The Thermodynamics of Life:
The Role of Boundaries in Non-Equilibrium Evolution

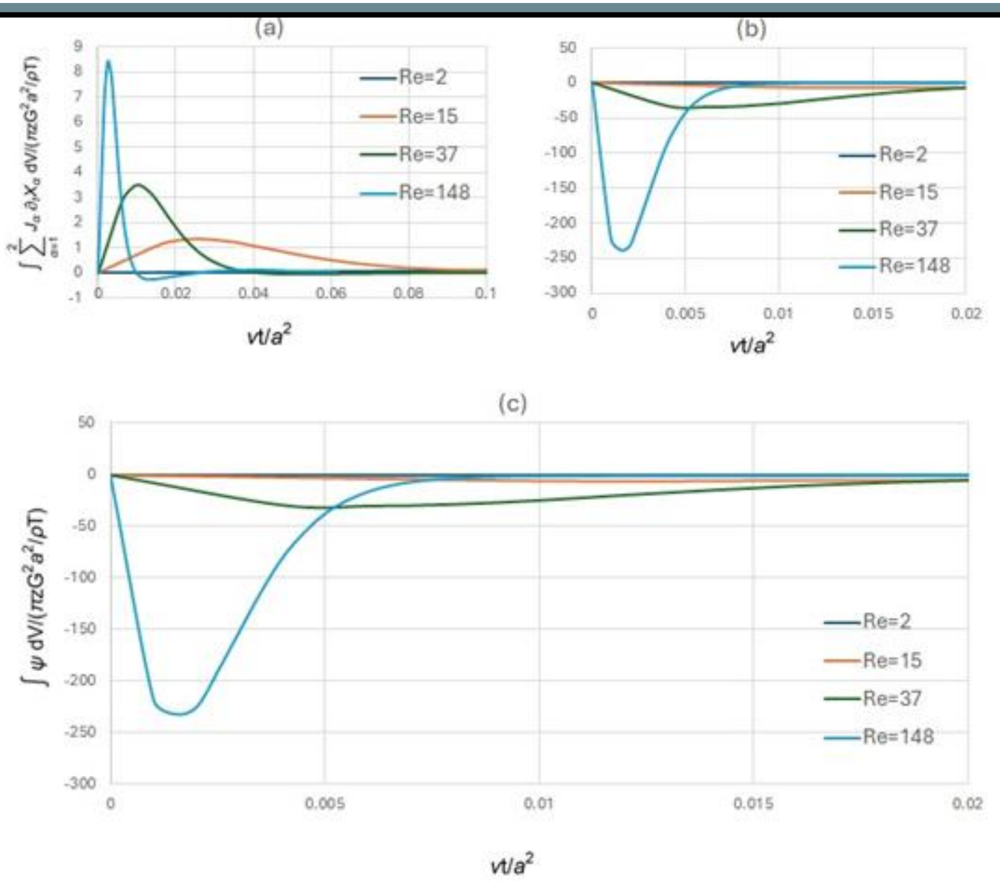

Fig. 1. Entropy production within a helical flow subjected to time-dependent boundary conditions for different Reynolds numbers (Re): (a) Positive contribution from the interior volume; (b) Negative contribution from the surface boundary; (c) Total negative contribution, including both the interior volume and the boundary.

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Non-equilibrium thermodynamics provides the framework to understand dissipative systems across physics, engineering, and biology. The classical **General Evolution Criterion (GEC)** by Glansdorff and Prigogine defines the evolution of thermodynamic forces under fixed boundary conditions, but it fails to address real systems where boundaries change in time.

In this work, we introduce an **Extended General Evolution Criterion (EGEC)** that explicitly accounts for **time-dependent boundaries**. The new inequality incorporates both **bulk** and **surface contributions**, showing that system evolution is governed not only by internal thermodynamic forces but also by boundary dynamics.

Beyond fluid dynamics, the EGEC has broader implications. In **biological systems**, where cells and tissues act as open thermodynamic structures, boundaries such as membranes or extracellular conditions play a decisive role. Our results indicate that **time-dependent boundary effects on entropy production and dissipation** may provide new insights into **self-organization, homeostasis, and the emergence of order in living systems**.

In summary, the EGEC underscores the **fundamental role of boundary conditions** in shaping dissipative processes and offers a more general framework for studying how systems evolve toward steady states across disciplines.

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