Fluid Flow Control Devices with Graded Permeability

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Introduction

Chemical engineering systems often rely on components made of porous media (*e.g.* catalyzed reactive flows, fluid purifiers, and chromatographic separations). It is often necessary to distribute the fluid from a relatively narrow tube to a broader cross section, to an array of tubes, or into a porous medium that can be modeled by Darcy's Law, where the volumetric flow rate is proportional to the permeability. As a test problem, we seek to achieve this in a minimal thickness while maintaining spatial uniformity in the steady-state outlet fluid velocity.

Hypothesis

Additive manufacturing (AM) techniques raise the possibilities that porous media can be fabricated in which the permeability can be arbitrarily specified in three dimensions. We hypothesize that varying permeability would allow us to achieve outlet flow uniformity over larger areas with thinner structures. By varying laser power and speed, and tuning particle size distribution, Mott Corporation has claimed the ability to spatially vary permeability using laser sintering AM methods [1]. We have produced porous metal using similar methods.

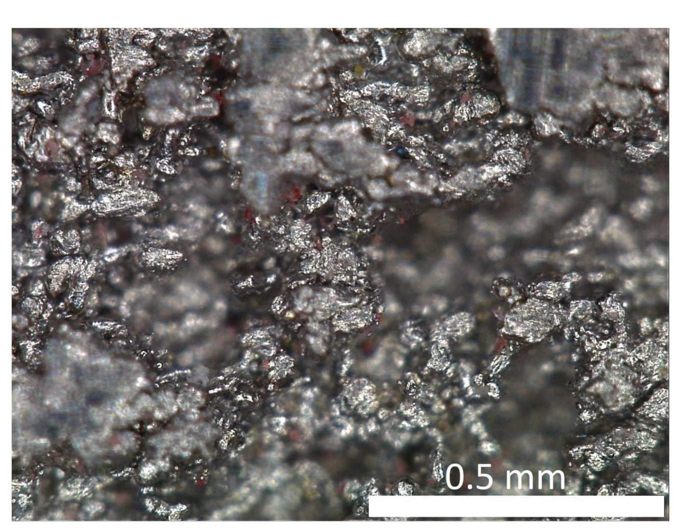

Figure 1: Porous stainless steel obtained by adjusting laser power and speed in a conventional laser AM instrument without using a specialized powder.

Flow in a Diffuser

We test our hypothesis on an open-ended diffuser (Figure 2). We consider two cases: an axisymmetric structure with permeability varying in the radial direction only and a 2D structure with a permeability varying in two directions. Both have an inlet Reynolds number of about 50, in the laminar flow regime.

