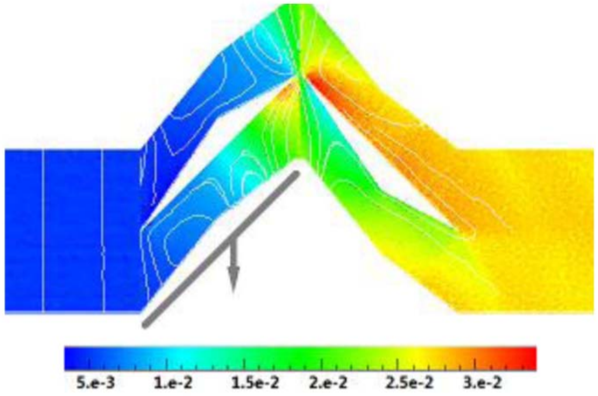
- *DSMC 2D, flat plate blades*
- *5 rotor-stator stages (entire) pump*
- *Effect of rarefaction and blade speed on S and k*
- *Interesting results about speed*





G.A. Bird, Effect of inlet guide vanes and sharp blades or the performance of a turbomolecular pump, JVST A Jan/Feb 2011

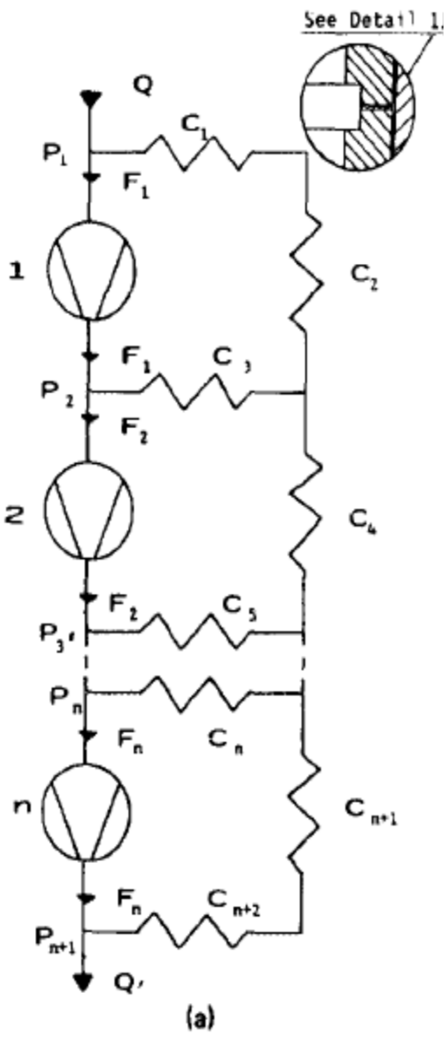
- *2D DSMC model of single rotor-stator pairs*
- *“Sophisticated” DSMC on 2D moving reference frame*
- *Effect of blade bluntness and first stage peertubation on chamber and compression ratio*
- *Good computational efficiency (a week timeframe for a multistage pmp)*



TMP stages modelling (4): open questions

Clearances modelling

- Small clearances are foundamental for compression
- Casaro-Levi, 1990: lumped parameter model in molecular regime
- *Missing dedicated model in transition regime*
- *Is there any interaction between flow field and radial clearances at rotor tip or stator root, requiring more than lumped paramers?*

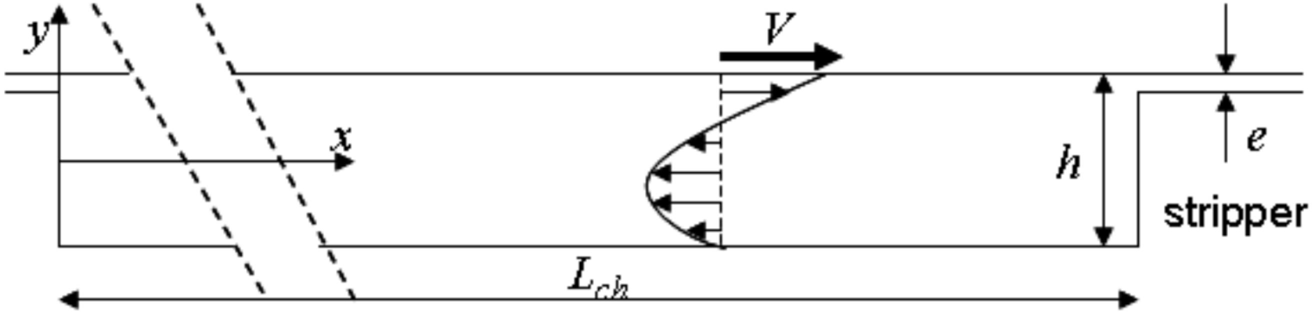


Are 3D effects important?

