

Thermal Creep

An Introduction

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Outline

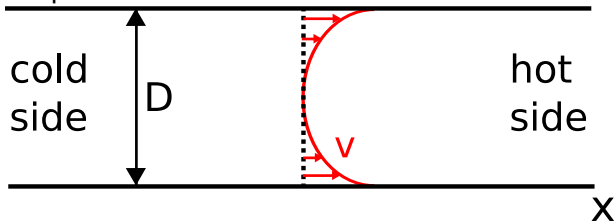
- 1 Thermal Creep
 - Explanation
 - History
 - Today's Importance
- 2 Simulation of rarefied gases
- 3 Possible set-ups for my diploma theses

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What is Thermal Creep

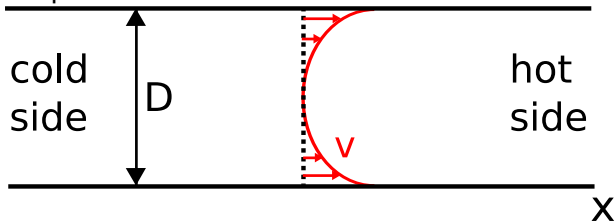
- A temperature gradient induced flux towards the higher temperature



- Only observable at “high” Knudsen Numbers
- Knudsen Number $kn = \frac{\lambda}{D}$.
 λ is the mean free path and D the “Size” of the system
- “High” means $kn \geq 1$ achieved by down scaling or rarefying

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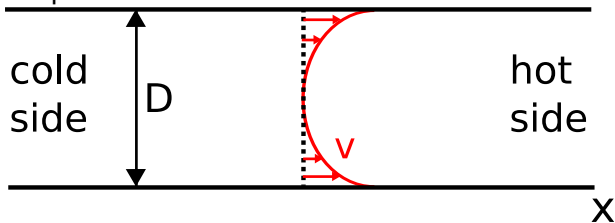
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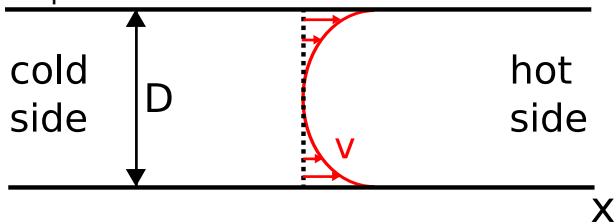
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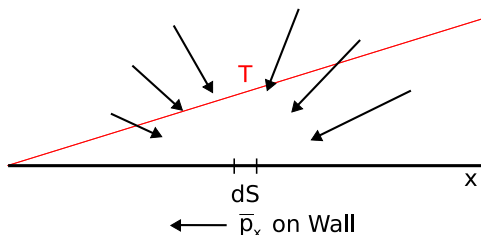
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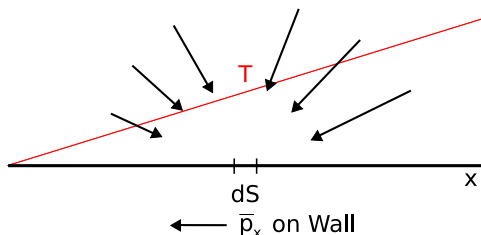
Premises for Thermal Creep



What you need:

- Molecules hardly interact with each other
 \implies their velocity \mathbf{v} is determined by where they came from
- Interaction with wall is diffusive
 \implies at dS the molecules are set to a new T and new isotropic \mathbf{v}

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Explanation for Thermal Creep

What happens:

- Incoming molecules leave dS with zero mean tangential momentum $\bar{p}_x = 0$ (diffusive “reflection”!)
- The tangential momentum p_x was transmitted to the wall at dS
- Because p_x from molecules hitting dS coming from **hot** side is larger than the ones coming from **cold** side
 \implies net momentum transfer \bar{p}_x on wall towards **cold** side
- Conservation of momentum \implies gas receives $-\bar{p}_x$
 \implies Flux towards **hot** side

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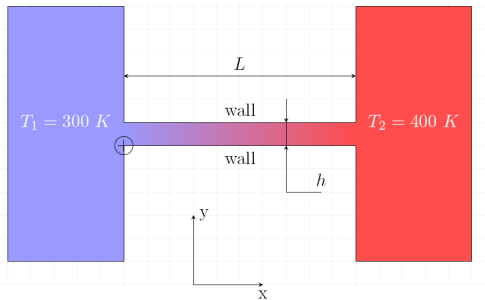
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Equation of steady state