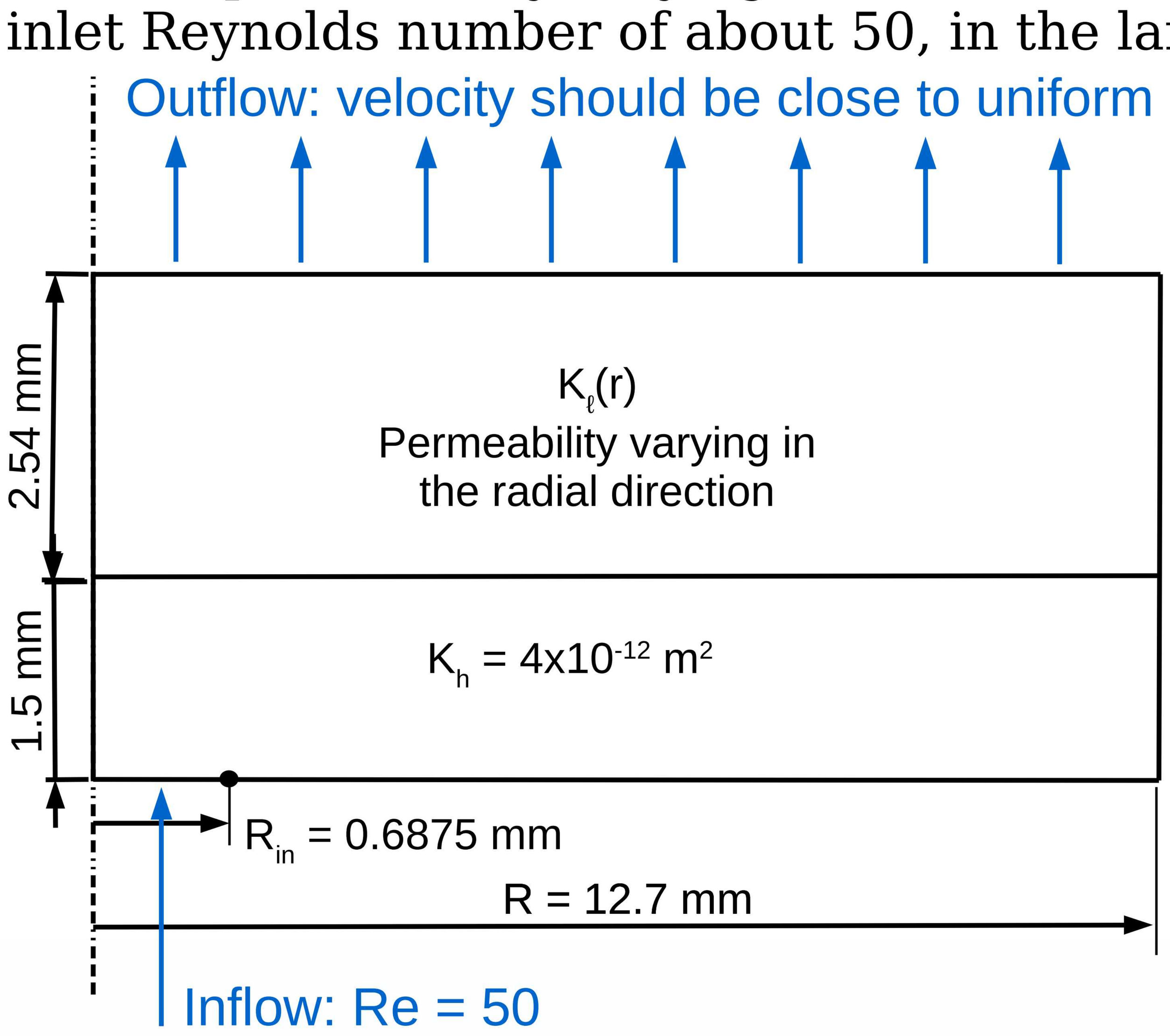

Figure 2: Schematic of an open-ended axi-symmetric diffuser geometry with two regions of high and low permeability. The low permeability varies linearly in the radial direction.

Radial Permeability Field

The diffuser consists of two regions with high and low permeabilities. We consider the low permeability changing along the diffuser radius. We compute the velocity fields at the outlet using a Darcy model in COMSOL 5.4 where hydrogen is the working fluid.

We find the optimal permeability $K_\ell(r)$ iteratively starting from a uniform K then updating it based on the resulting outlet velocity field V(r) following: $K_{\ell,i+1}(r) = V_{max}.K_{\ell,i}(r)/V_i(r)$

The velocity converges into a uniform profile in few iterations as shown in Figure 3.

