Capillary-driven Condensation for Heat Transfer Enhancement in Steam Power Plants

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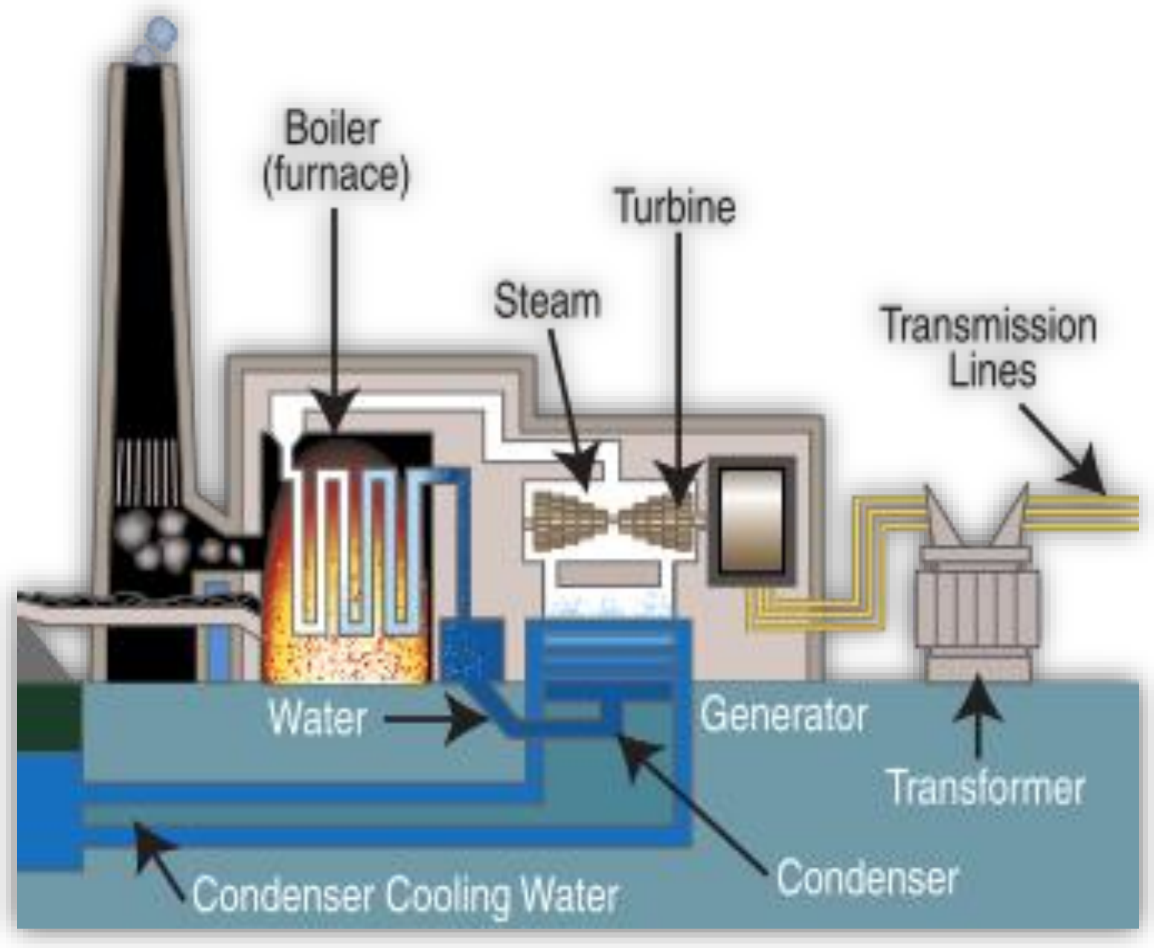
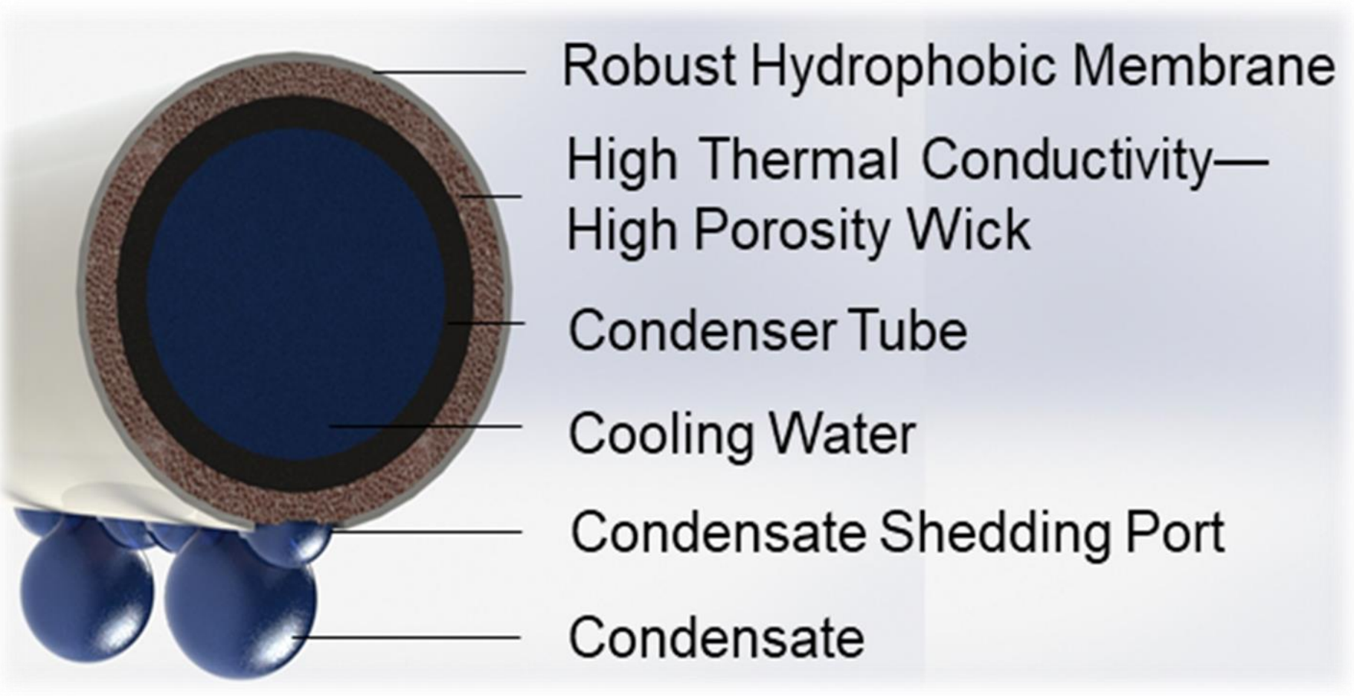
INTRO/NEED