- *Is there a significant pressure gradient in TMP stages?*
- *Is balde twisting (blade angle α(r)) useful? What is the optimum blades twist for pumping speed and compression?*
- Sharipov and Bird don’t agree on predictiveness properties of 2D models: *is there an optimum radial weighting of 2D parameters for long blades compared to radius (l/R > 0.5), for 2D predictive modelling?*

MDP stages modelling (1)

Couette-Poiseuille Gaede pump 1D model: (Helmer and Levi, JVST A 1992)

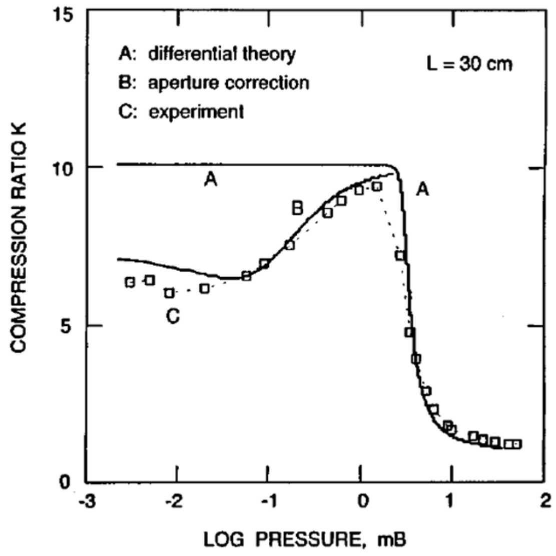


$$\frac{dp}{dx} = \frac{12\boxed{\mu} u}{h^2}\left(1 - \frac{Q}{puA_{ch}}\right)$$

$$Q_m = p_{out} u A_{pl}$$

$$K_0 = A_{ch} / A_{pl} \cong h / e$$

- Only Couette Leakage, no diffusive contribution
- Compares well with experiments, even in molecular regime, because of nature of leakage
- Transition effect are hidden in μ



MDP stages modelling (2)

Couette-Poiseuille Howeck pump 2D model: (Sawada, JVST A 1999)

$$\frac{\partial p}{\partial x}=0, \quad \frac{\partial p}{\partial z}=0,$$

$$\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial z^2}=\frac{1}{\mu}\frac{\partial p}{\partial y}$$

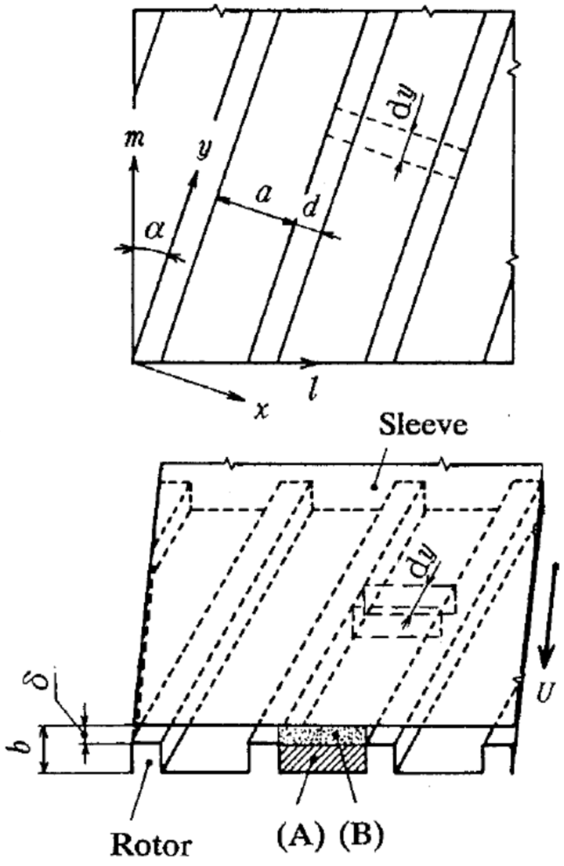
$$\frac{d\bar{p}}{dl}=\frac{2\mu UF\cos\alpha\sin\alpha+2\mu GQ/(\rho b)}{b^2(H\sin^2\alpha+\gamma_p q_p'/\epsilon)}, \qquad (17)$$

where

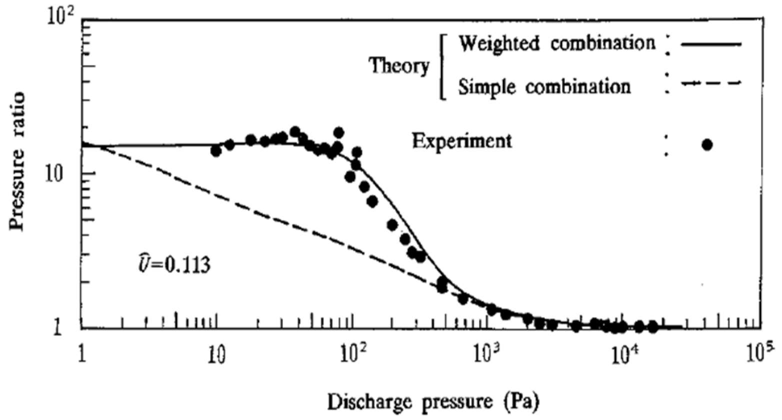
$$F=-(1-\epsilon)\left\{q_p'(q_V+q_V'-\gamma_V)+\gamma_p\left(\frac{\epsilon}{1-\epsilon}q_V-q_V'+\gamma_V\right)\right\},$$

$$G=\frac{1-\epsilon}{\epsilon}q_p'+\gamma_p, \qquad (18)$$

$$H=(1-\epsilon)\left\{q_p'(q_p+q_p')+\gamma_p\left(\frac{\epsilon}{1-\epsilon}q_p-2q_p'+\gamma_p\right)\right\}.$$