For tow containers connected with a capillary thermal creep leads to the steady state

$$\frac{P_1}{P_2} = \sqrt{\frac{T_1}{T_2}} \quad (1)$$



Deviation of steady state equation

The deviation of relation 1 with Boltzmann equation

$$\frac{\partial}{\partial t} f + \mathbf{v} \nabla f + \frac{\mathbf{F}}{m} \nabla_{\mathbf{v}} f = coll(f)$$

needs:

- External force $\mathbf{F} = 0$
- Collision integral

$$coll(f) = \begin{cases} x & \text{at walls with } x \neq 0 \\ 0 & \text{everywhere else} \end{cases} \Rightarrow kn = \infty$$

- Diffusive and isotropic reflection at walls

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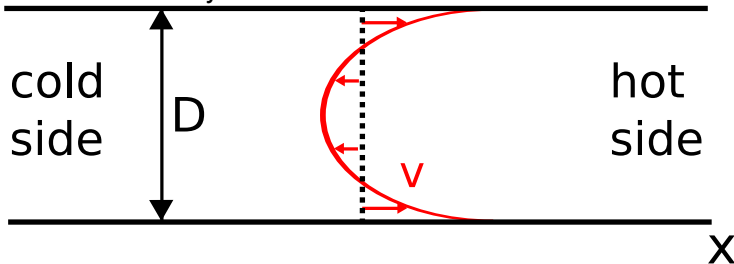
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Steady state flux profile

Thermal transpiration and pressure induced flux add up to zero net flux in steady state



Time-scale

- In 1879 O. Reynolds and J. C. Maxwell published first papers on Thermal Transpiration
- Their motivation was to explain the physics of the light mill
- O. Reynolds used experiments with porous material to prove existence of Thermal Transpiration
- In 1910 Knudsen made further experiments with porous materials
- He suggested to use Thermal Transpiration to build compressors / pumps without moving parts or working fluids
- In the 1990s first microknudsenpumps were build in labs

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Pros and cons of a Knudsen Pump

Pros:

- No working fluids (like oil)
- No moving parts
 - ⇒ good for miniaturising
 - ⇒ potentially maintenance free
- Can be stacked to multi stage pumps

Cons:

- Low volume flow rates and
- low efficiency ($\frac{\text{flux}}{\text{energy}}$) compared to conventional pumps
- Cannot operate through a wide pressure range
($\frac{\lambda}{D} \gg 1 \vee \frac{\lambda}{D} \ll 1 \implies$ neglectable flow rates)

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Knudsen pumps as part of MEMS

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- The pumps can be part of microelectromechanical systems (MEMS)
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Problems with rarefied gases

- Surface effects dominate
- λ & the mean time between two collisions τ are high
⇒ Even locally the gas is not in thermodynamic equilibrium (respectively does not obey the Maxwell distribution)
⇒ Premises for classical Hydrodynamics are not fulfilled so Navier-Stokes equations with no-slip boundary condition $\mathbf{v}_{\text{wall}} = \mathbf{v}_{\text{fluid}}$ (at wall) is no realistic model for rarefied gases

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Hydrodynamical regimes

This empirical overview gives only a rough feeling for the order of magnitude

- Classical continuum regime $kn < 0.001$
→ Navier-Stokes equations with classical no-slip boundary condition
- Continuum regime with wall slip $0.001 < kn < 0.1$
→ Navier-Stokes equations with slip boundary condition
- Transition regime $0.1 < kn < 10$
→ as of today best models and equation are topic to research
- Free molecular flow $kn > 10$
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Possible methods to get models for rarefied gases

For the continuum model:

- derive new boundary conditions that allow the gas to slip at wall and T.C
- derive hydrodynamic equations that are valid for gases not in local thermodynamic equilibrium

For the particle / mechanical models:

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Continuum models: New boundary conditions

- In 1879 Maxwell derived boundary conditions that introduce wall slip and T.C. to classical hydrodynamics

$$u_s = \frac{2 - \sigma}{\sigma} \lambda \left(\frac{\partial u_x}{\partial n} + \frac{\partial u_n}{\partial x} \right) + \frac{3\mu}{4\rho T} \frac{\partial T}{\partial x}$$

σ : fraction of molecules reflected diffusively, $u_{s/x/n}$: velocity component at wall / tangential to wall / normal to wall, μ : gas viscosity, ρ : density

- The linearity of the terms comes from first order approximations of general functions
- There are still widely used in rarefied gas simulations

