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Planar Bridging-Droplet Thermal Diodes

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14. ABSTRACT

We invented and characterized a one-way heat transfer device that we call a bridging-droplet thermal diode. While several types of thermal diodes already exist, they are all hampered by severe constraints that limit practical application. Solid-state thermal diodes are highly ineffective, while phase-change thermal diodes are effective but constrained by either a gravitational dependence, a one-dimensional configuration, or poor durability. Our bridging-droplet thermal diode was demonstrated to bypass all these shortcomings of existing thermal diodes. Two opposing copper plates were separated by an insulating gasket to form a vapor chamber; one plate contained a superhydrophilic wick structure while the other contained a smooth hydrophobic coating. The interior of the chamber was charged with water and the noncondensable gases were evacuated. In the forward mode of operation, water evaporates from the heated wicked plate and condenses on the hydrophobic plate. When dew drops grow large enough to touch the opposing wicked evaporator, they bridge across the gap to return to the wick, resulting in sustained phase-change heat transfer.

Conversely, in the reverse mode of operation, the heat source is on the side featuring the hydrophobic plate. This results in all water getting trapped in the opposing wick structure, causing dryout at the heat source to enable excellent insulation across the vapor space. An orientation-independent heat transfer ratio (i.e. diodicity) ranging from roughly 10-100 was demonstrated. To our knowledge, this is the first demonstration of a highly effective thermal diode that also satisfies all the following practical considerations: gravitational independence, inherently scalable planar configuration, and no requirement of a fragile superhydrophobic condenser.

The research was broken down into three core tasks. The first task was to fundamentally characterize the bridgingdroplet hydrodynamics of droplet transfer from a solid donor substrate into a porous receiving surface. We used sideview high-speed imaging to capture bridging-droplet transfer, varying the donor wettability, the porosity and pore size of the receiving surface, and the droplet's volume, surface tension, and viscosity. Video analysis revealed that droplet transfer is split into two major regimes: wetting and wicking. The wetting regime is split into two sub-regimes: a donor-independent regime that mimics the known dynamics of droplet coalescence, and a novel donor-dependent regime that is limited by the flow in the receding contact line's viscous wedge. The wicking regime is governed by Darcy's Law, which is substantively longer than the wetting time scale and completes the transfer of the droplet to the inside of the wick structure. The second task was to design, build, and characterize a prototypical bridging-droplet thermal diode. This culminated in the successful measurement of a diodicity ranging from 10-100, regardless of orientation, with the exact diodicity depending on the vapor temperature. The third task was to model and optimize the performance of the bridging-droplet thermal diode. A lumped resistance thermal model was developed that estimated the effective heat transfer coefficient in either the forward or reverse modes of operation. This model showed that further optimization of the diodicity is theoretically possible, for example by reducing the thickness of the wick structure and/or gap height, which we hope will guide the future development of commercial thermal diode technology.

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3rd Annual Report for FA9550-17-1-0500: Planar Bridging-Droplet Thermal Diodes

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Abstract (encompasses entire research project):

We invented and characterized a one-way heat transfer device that we call a bridging-droplet thermal diode. While several types of thermal diodes already exist, they are all hampered by severe constraints that limit practical application. Solid-state thermal diodes are highly ineffective, while phase-change thermal diodes are effective but constrained by either a gravitational dependence, a one-dimensional configuration, or poor durability. Our bridging-droplet thermal diode was demonstrated to bypass all these shortcomings of existing thermal diodes. Two opposing copper plates were separated by an insulating gasket to form a vapor chamber; one plate contained a superhydrophilic wick structure while the other contained a smooth hydrophobic coating. The interior of the chamber was charged with water and the non-condensable gases were evacuated. In the forward mode of operation, water evaporates from the heated wicked plate and condenses on the hydrophobic plate. When dew drops grow large enough to touch the opposing wicked evaporator, they bridge across the gap to return to the wick, resulting in sustained phase-change heat transfer. Conversely, in the reverse mode of operation, the heat source is on the side featuring the hydrophobic plate. This results in all water getting trapped in the opposing wick structure, causing dryout at the heat source to enable excellent insulation across the vapor space. An orientation-independent heat transfer ratio (i.e. diodicity) ranging from roughly 10-100 was demonstrated. To our knowledge, this is the first demonstration of a highly effective thermal diode that also satisfies all the following practical considerations: gravitational independence, inherently scalable planar configuration, and no requirement of a fragile superhydrophobic surface.