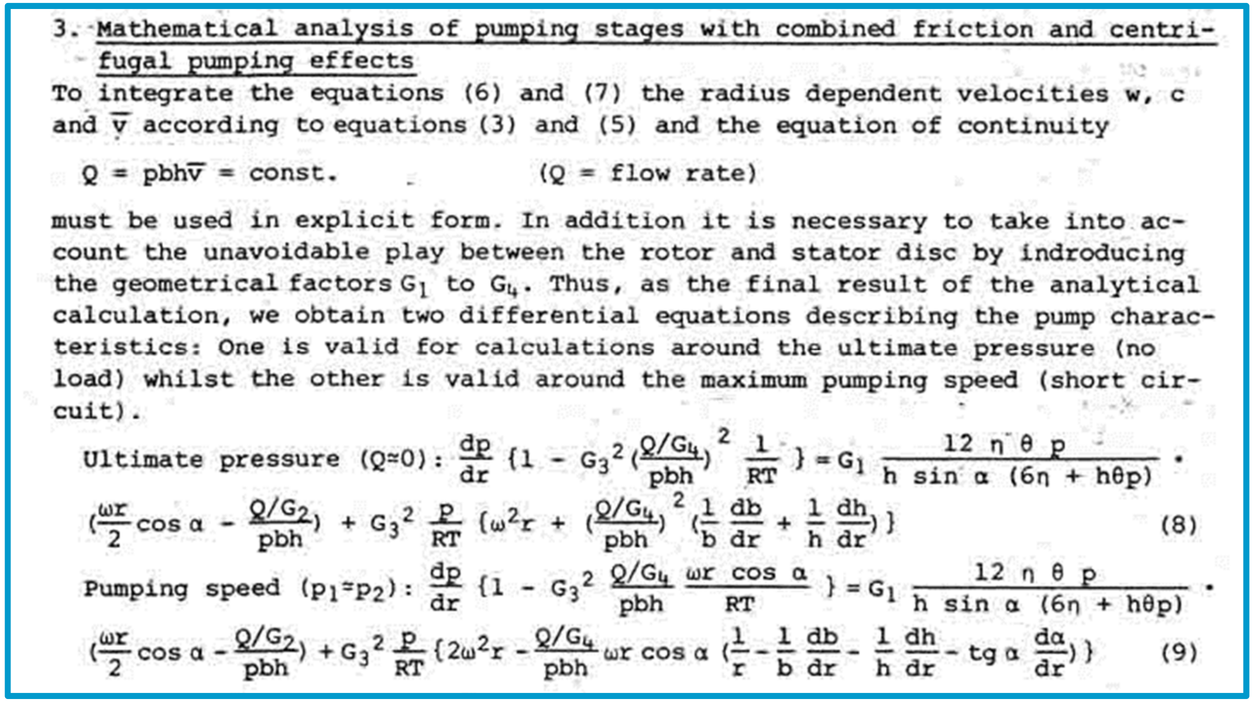


- Transition effect hidden in μ
- 2D geometry effects
- Compares well with experiments



MDP stages modelling (3)

Navier Stokes Siegbahn pump 2D model: (E. Moll, La vide 1980)



3. Mathematical analysis of pumping stages with combined friction and centrifugal pumping effects

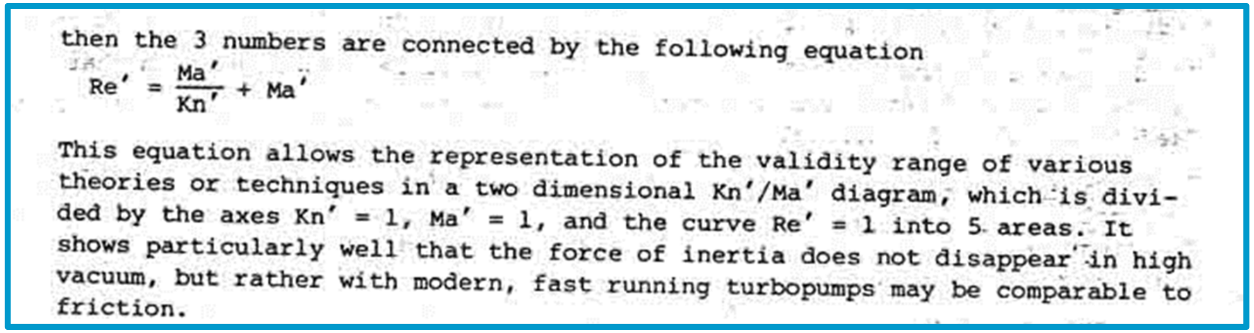
To integrate the equations (6) and (7) the radius dependent velocities w, c and $\overline{v}$ according to equations (3) and (5) and the equation of continuity

