

When Fluid Dynamics Meets Epidemics: A Navier–Stokes–Inspired SIR Flow on Networks

Zonghan Zhang,¹ Marouane Benbrahim,¹ Tamanna Rashme,¹ Lin Mu,² and Zhiqian Chen¹

1. Computer Science and Engineering, Mississippi State University, Mississippi State, MS, USA; 2. Mathematics, University of Georgia, Athens, GA, USA;

Fluid dynamics and epidemic spreading describe seemingly different phenomena, yet both govern how quantities move, accumulate, and dissipate over structured domains. In fluid systems, momentum, pressure, and viscosity determine how mass is transported through space; in epidemics, infection propagates through contact networks under heterogeneous transmission, recovery, and intervention effects. While fluid dynamics explicitly models transport through conservation laws and flow equations, epidemic spreading is often described using compartmental models such as SIR, which emphasize local reaction dynamics at nodes. As a result, transport-related effects in epidemics, such as directional propagation, spatial smoothing, and inertia in spreading dynamics, are typically treated implicitly rather than modeled directly.

Motivated by this analogy, we introduce a Navier-Stokes-inspired SIR (NS-SIR) formulation that recasts epidemic spreading as a physical flow evolving on a network. Building on the classical SIR framework, we define the *infection velocity* $u_i(t)$ as the rate of change of infection at node i and model its evolution using graph-based differential operators. As illustrated in **Fig. 1(Middle)**, the dynamics combine pressure-driven transport, viscous diffusion over network structure, external forcing that captures interventions or behavioral adaptation, and recovery-induced damping. Infection pressure is determined by a graph Poisson equation, which provides a closure condition that enforces conservation of epidemic flow across the network. Together, these components yield a network analogue of the Navier-Stokes equations while preserving epidemiological interpretability.

The NS–SIR formulation naturally supports **data-driven operator discovery**. By decomposing epidemic evolution into explicit graph operators, including gradient, diffusion, pressure-velocity coupling, and nonlinear reaction, the model aligns well with symbolic regression and neuro-symbolic learning approaches. These tools can recover dominant transport pathways, estimate latent advection fields, infer effective viscosity, or identify additional coupling terms from simulated or empirical time series. This perspective enables researchers to assess when classical SIR dynamics provide an adequate approximation and when transport-dominated behavior requires a more expressive physical formulation. Under the assumptions of network homogeneity and flow conservation, the NS-SIR model reduces smoothly to the classical SIR ODEs, demonstrating that the proposed model generalizes standard epidemiological dynamics while capturing spatial, structural, and dynamical heterogeneity.

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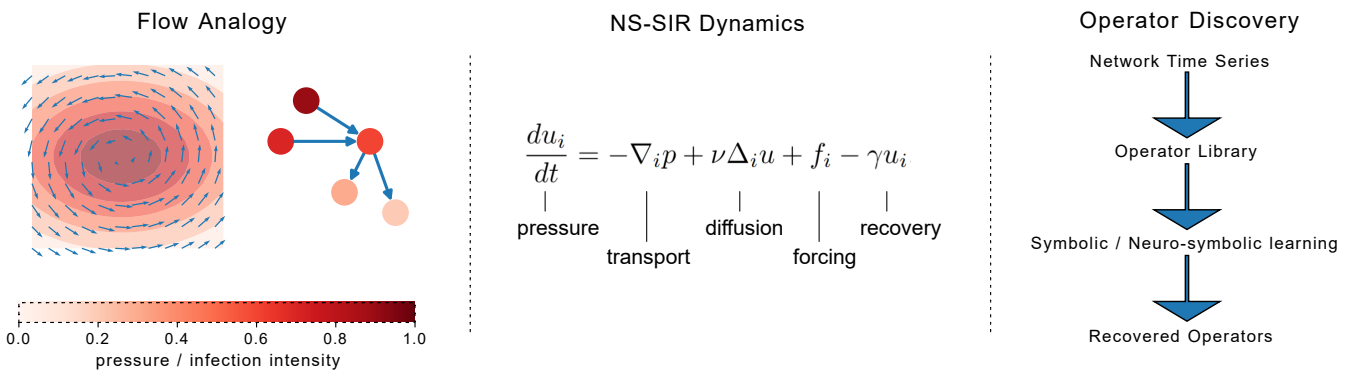


Figure 1: Overview of the NS-SIR framework: (Left) epidemic spreading viewed as a transport process analogous to fluid flow on networks; (Middle) Navier-Stokes-inspired SIR dynamics combining transport, diffusion, forcing, and recovery; (Right) explicit operator structure supporting data-driven discovery of epidemic transport mechanisms.