The research was broken down into three core tasks. The first task was to fundamentally characterize the bridging-droplet hydrodynamics of droplet transfer from a solid donor substrate into a porous receiving surface. We used side-view high-speed imaging to capture bridging-droplet transfer, varying the donor wettability, the porosity and pore size of the receiving surface, and the droplet's volume, surface tension, and viscosity. Video analysis revealed that droplet transfer is split into two major regimes: wetting and wicking. The wetting regime is split into two sub-regimes: a donor-independent regime that mimics the known dynamics of droplet coalescence, and a novel donor-dependent regime that is limited by the flow in the receding contact line's viscous wedge. The wicking regime is governed by Darcy's Law, which is substantively longer than the wetting time scale and completes the transfer of the droplet to the inside of the wick structure. The second task was to design, build, and characterize a prototypical bridging-droplet thermal diode. This culminated in the successful measurement of a diodicity ranging from 10-100, regardless of orientation, with the exact diodicity depending on the vapor temperature. The third task was to model and optimize the performance of the bridging-droplet thermal diode. A lumped resistance thermal model was developed that accounted for the effective heat transfer coefficient in either the forward or reverse modes of operation. This model showed that further optimization of the diodicity is theoretically possible, for example by reducing the thickness of the wick structure and/or gap height, which we hope will guide the future development of commercial thermal diode technology.

Year 3 Summary:

In the third and final year of the research period (1.5 years including the no-cost extension), we made substantive progress on all three core tasks to complete the overall objective of experimentally and theoretically characterizing our bridging-droplet thermal diode invention. These year-specific developments will now be summarized in order of the associated task. As described in the Qualtrics survey, our three tasks did evolve over the course of the research and we will refer here to the final definition of the three core tasks.

Task 1: Characterize the bridging-droplet hydrodynamics.

The bridging hydrodynamics were fairly well fleshed out for the first annual AFOSR report. In particular, we had successfully identified the two core regimes of wetting followed by wicking. However, the wetting regime was itself composed of two sub-regimes, with the initial donor-independent regime being understood to follow classic capillary-inertial or capillary-viscous scaling laws but the subsequent donor-dependent regime being a mystery.

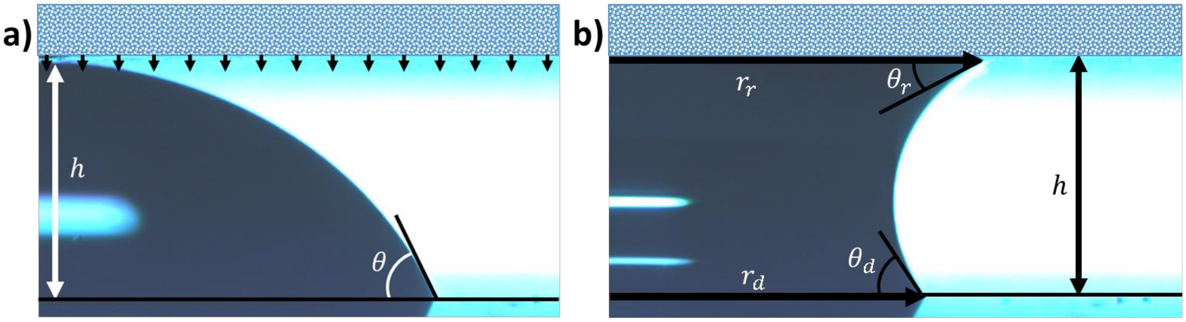

Figure 1: Side-view images of visualizing bridging-droplet transfer dynamics.