$Q = pbh\overline{v} = \text{const.}$ (Q = flow rate)

must be used in explicit form. In addition it is necessary to take into account the unavoidable play between the rotor and stator disc by indroducing the geometrical factors G_1 to G_4. Thus, as the final result of the analytical calculation, we obtain two differential equations describing the pump characteristics: One is valid for calculations around the ultimate pressure (no load) whilst the other is valid around the maximum pumping speed (short circuit).

$$\text{Ultimate pressure } (Q \approx 0): \frac{dp}{dr}\left\{1 - G_3^2 \left(\frac{Q/G_4}{pbh}\right)^2 \frac{1}{RT}\right\} = G_1 \frac{12\,\eta\,\theta\,p}{h \sin\alpha\,(6\eta + h\theta p)} \cdot \left(\frac{\omega r}{2}\cos\alpha - \frac{Q/G_2}{pbh}\right) + G_3^2 \frac{p}{RT}\left\{\omega^2 r + \left(\frac{Q/G_4}{pbh}\right)^2 \left(\frac{1}{b}\frac{db}{dr} + \frac{1}{h}\frac{dh}{dr}\right)\right\} \qquad (8)$$

$$\text{Pumping speed } (p_1 = p_2): \frac{dp}{dr}\left\{1 - G_3^2 \frac{Q/G_4}{pbh}\frac{\omega r \cos\alpha}{RT}\right\} = G_1 \frac{12\,\eta\,\theta\,p}{h \sin\alpha\,(6\eta + h\theta p)} \cdot \left(\frac{\omega r}{2}\cos\alpha - \frac{Q/G_2}{pbh}\right) + G_3^2 \frac{p}{RT}\left\{2\omega^2 r - \frac{Q/G_4}{pbh}\omega r \cos\alpha\left(\frac{1}{r} - \frac{1}{b}\frac{db}{dr} - \frac{1}{h}\frac{dh}{dr} - \operatorname{tg}\alpha\,\frac{d\alpha}{dr}\right)\right\} \qquad (9)$$



then the 3 numbers are connected by the following equation

$$Re' = \frac{Ma'}{Kn'} + Ma'$$

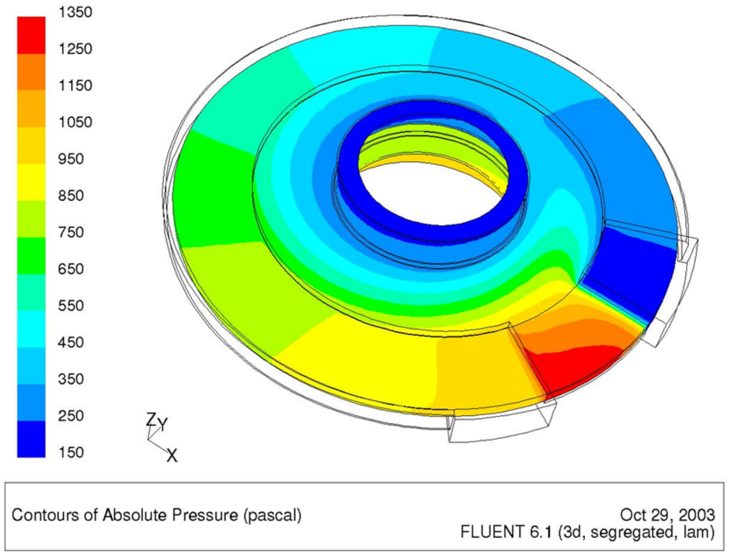
This equation allows the representation of the validity range of various theories or techniques in a two dimensional Kn'/Ma' diagram, which is divided by the axes Kn' = 1, Ma' = 1, and the curve Re' = 1 into 5 areas. It shows particularly well that the force of inertia does not disappear in high vacuum, but rather with modern, fast running turbopumps may be comparable to friction.

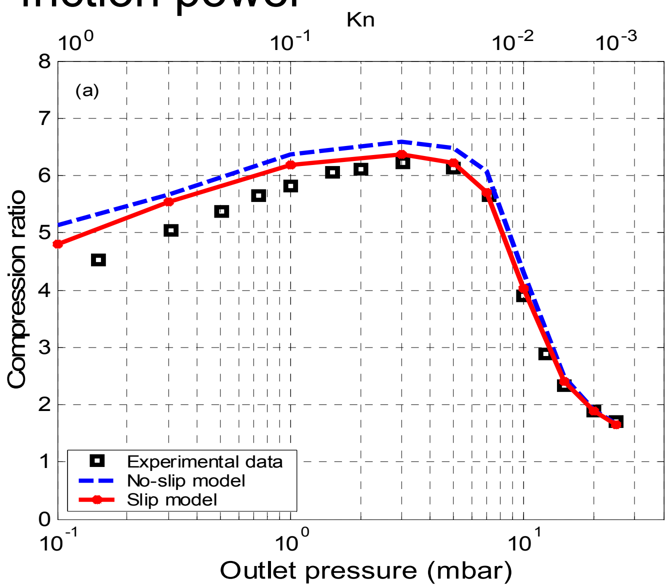
- Viscous model with tranistion to be effect included in μ and slip B.Cs.
- Effect of leakage and of Centifugal/Coriolis forces not clearaly analyzed