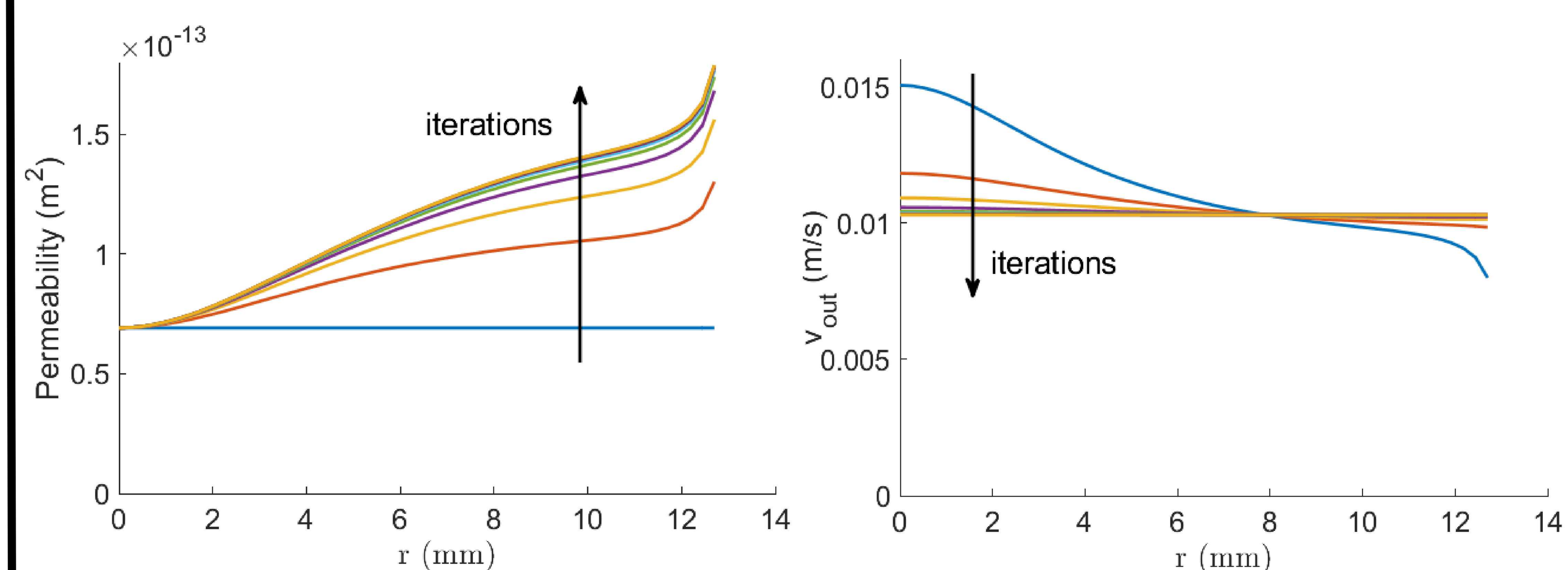

Figure 3: Plots showing the convergence of the permeability field $K_\ell(r)$ (left) after several iterations, resulting in the uniform output velocity V_{out} (right). Results are generated for R=12.7 mm.

Two-dimensional Permeability Field

In this case, we assume that the permeability K(x,y) varies in both x- and y- directions. The optimal K(x,y) shown in Figure 4 is computed using PDE constrained optimization through the Intrepid and ROL libraries of the Trilinos software series [2]. Permeability is introduced as a modification to the Navier-Stokes equations [3].