Over the final 1.5 years of research, we have matured this model considerably to come to a full understanding of this novel donor-dependent transfer regime that seems to be unique to our bridging-droplet system. The basic schematic of our bridging-droplet study is shown in Figure 1, where image analysis extracts the contact radii and contact angles of the bridge as it transfers from the donor substrate (bottom) to the receiving porous surface (top). This past year, we developed an image analysis program to extract the temporal evolution of the donor and receiving radii. This is shown in Figure 2 below across a wide variety of experimental conditions, where the wettability of the donor substrate is varied in Figure 2a, the working fluid for the droplet is varied in Figure 2b, and the droplet volume and pore radius of the receiving surface are varied in Figure 2c. At the very earliest time scales (~0.001 s), the droplet transfer is governed by the classic capillary-inertial and capillary-viscous scaling laws, depending on the viscosity of the working fluid (see 1st annual report). However, most of the early-time transfer (by ~0.01 s) is governed by a donor-dependent regime, where the donor contact area has to recede in order for the transfer process to continue further. This is the focus of our novel modeling efforts for this final 1.5 years of performance.

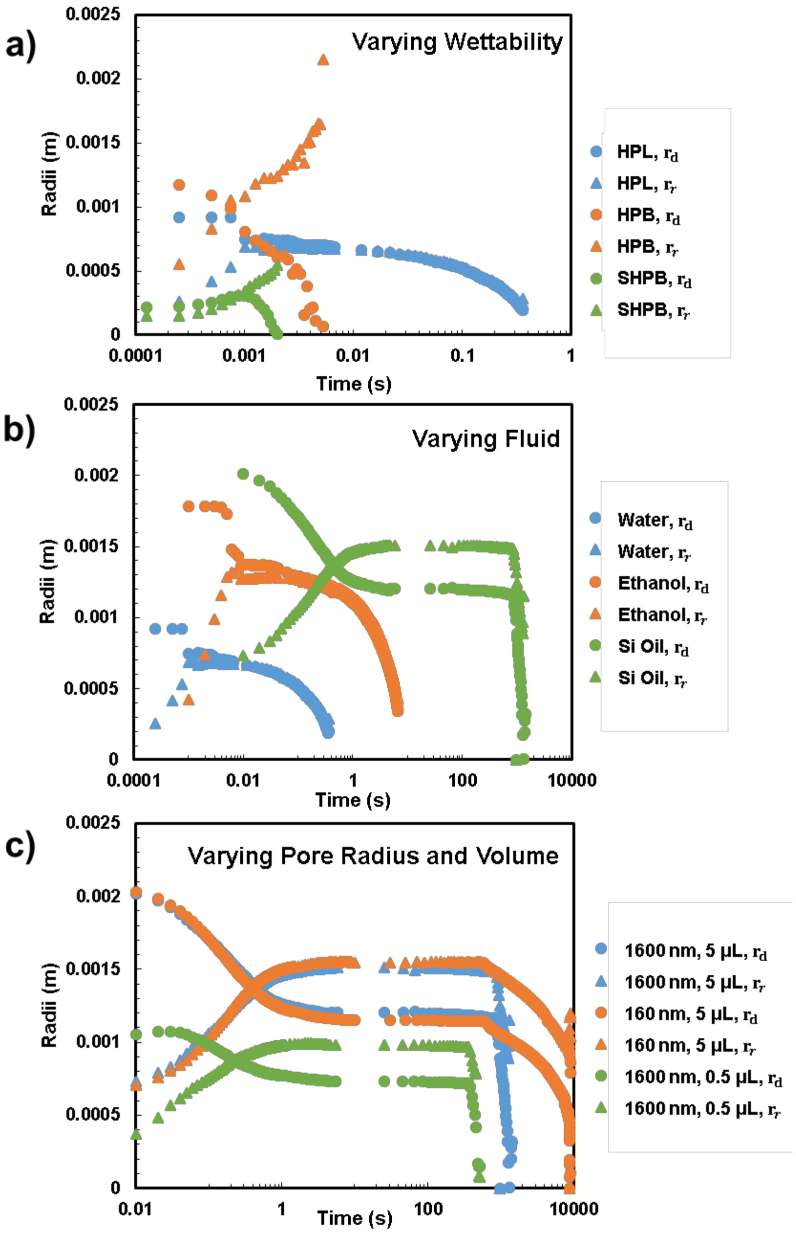

Figure 2: Analyzed data for temporal evolution of donor and receiving bridge radii.

There is nothing in the literature regarding this donor-dependent droplet transfer regime, so we developed a working model from scratch. A visual summary of our model is shown in Figure 3 below. The left-hand side of Figure 3 depicts the mismatch in the radii of curvature, when comparing the top of the bridge to the bottom of the bridge. This results in a mismatch in the corresponding Laplace pressures, resulting in the driving force for the bridging to continue. The resisting force was more difficult, as it could not be modeled in terms of any sort of viscous or inertial resistance of the liquid bridge taken as a whole. Rather, we eventually realized that the resistance is locally dominated by the receding contact line as it shrinks on the donor surface over time. A viscous wedge model was therefore used, where the effective height of the receding wedge is a semi-empirical fitting factor that is chosen to match the equation to the raw experimental data.

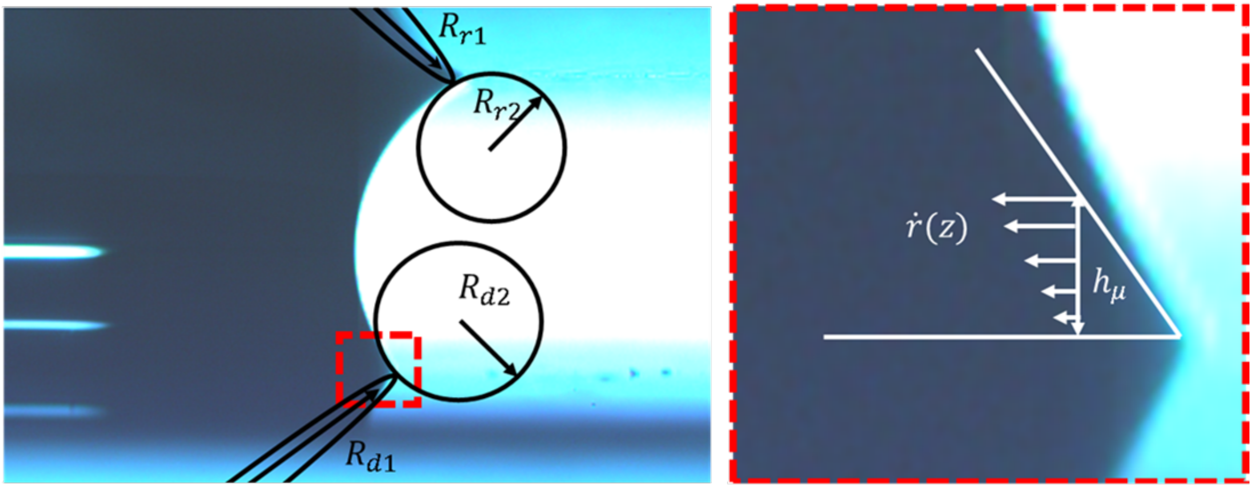

Figure 3: Visual overview of: (left) the mismatch in Laplace pressure across the bridge that drives the transfer process, and (right) the receding viscous wedge at the donor surface that is the rate-limiting process for droplet bridging during the wetting regime.