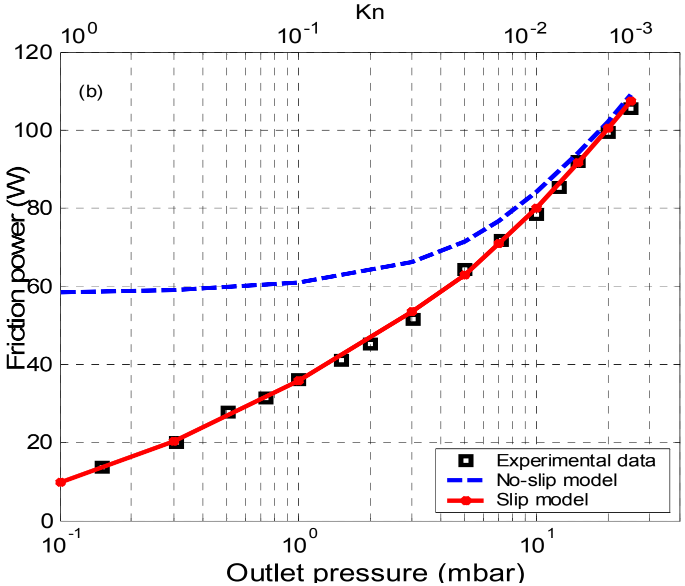
MDP stages modelling (4)

CFD Gaede model with slip flow BCs (Giors, Subba, Zanino, JVST A 2005)

- 3D model of single stage
- Good match with experimental compression, thanks to the Couette nature of the leak
- Slip flow BCs allow good reproduction of friction power