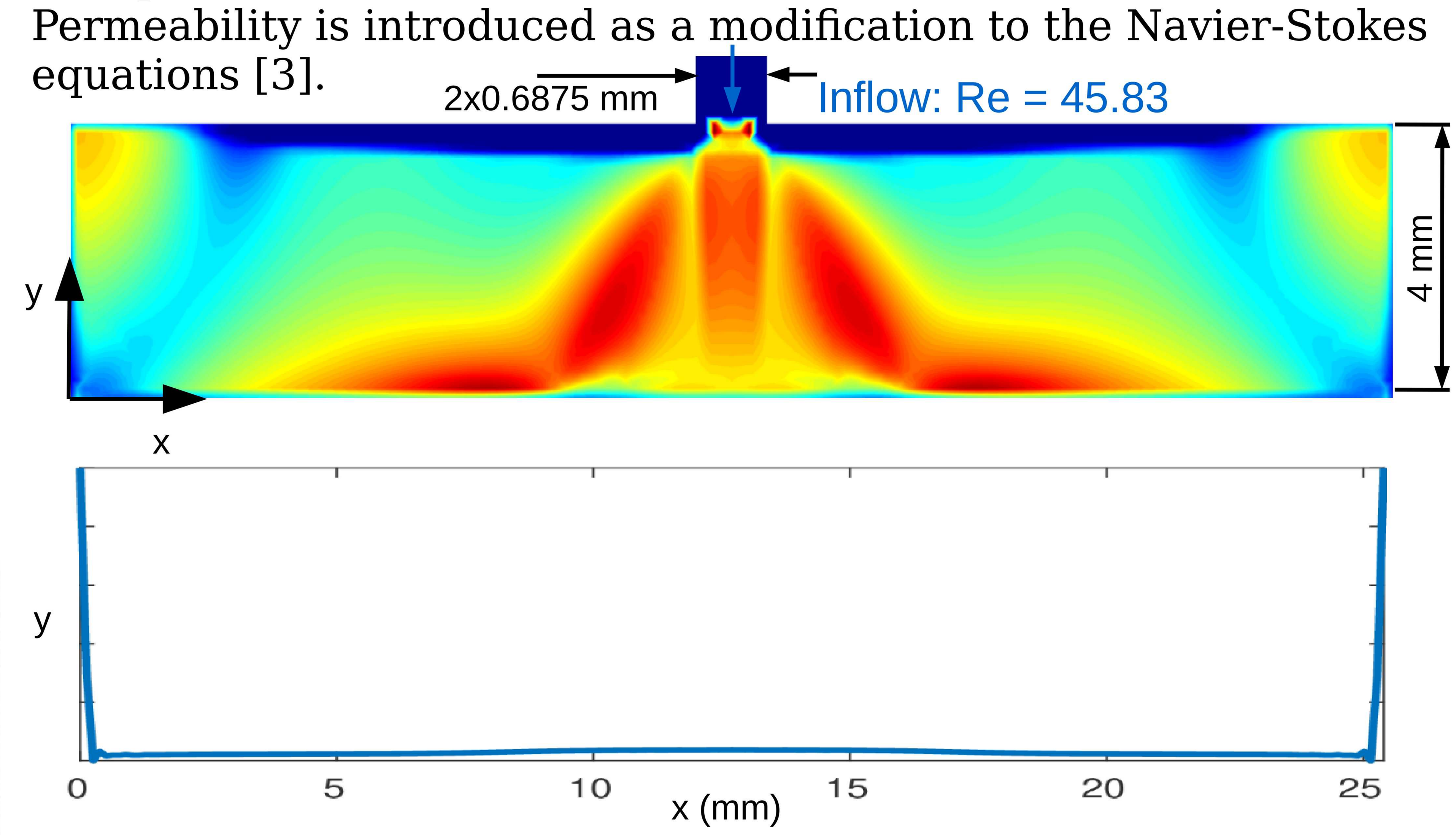

Figure 4: Plots showing the optimal permeability field K(x,y) (top), where blue indicates high and red indicates low permeability, and the resulting velocity profile (bottom) at the diffuser outlet.

Conclusion

We have established modeling and optimization methods that allow us to design devices that control fluid flow. Our results show that, for a given inlet and outlet geometry, spatial variation of permeability can result in uniform outlet flow profiles that could not be achieved in structures with spatially uniform permeability. These results motivate efforts to improve our ability to manufacture structures with varying permeability using additive manufacturing techniques.

References

[1] V.P. Palumbo et al. "Porous Devices Made by Laser Additive Manufacturing." US Patent Application 2017/0239726 A1, Mott Corporation, 2017.
[2] M. A. Heroux, R.A. Bartlett et al. "An overview of the Trilinos project" ACM Trans. Math. Softw. 31(3), 397-423, 2005.
[3] Thomas Borrvall and Joakim Petersson. "Topology Optimization of Fluids in Stokes Flow." Int. J. Numer. Meth. Fluids 41, 77–107, 2003.

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