- Steam cycles produce 90% of electrical power in the U.S.[1]
- Power plants are responsible for the largest amount of water withdrawn from U.S. water bodies[2]
- Conventional condenser surfaces form thick liquid films, hindering heat transfer
- Condenser efficiency ↑, power production ↑, water consumption ↓

APPROACH

- Capillary-enhanced condensation in high thermal conductivity wicking structures



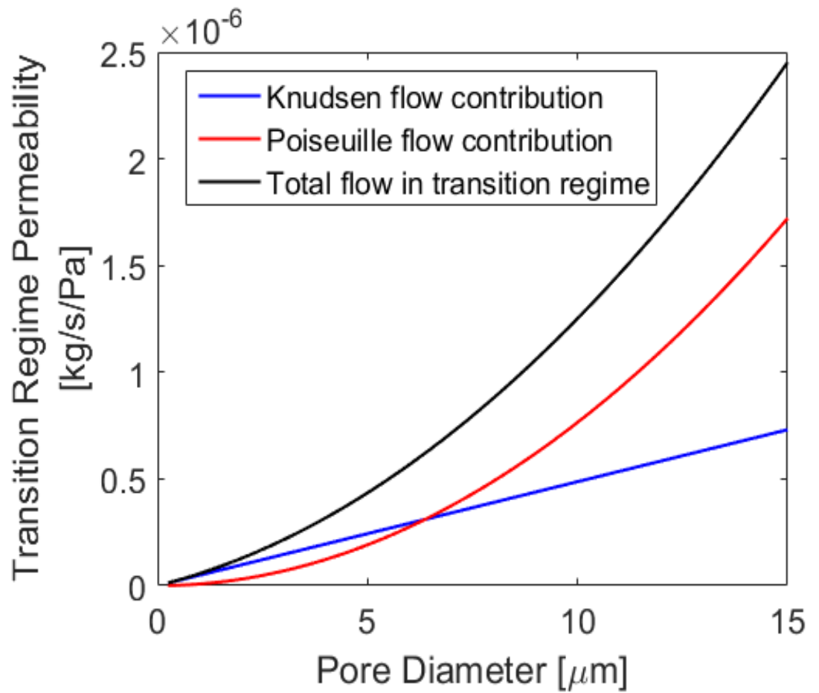
- Steam condenses inside the wick
- Wick confines liquid film
- Membrane helps generate capillary pressure $P_{cap} \sim \frac{2\sigma}{r_p}$
- Capillary pressure drives the condensate flow out of the wick

