A new Lattice-Boltzmann method for the simulation of rarefied gas flows in complex porous media

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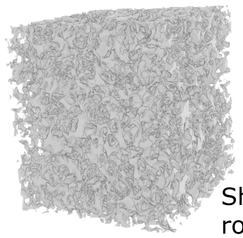
COMPLEX POROUS MEDIA

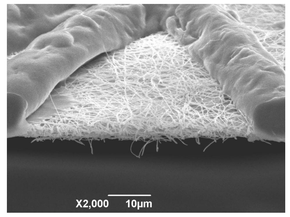
- **Complex porous media** contain pores with **strong local size variations**.
- Pore sizes span across **orders of magnitude**.
- Multiple applications require computation of **precise velocity fields** through complex porous media subject to a **rarefied gas flow regime.**



Shale rock section

$$Kn = \frac{\lambda}{L_c}$$

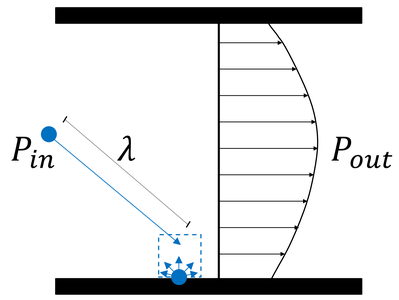
Heat shield



Air filter

SLIP FLOW

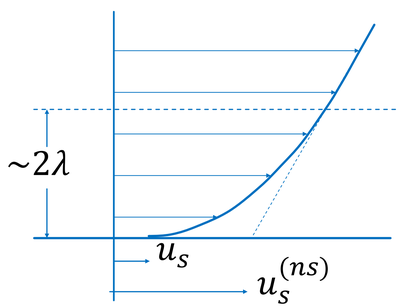
- **Slip flow** appears as a **non-zero relative velocity** to a solid boundary.
- **Ballistic propagation** contributes to the flow velocity close to the wall due to **high Knudsen number**.

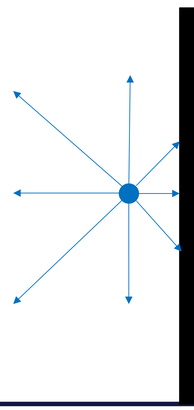


KNUDSEN LAYER

- The **mean free path** of gas molecules is directly **proportional** to its **viscosity.**
- In the **Knudsen layer**, solid boundaries restrict molecular paths and **diminish** local effective **viscosity**.

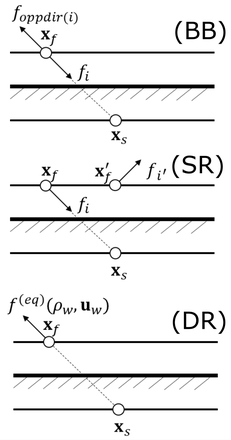
$$\lambda = \frac{\mu}{P}\sqrt{\frac{\pi RT}{2}}$$





THE LATTICE-BOLTZMANN METHOD

- **Discretization** in time, space and velocity of the **Boltzmann equation** on a **cartesian grid.**
- It is the **method of choice** for flow field calculation through **porous media**.
- **Populations** evolve according to a collision-propagation scheme **tuned with multiple relaxation times**.
- Boundary conditions and effective viscosity can be implemented through **bounce-back ratios** and **relaxation times**.

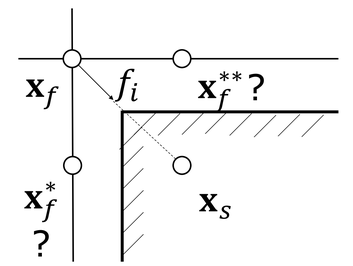


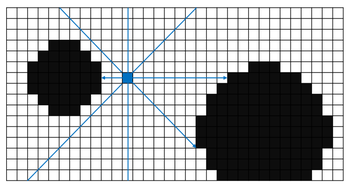
OBJECTIVES

To **develop** a Lattice-Boltzmann method incorporating **slip flow** and **Knudsen layers** to compute **precise velocity fields** through **complex porous media**.

