Improved Charge Amplification in Liquid-Metal Microfluidic Energy Harvester

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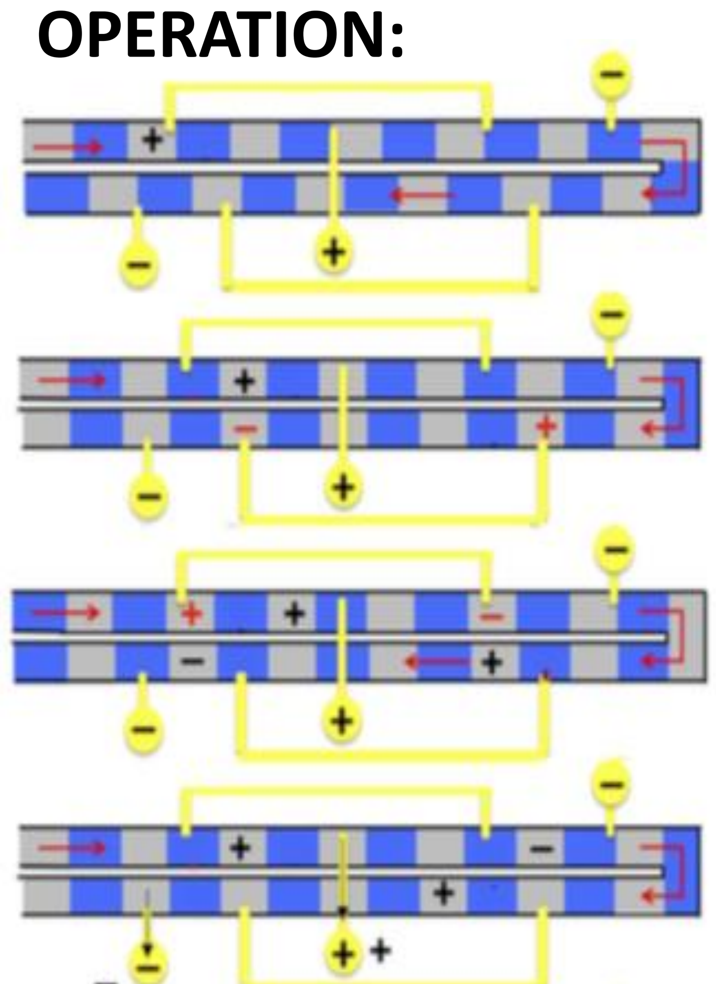
LIquid-Metal Microfluidic Portable Energy Transducer:

- Mechanical-to-electrical energy converter in a liquid-metal architecture.
- Theoretically possible exponential voltage growth if charge amplification factor, $\Gamma = q_f/q_i > 1$, where q_f is the induced charge and q_i is the charge on the inducing droplet.
- Analytical calculation of Γ feasible only for simplified geometries.
- COMSOL Multiphysics is used to numerically investigate key design parameters affecting Γ.

OPERATION:



1. Droplets of oil and mercury flow in serpentine channel.
2. Electrostatic induction causes charge separation on adjacent droplets via charge bridge.
3. Successive cycles amplify the charge per droplet.
4. Embedded electrodes collect and store excess charge.

Figure 1. Cyclic operation of LIMMPET

COMPUTATIONAL METHODS:

- Charge conservation from Electric Currents interface (AC/DC module) coupled to Laminar Two-Phase Flow (CFD module).
- Charge is injected into liquid-metal droplet domains using an 800 ns Current Source pulse.
- Phase field formulation defines interface between conducting and insulating mediums.

$$\frac{\partial\phi}{\partial t} + \mathbf{u}\cdot\nabla\phi = \nabla\cdot\frac{\gamma\lambda}{\epsilon_{\mathrm{pf}}^2}\nabla\psi, \qquad \phi = \text{phipf}$$

$$\psi = -\nabla\cdot\epsilon_{\mathrm{pf}}^2\nabla\phi + (\phi^2-1)\phi + \frac{\epsilon_{\mathrm{pf}}^2}{\lambda}\partial f/\partial\phi, \qquad \psi = \text{psi}$$

$$\lambda = \frac{3\epsilon_{\mathrm{pf}}^2\sigma}{\sqrt{8}}, \qquad \gamma = \chi\epsilon_{\mathrm{pf}}^2$$