DESIGN CONSIDERATIONS

- Hydrophobic membrane: hydrophobicity (contact angle), pore size, thickness, durability

Effective permeability: $\bar{K} = \frac{M A_{\text{total}} \phi}{R T t_{\text{membrane}}} \left(\frac{1}{3} d_{\text{p}} \left(\frac{8RT}{\pi M} \right)^{\frac{1}{2}} + \bar{P} \frac{d_{\text{p}}^2}{32 \mu_{\text{v}}} \right)$

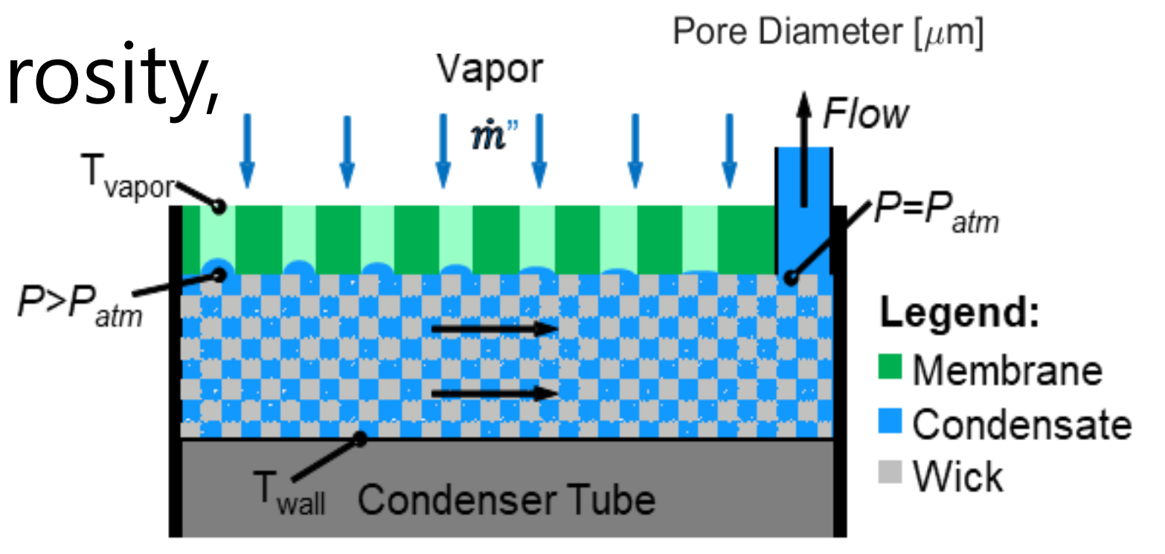
Mass flow rate through pores: $\dot{m} = \bar{K} \Delta P$



- Hydrophilic wick: thermal conductivity, porosity, permeability, thickness

Flooding criterion: $P_L - P_{atm} = \Delta P = \frac{\dot{m}'' L^2 \mu}{2 \rho \kappa_{\text{wick}} t_{\text{wick}}}$