Analytically, the donor-dependent regime is expressed as:

$$P_d - P_r = \frac{\mu \dot{r}_d}{h_\mu}$$

where the donor and receding Laplace pressures on the left-hand side are calculated by image analysis of the radii of curvature at the bottom and top of the bridge, respectively. The change in Laplace pressure across the bridge tended to scale as ~100 Pa. On the right-hand side of the equation, the time-rate change of the donor radius is solved and compared to the experimental measurements. This is shown in Figure 4, where it can be seen that there is excellent agreement between our model and experimental data for this novel donor-dependent transfer regime. With the subsequent wicking regime already well understood (see 1st year's report), this concludes our fundamental understanding of the bridging-droplet hydrodynamics.

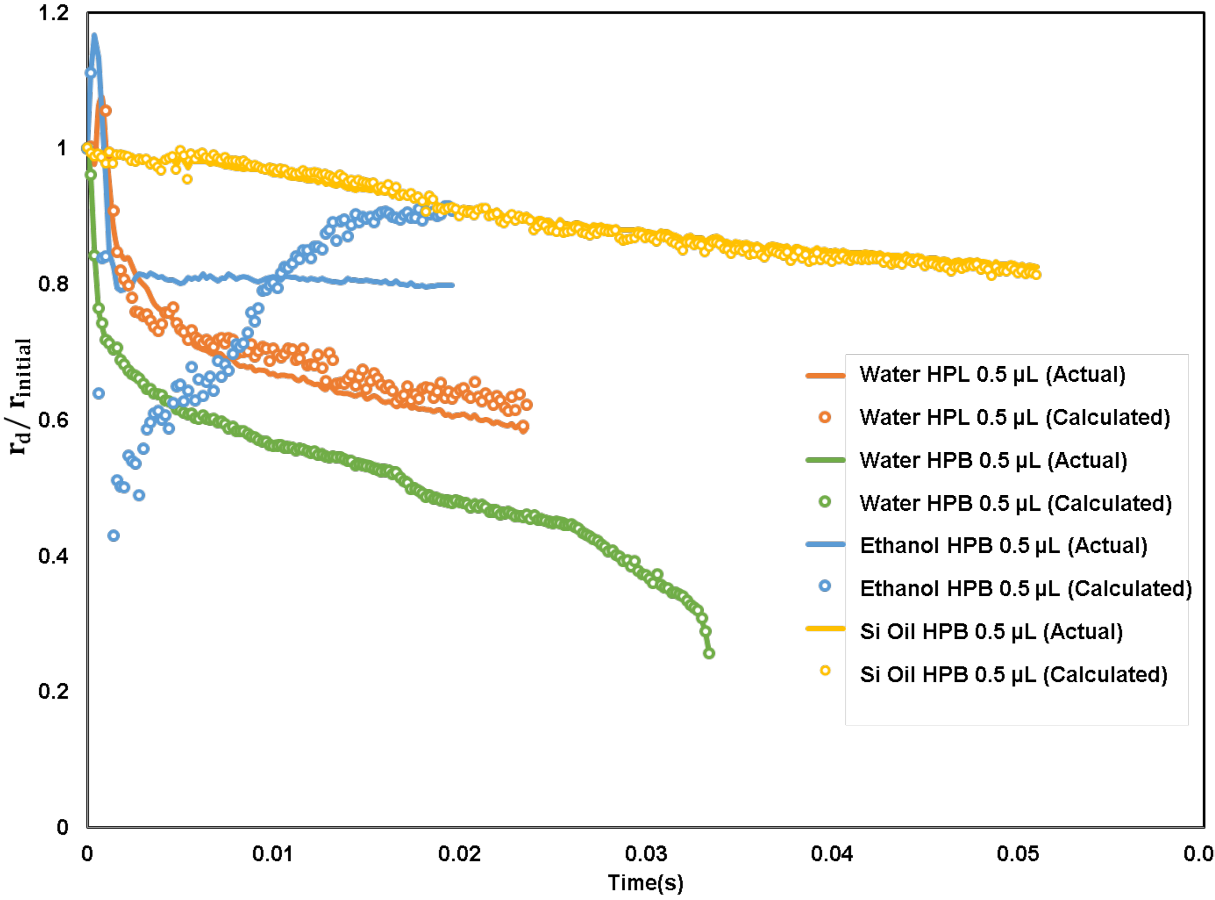

Figure 4: Graph comparing the experimental evolution of the donor radius (data series with circles) with the value calculated by our model (solid trend lines) for the donor-dependent regime of bridging-droplet transfer.