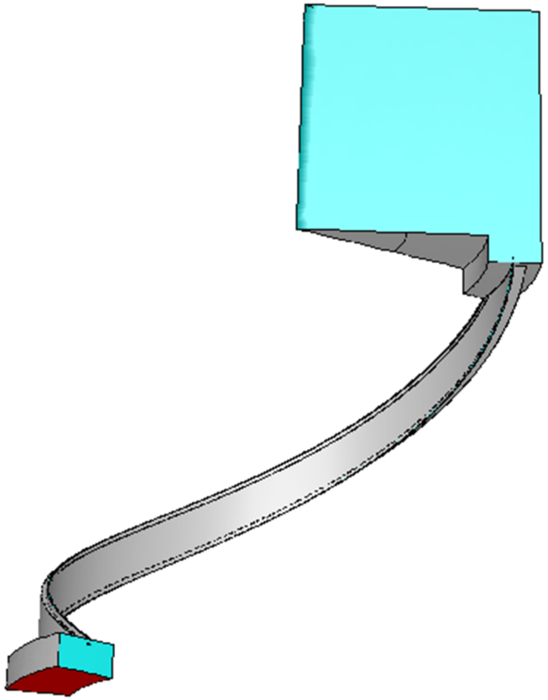


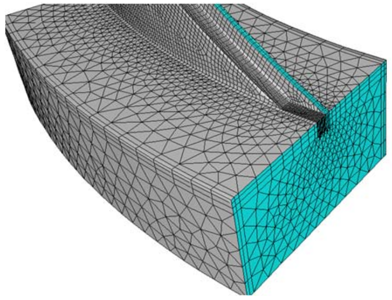


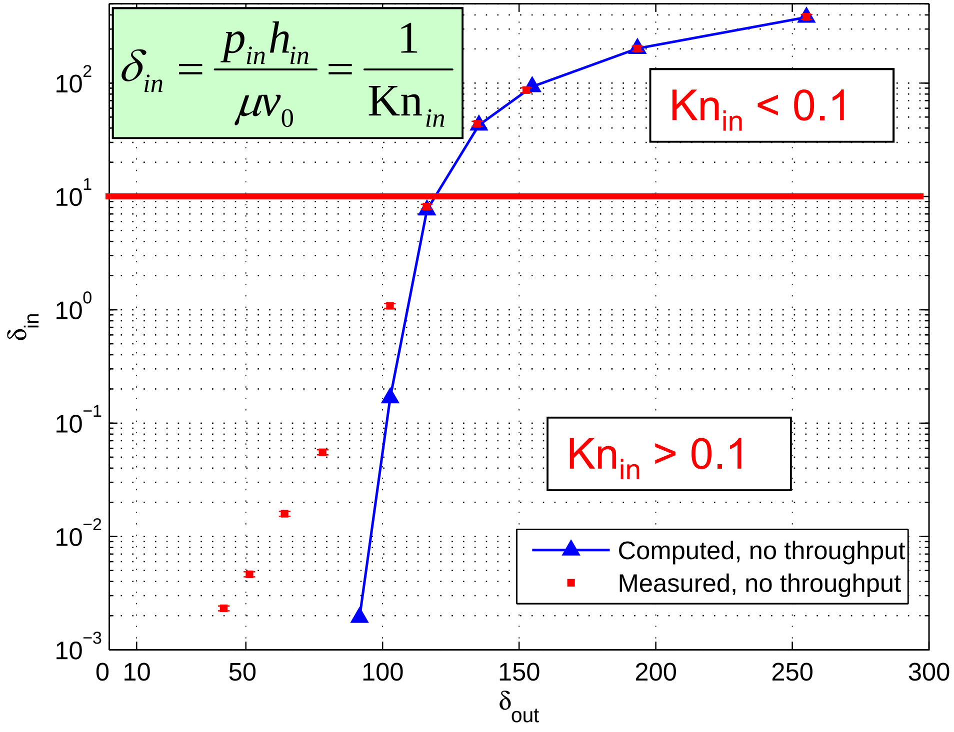


MDP stages modelling (5)

CFD Holweck model with slip flow BCs (Giorsat al, JVST A 2006)



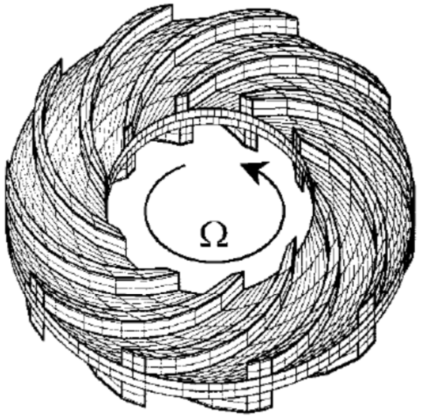




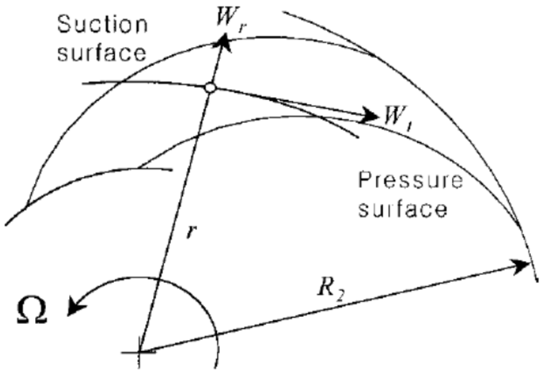
- 3D periodic model of single stage
- Slip flow BCs allow good match with experimental compression, up to Kn = 0.1 at inlet, 0.01 at outlet

MDP stages modelling (6)

DSMC solutions for Siegbahn strage (Heo and Hwang, JVST A 2000-2002)

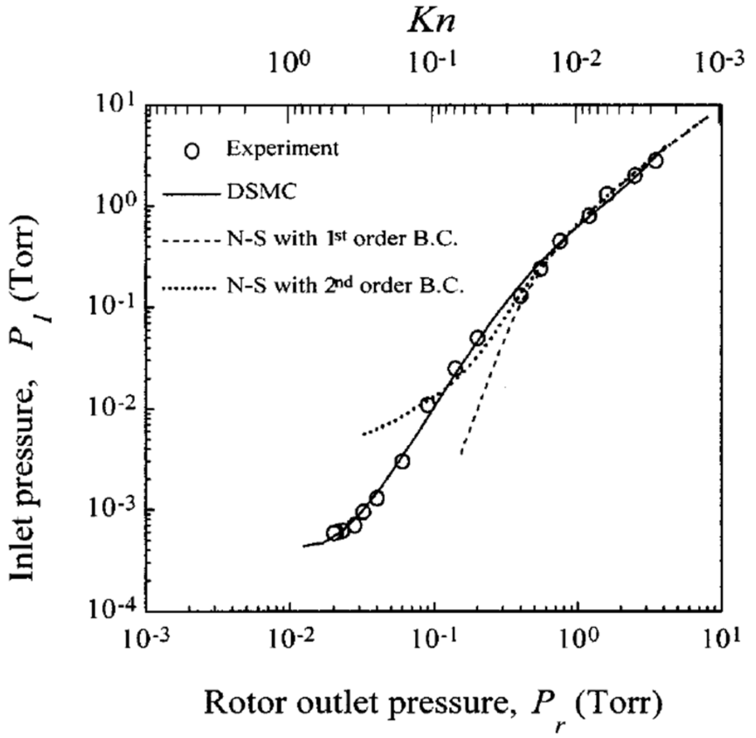


(b)



(c)

- 3D model with leakages, centripetal and centrifugal
- Good match of perfromances with experiment
- Comparison with Navier-Stokes with slip flow BCs



MDP stages modelling (7)

Solution of Boltzmann equation for Holweck (Sharipov and Zipp, JVST A 2005)