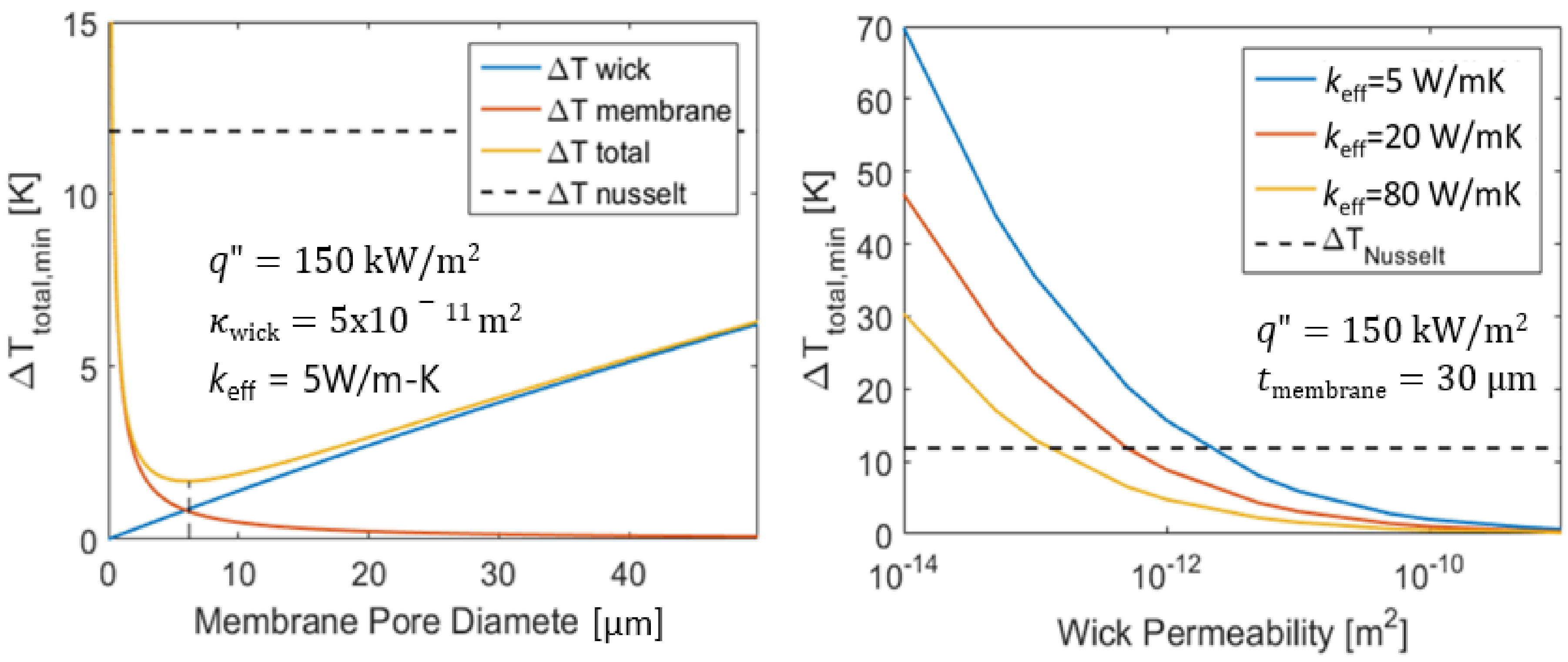
Heat transfer through wicks: $q'' = \frac{k_{\text{eff}}}{t_{\text{wick}}} \Delta T_{\text{wick}}$