METHODOLOGY

- **Develop a new** diffusive-bounce back **boundary condition** more suitable for complex boundaries
- **Derive relationships** for bounce-back ratios and relaxation times including **local effective viscosity**
- **Calculate local effective viscosity** for any complex geometry using a **ray-tracing method**

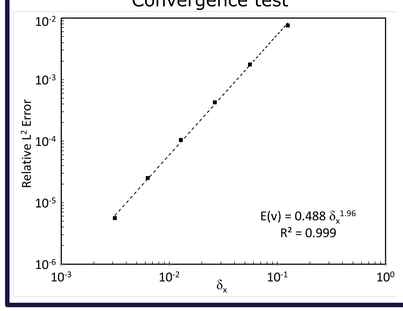




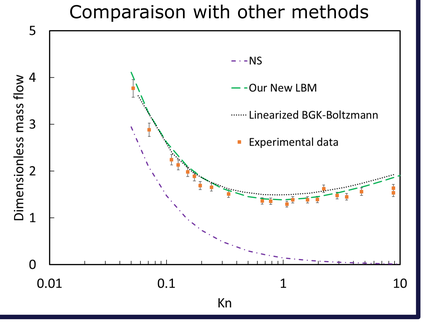
VERIFICATION AND VALIDATION

Simulation of rarefied gas flow through a duct

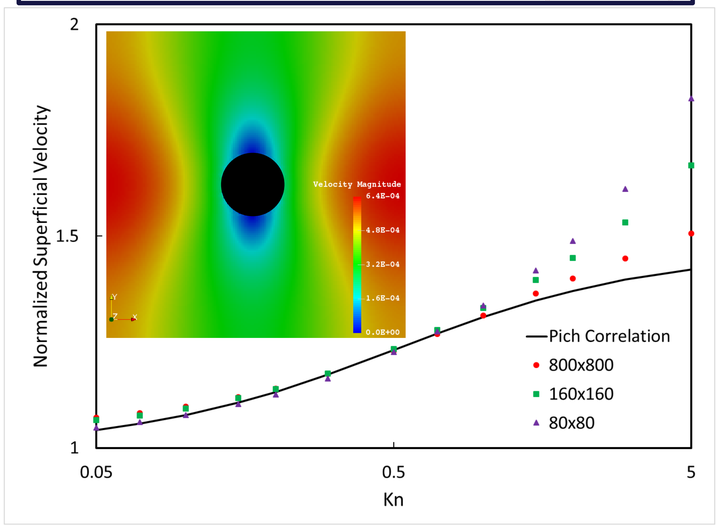
Convergence test



Comparaison with other methods



VERIFICATION AND VALIDATION (CONT'D)



CONCLUSIONS

- An intrinsic **second-order convergence** on planar flows has been established for the **new boundary condition**.
- **New relationships** for bounce-back ratios and relaxation times have been **verified** and **validated** for both planar and non-planar geometries.
- **Satisfactory results** were obtained up to **Kn = 10** for planar flows and up to **Kn = 2** for non-planar flows.

FUTURE WORK

- The new method will be **implemented** on a **three-dimensional Lattice-Boltzmann** code and the **ray-tracing method** will be ported on **GPU architectures**.
- The **new Lattice-Boltzmann method** will be applied to better understand the **impact of multilayering** in air filters made of **microfibers** and **nanofibers** layers.

NOMENCLATURE

Kn:	Knudsen number
λ:	Mean free path of the gas molecules
L_c:	Characteristic length of the system
P_{in}:	Inlet pressure
P_{out}:	Outlet pressure
P:	Thermodynamical pressure
μ:	Dynamic viscosity
R:	Ideal gas constant
T:	Temperature
f_i:	Population corresponding to velocity i
(BB):	Bounce-back boundary condition
(SR):	Specular reflection
(DR):	Diffusive reflection
x_f:	Location of a fluid node
x_s:	Location of a solid node
B:	Half-section of a duct
F:	Body force
δ_x:	Grid size
$E(v)$:	Relative L^2 error on the flow field
NS:	Navier-Stokes solution

ACKNOWLEDGMENTS

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