Task 2: Fabrication and proof-of-concept of the bridging-droplet thermal diode.

This task of developing and testing a prototype was the primary focal point for the 2nd year of the research, see the corresponding report for more information. In the beginning of this final 1.5 years of performance, we successfully published a paper titled "Bridging-Droplet Thermal Diodes" in the premium journal *Advanced Functional Materials* (Impact Factor = 16.8). This paper was featured in *Virginia Tech News* and received media attention from various outlets such as *Physics World* and *Electronic Design*. Rather than repeat the details of the paper here, we are attaching the paper in its entirely as an Appendix Document. We also note that this paper and its media coverage got the attention of industry, for example we are currently in the early stage of collaborating with Northrop Grumman to perform follow-on R&D for our bridging-droplet thermal diode technology.

Task 3: System modeling and optimization.

The original idea for the final task of the proposed research was to graft an ultra-thin but durable hydrophobic polymer coating to the condenser. (The monolayer hydrophobic coating used for our prototype was fine for lab characterization but would not be durable for many months or years, making it unsuitable for commercial use.) However, we realized that an even better approach to making the thermal diode durable is to not use any coating at all, but rather simply condense on the bare copper surface. While this would decrease the contact angle of the droplets, this could be compensated for by simply reducing the gap height of the chamber. In this final 1.5 years of research, we therefore redefined Task 3 with a focus on optimizing and modeling the bridging-droplet thermal diode device, particularly by tuning the wick height, gap height, and droplet contact angle of the condenser. In addition to the theoretical analysis, this new work also did additional experiments on our thermal diode prototype to vary the applied heat flux, which was fixed in the original paper tied to Task 2. An early draft of a journal article on this topic of modeling and optimization is attached in its entirety as an Appendix Document. We are going to submit this manuscript shortly to the *International Journal of Heat and Mass Transfer*. The key takeaways from this paper are that the forward mode heat transfer, and by extension the diodicity, can be improved by doing any of the following:

- Increasing the applied heat flux
- Decreasing the gap height between the wick and condenser
- Decreasing the height and/or pitch of the wick micropillars
- Increasing the diameter of the wick micropillars
- Decreasing the contact angle of the dew droplets on the condenser

Future Work:

Moving beyond the official period of performance with AFOSR, we have two primary goals. The first is to submit and publish the papers corresponding to Task 1 (bridging hydrodynamics) and Task 3 (diode optimization and modeling) in peer-reviewed journals. The targets are the *Journal of Fluid Mechanics* for the Task 1 paper and the *International Journal of Heat and Mass Transfer* for the Task 3 paper. The second goal is to officially begin a collaboration with Northrop Grumman for follow-on R&D on the bridging-droplet thermal diode, with an eye toward commercial implementation.

Acknowledgements:

We wish to acknowledge the generous support and helpful feedback of program director Dr. Byung (Les) Lee. Over the past 3.5 years, we have experienced unexpected setbacks, in particular graduate student Kevin Murphy was on medical leave for 1.5 years due to a sudden auto-immune disorder, requiring the training of entirely new grad students to continue the project. Additionally, COVID-19 resulted in a lab shutdown for much of the final year of the research, requiring a modification of the research tasks and a no-cost extension. Yet throughout these trials, Dr. Lee has always given his helpful guidance and flexible support to the project, which has resulted in the very successful development of the bridging-droplet thermal diode, as evidenced by publication in the prestigious journal *Advanced Functional Materials*, a full patent application, and a likely follow-on partnership with Northrop Grumman. We are therefore indebted to Dr. Lee's patient support of our AFOSR YIP research.