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- Higher order hydrody. eq. can be derived by solving the Boltzmann eq. with an approximated solution of the distribution function $f(\mathbf{r}, \mathbf{v}, t)$
- f is replaced by a perturbation of the distribution function of the local equilibrium state f_l
- The Boltzmann eq. of the perturbation ϕ is solved with the ansatz $\phi = \sum_n^N \lambda^n \phi^{(n)}$
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- For $N = 2$ ($N = 3$) the (Super-) Burnett eq. can be derived
- The Burnett eq. have additional higher order derivatives compared to Navier-Stokes
- Due to their construction they should be valid for larger λ (larger kn) and gases further away from thermody. equilibrium respectively (e.g. rarefied gases)
- The implementation of Burnett eq. is part of current research (best numerical approximations / algorithms)

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A particle model: “Direct simulation Monte Carlo” (DSMC)

- DSMC is a particle model especially for rarefied gases / high Kn / T.C.
- Only wall/molecule encounters and the motions are calculated deterministically
- Instead of calculating molecule collisions some molecules in a grid cell get new \mathbf{v}_i after a specific time step Δt
- The new \mathbf{v}_i distribution respects the macroscopic state quantities in the cell
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- DSMC only needs $O(n)$ instead $O(n^2)$

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A particle model: “Direct simulation Monte Carlo” (DSMC)

- DSMC is a particle model especially for rarefied gases / high Kn / T.C.
- Only wall/molecule encounters and the motions are calculated deterministically
- Instead of calculating molecule collisions some molecules in a grid cell get new \mathbf{v}_i after a specific time step Δt
- The new \mathbf{v}_i distribution respects the macroscopic state quantities in the cell
- The new \mathbf{v}_i are randomly distributed to the molecules in a cell
- DSMC only needs $O(n)$ instead $O(n^2)$

Comparison particle / continuum models for rarefied gases

- Particle models are the most fundamental ones with respect to the kinetic gas theory
- Particle models consume more computing power / resources than continuum approaches

Comparison particle / continuum models for rarefied gases

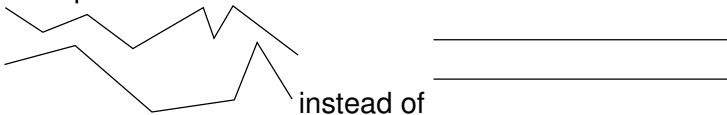
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Outline

- 1 Thermal Creep
 - Explanation
 - History
 - Today's Importance
- 2 Simulation of rarefied gases
- 3 Possible set-ups for my diploma theses

Proposal 1

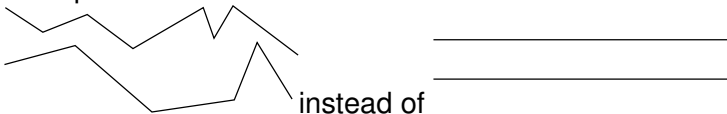
- Simulating T.C. in a capillary with non trivial geometry. For example



- Present simulations of T.C. mostly use either simple geometries or empirical equations
- Finite element method for continuum model needed

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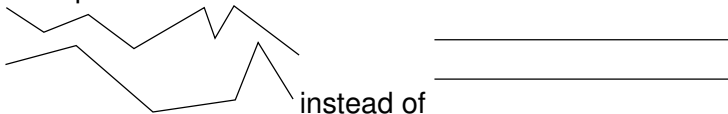
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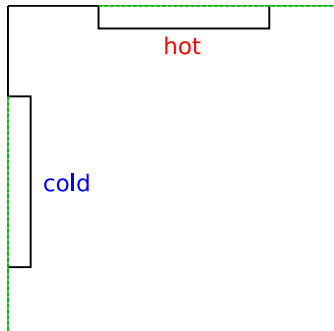
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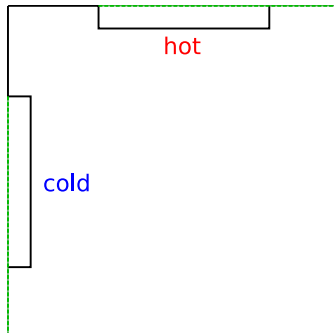
Proposal 2

- Calculating the force on the paddles of a light mill induce by T.C.
- T.C. and “Einstein Force” contribute to movement of paddles but the ratio is unknown
- Due to the geometry finite difference method is sufficient



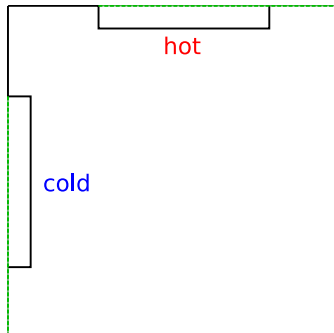
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The end

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