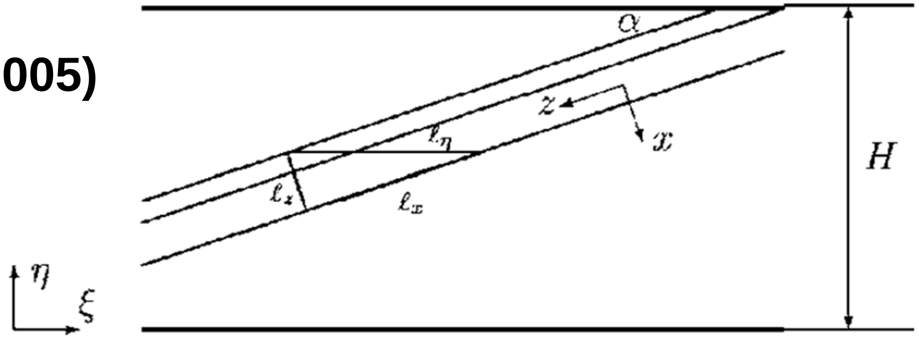
$$\mathbf{v}\cdot\frac{\partial f}{\partial \mathbf{r}} = \frac{P}{\mu}(f_M - f),$$

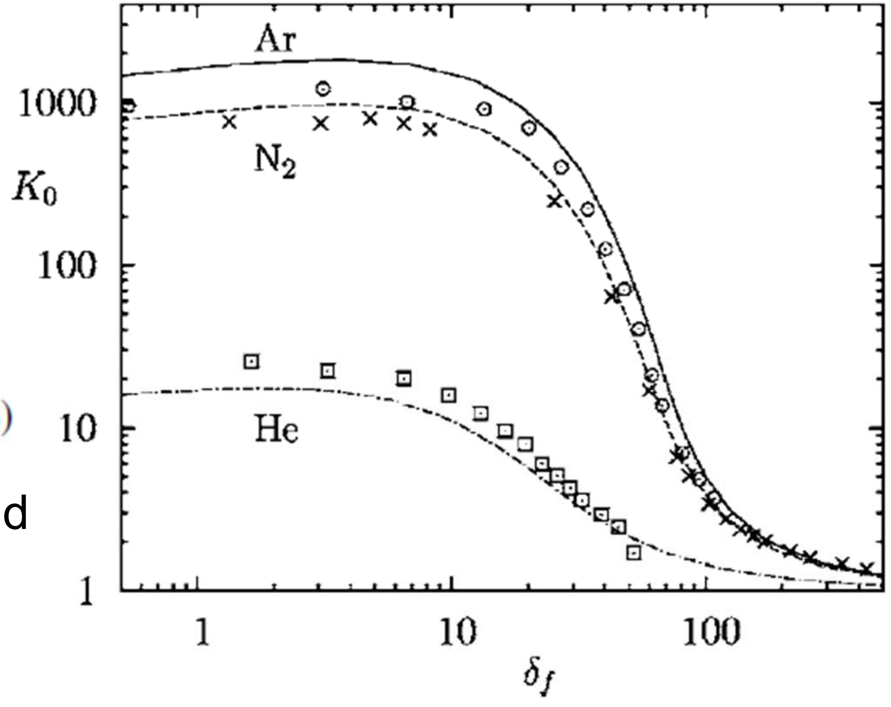
- Linearized BGK
- Longitud. Couette
- Transverse Couette (leakage)
- Longitud. Poiseuille
- Trasv. Poiseuille (leakage)

$$\ell\frac{dP}{d\eta} = \sin\alpha\left\{\frac{U}{v_m}P\cos\alpha\left[G_z^{(C)}(\delta) - \frac{\ell_z}{\ell}G_x^{(C)}(\delta)\right] - G_\eta P_h\right\} \times \left[G_z^{(P)}(\delta)\sin^2\alpha + \frac{\ell_z}{\ell}G_x^{(P)}(\delta)\cos^2\alpha\right]^{-1} \qquad (46)$$

- Very nice dimensionality reduction and effective numerical solution
- Very good match with experiments
- Also predict pump torque (not shown)