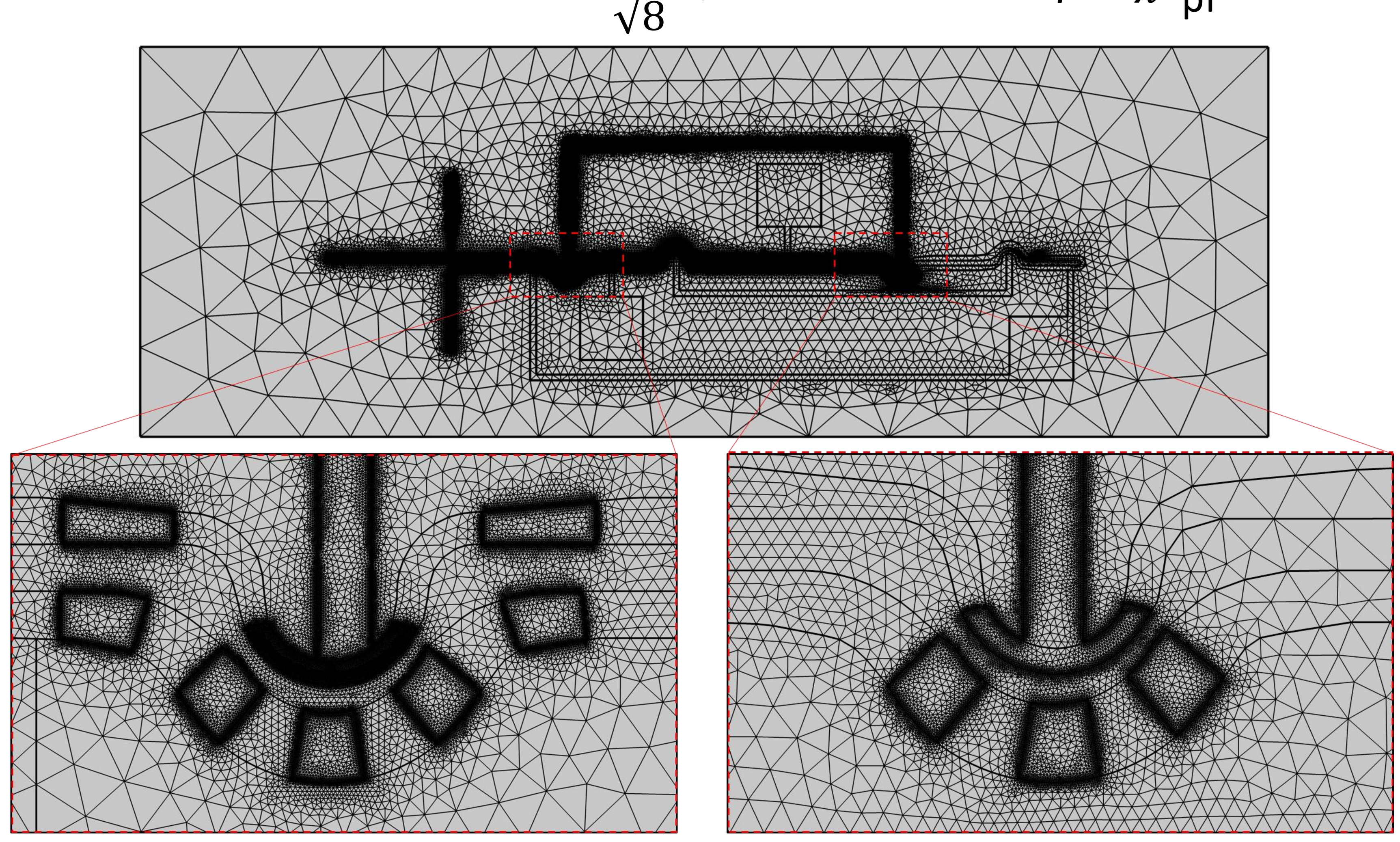


Figure 2. Image of numerical mesh containing approximately 260,000 elements used to resolve the phase field interfaces and subsequent charge accumulation.

RESULTS:

- A three-step, time-dependent study is used to solve the Phase Initialization, Phase Field, and Electric Currents interfaces.
- Several geometric configurations were tested in COMSOL Multiphysics to explore the effect of inter-channel spacing, curvature, and channel width ratio on Γ.
- Domains are drawn around each droplet to integrate the space charge density to determine $\Gamma = q_f/q_i$.
- It was found that channel width ratio and curvature play the most significant role in increasing Γ as high as 2.76 for the models tested.