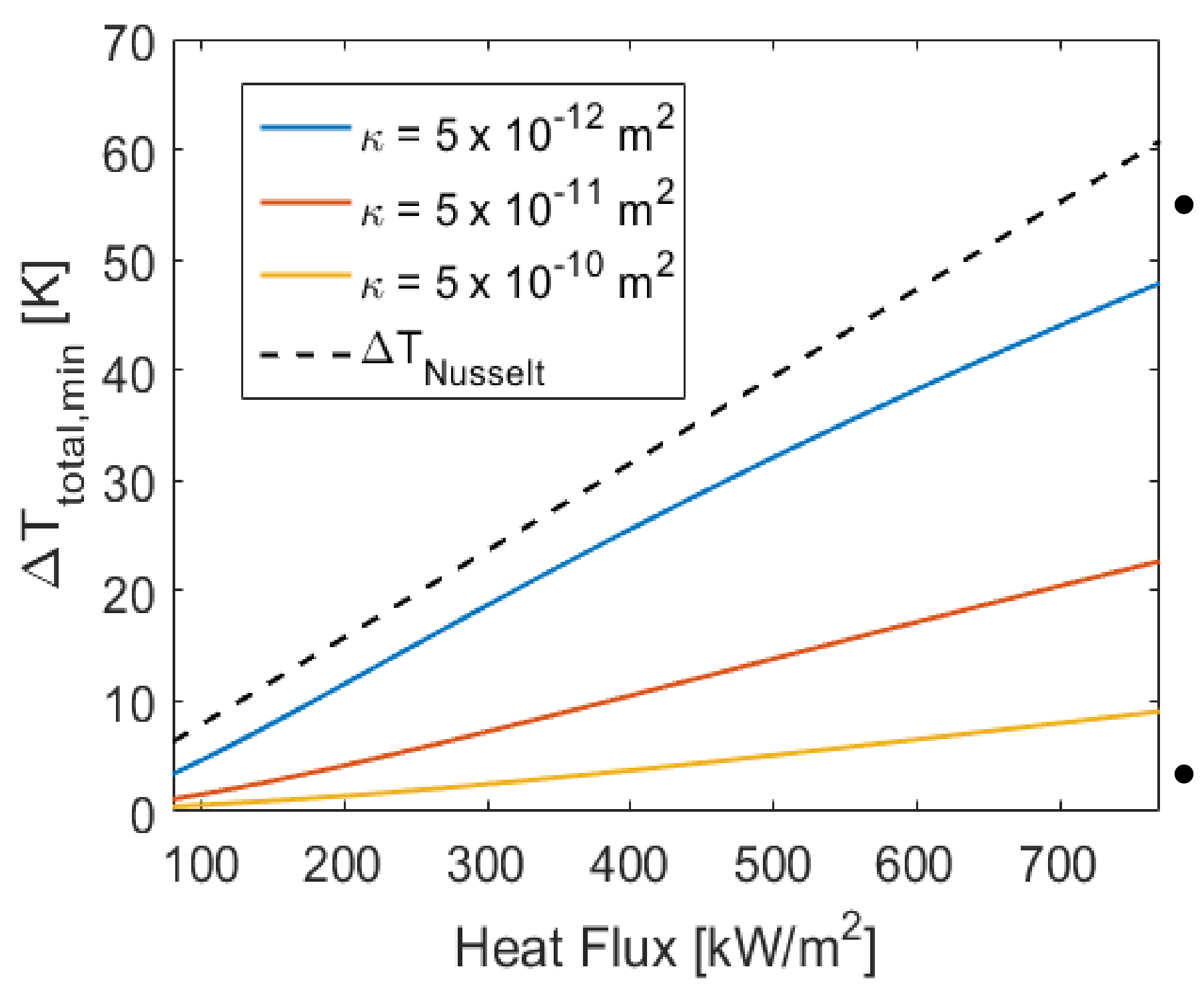
MATERIALS SEARCH RESULTS

	Commercial Production	Lab-scale Fabrication
Hydrophobic Membrane	PTFE/PP/PVDF membranes: contact angle > 90°, pore size 10^{-1} -10 μm, thickness 10-10^2 μm, widely used in membrane distillation industry.	electrospun nanofiber membranes, nanoparticle-incorporated membranes, multi-layer composite membranes, etc.: well-controlled pore size and pore size distribution.
Hydrophilic Wick	nickel/copper/stainless steel sintered powder wicks/metal foams: thickness ≥10μm, permeability ≤ 10^{-9} m^2, widely used in heat pipe industry.	microgroove wick structures, micro/nanostructured copper foams, composite wick structures, etc.: well-controlled geometry, κ_{wick} ↑, k_{eff} ↑.

MODELING RESULTS



Parametric sweeps of the total temperature drop across the wick and membrane as a function of membrane pore diameter and of wick permeability at a constant heat flux 150 kW/m^2.



Parametric sweeps of the total temperature drop across the wick and versus heat flux for three permeability values of the porous structured wick.

BENEFITS AND FUTURE WORK

- $r_p = r_{p,\text{ optimal}}$, κ_{wick} ↑, k_{eff} ↑, $\Delta T_{\text{total, min}}$ ↓, HTC ↑.
- Economic evaluation of the currently designed condenser versus a plain condenser for a typical 950 MW nuclear fired power plant[3] shows increased power output of 13.80 MW, which corresponds to a capital value of $27.6 million dollars.
- Future work entails:
  - Refine model to guide surface design to achieve optimal heat transfer
  - Characterize and fabricate condenser surfaces (hydrophilic wicks + hydrophobic membranes)
  - Experimental demonstration of heat transfer enhancement both in lab and in industrial conditions.

ACKNOWLEDGEMENTS

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REFERENCES

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