$$\dot{M}_x + \dot{M}_z + \dot{M}_\eta = 0.$$



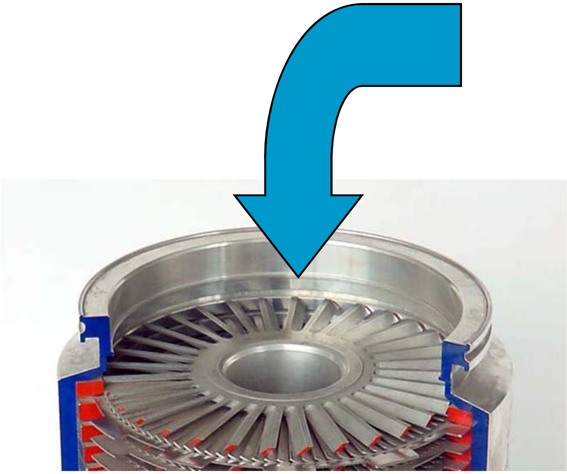


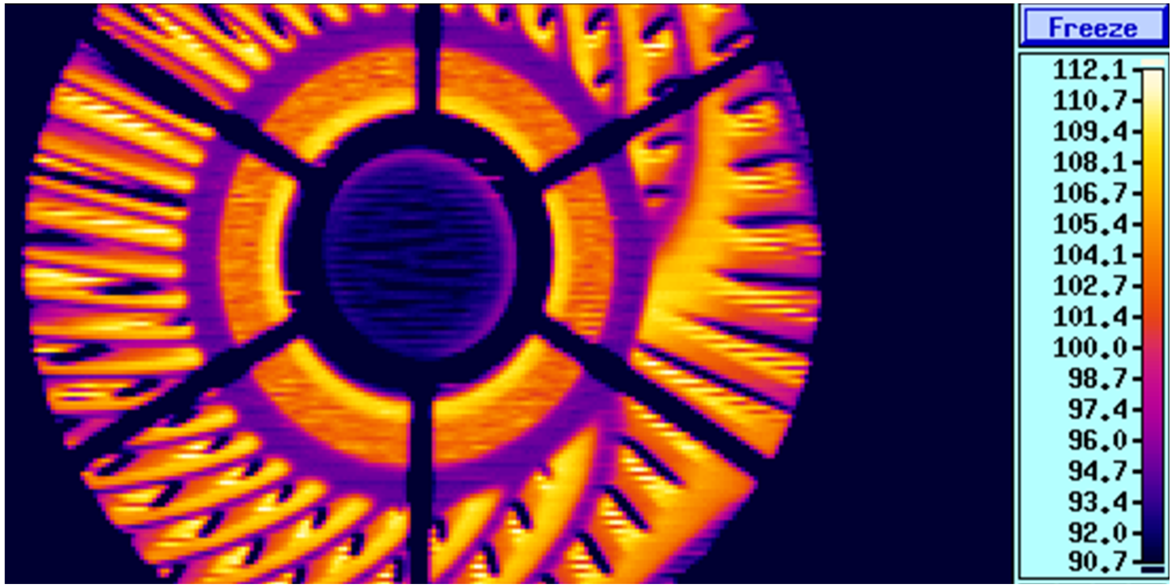
MDP stages modelling (8): open questions

Are 3D effects and centrifugal forces important in Siegbahn stages?

- What’s the difference in working principle between Howeck and Sigbahn MDP? → *It is not clear the role played by centrifugal and Coriolis forces in Siegbahn stages compared to molecular drag*
- Is it possible to extend Sharipov Howeck model based on model Boltzman equation to Siegbahn? → *see next paper by Arpa, Cozza et.al, presented by I. Cozza*
- Most power in TMDP is absorbed by MDP stages: *it is foundamnetal to show model capability to predict friction torque and power*

Heat exchange modelling in TMDP (1)





Reasons for rotor heating

- Electric motor inefficiency
- Gas friction between sonic rotor and still stator in transition and viscous regime
- Limited heat exchange between rotor and stator (rarefied gas, ceramic or magnetic bearings)

High temperature related issues:

- Tiny clearances between rotor and stator
- Reliability of lubrication
- Rotor is made of aluminum alloy ⇒ its strength degrades with temperature (aging and creep)

Heat exchange modelling in TMDP (2)

- **Final goal: predict rotor tempertaure as a result of geometry, gas and operating conditions**
- A few works on MDP model friction torque (Cerruti and Spagnol for Gaede, JVST A 1999, Giors for Gaede and Holweck JVSTA 2005/2006, Sharipov for Holweck, JVSTA 2005)
- None, to authors' knwoledge, model heat exchange in TMDP
- Phenomena to be modelled in a complex multistage geometry are:
  - Power generated by friction
  - Power generated by eddy currents (welectric motore or operation in magnetic fields)
  - Conduction in solid parts
  - Thermal radiation
  - Conduction/convention in rarefied gas
- **It must be a heat balance of the complete rotor →** best approach, to the author's opinion, would be to couple lumped paramer models (e.g. for conduction and heat gaerenation), to models for radiation and vacuum gas dynamics of single stages.

Conclusions (1)

- VGD and vacuum industry community have explored many possible approaches to model TMDP stages in all working flow regimes.
- After almost 50 years from Kruger and Shapiro pioneering work, the computer power increase nowadays allows the efficient solution of the Boltzmann equation in complex 2D and 3D geometries.
- DSMC or direct numerical integration are the mostly used techniques
- The TMDP industry is eager to have a <u>validated commercial tool</u> available for pump design and optimization:
  - Simple tool for multistage first design
  - Complex tool for stages optimization

Conclusions (2)

The main open problems for VGD community are

TMP

- Clear understanding of radial effects in TMP and optimization of twisted blades
- Possible interaction of clearances with blades
- Development of a commercial tool bsed on DSMC for TMP stages optimization and predictive modelling

MDP

- Boltzmann model for Holweck and Siegbhan stages and clear understanding of Centrifugal and Coriolis effects in Siegbahn

Complete TMDP

- Simple lumped parameter model for optimizing the coupling of stages, previously simulated in more complex models
- Rotor temperature predictive model for heat exchange inside TMDP (including heat generation, conduction, radiation and gas-phase heat exchange)

Thank you!

silvio.giors@agilent.com