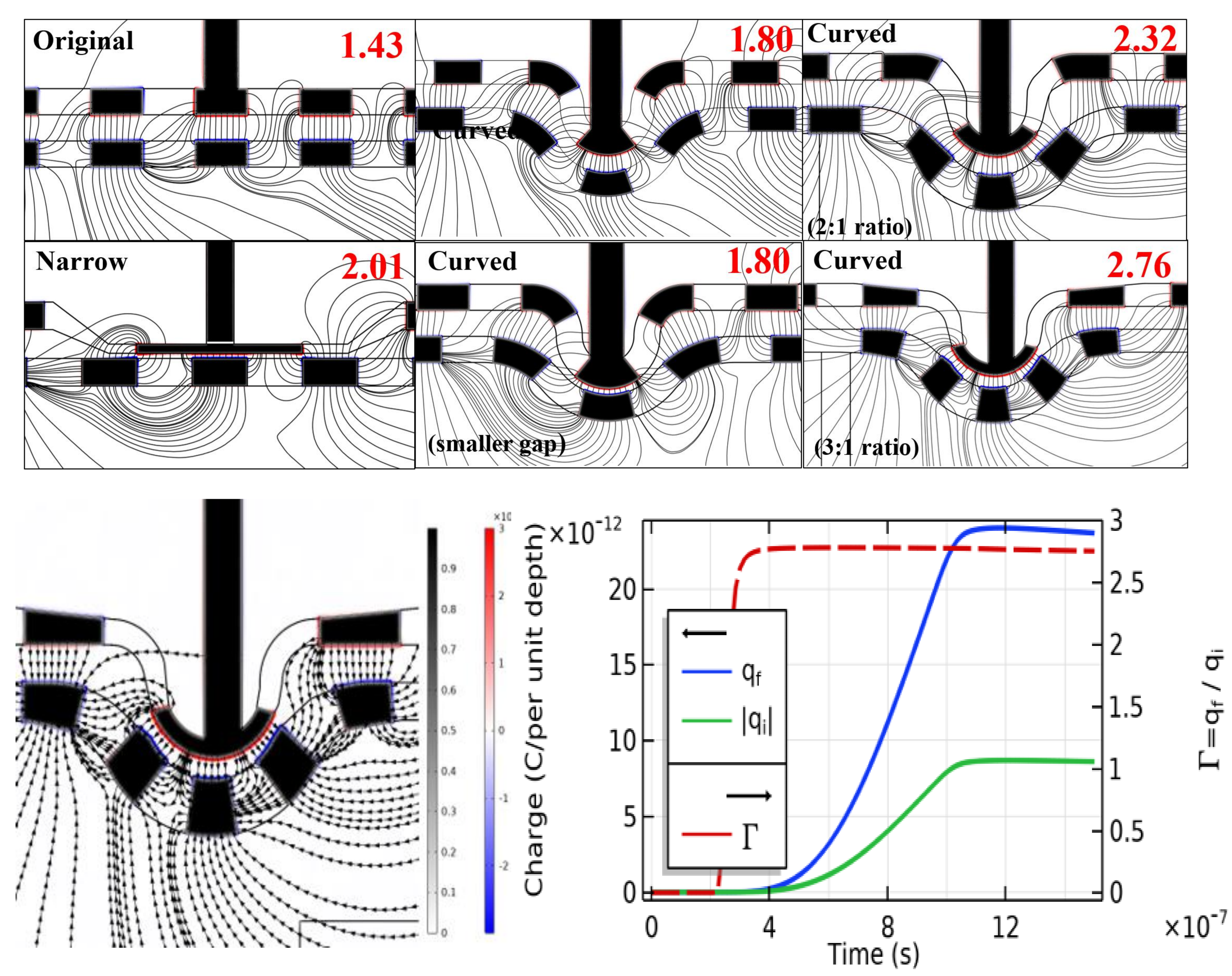


Figure 4. (Top) Six models were developed to investigate the effect of inter-channel spacing, curvature, and channel width ratio on the charge amplification factor, Γ (red). (Bottom Left) The field lines (black) and positive and negative space charge density (red and blue respectively) are shown for the Curved 3:1 geometry. (Bottom Right) The charge amplification factor Γ is plotted for the duration of the time-dependent study. The 800 ns Current Source pulse is turned on at 250 ns.

CONCLUSIONS:

- We introduce a 2D finite element model using COMSOL Multiphysics to numerically investigate and improve the charge amplification mechanism in the Liquid-Metal Microfluidic Portable Energy Transducer (LIMMPET).
- Several geometric configurations were modeled and it was determined the channel width ratio and curvature yield the greatest impact on Γ, giving a highest performing design of $\Gamma = 2.76$.

REFERENCES:

1. C. Conner, T. de Visser, J. Loessberg, S. Sherman, A. Smith, S. Ma, M. T. Napoli, S. Pennathur, D. Weld, Energy Harvesting with a Liquid-Metal Microfluidic Influence Machine, *Physical Review Applied*, **9**, 044008 (2018)