Gas Microfluidics using MEMS Micro-pumps

By

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What is Gas Microfluidics and Thermal Transpiration?

- **Gas Microfluidics:**
  - The study of how gases behave under sub-millimeter environments
  - Ex. Air flowing through a 15nm porous membrane
- **Thermal Transpiration:**
  - Mass flow of gas in the free molecular flow regime with a temperature gradient
  - Knudsen pump based on thermal transpiration

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Thermal Transpiration (cont.)

- Temperature gradient produces a pressure gradient
  - Gas moves cold to hot

- **Free molecular flow:** channel diameter must be at least 10x smaller than the gas's **mean free path** at the ambient pressure
  - $d < \frac{\lambda}{10}$; d = diameter, λ = mean free path
    - λ = 60 nm at 1 atm for air
  - $Kn = \frac{\lambda}{2a}$; a = microfluidic channel's inner radius
    - $\mathrm{Kn} \geq 10$
  - Needed for a Knudsen pump to function

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Thermal Transpiration (cont.)

- $$\dot{M} = \frac{aA\varepsilon P_{av}}{L}\sqrt{\frac{m}{2k_b T_{av}}}\left[\frac{\Delta T}{T_{av}}M_t - \frac{\Delta P}{P_{av}}M_p\right]$$

- Sharipov’s equation describes mass flow of gas through a channel in a Knudsen pump
- Lack of understanding how thermal transpiration affects MEMS devices
  - Want to investigate its effects on random-path and straight-path membranes

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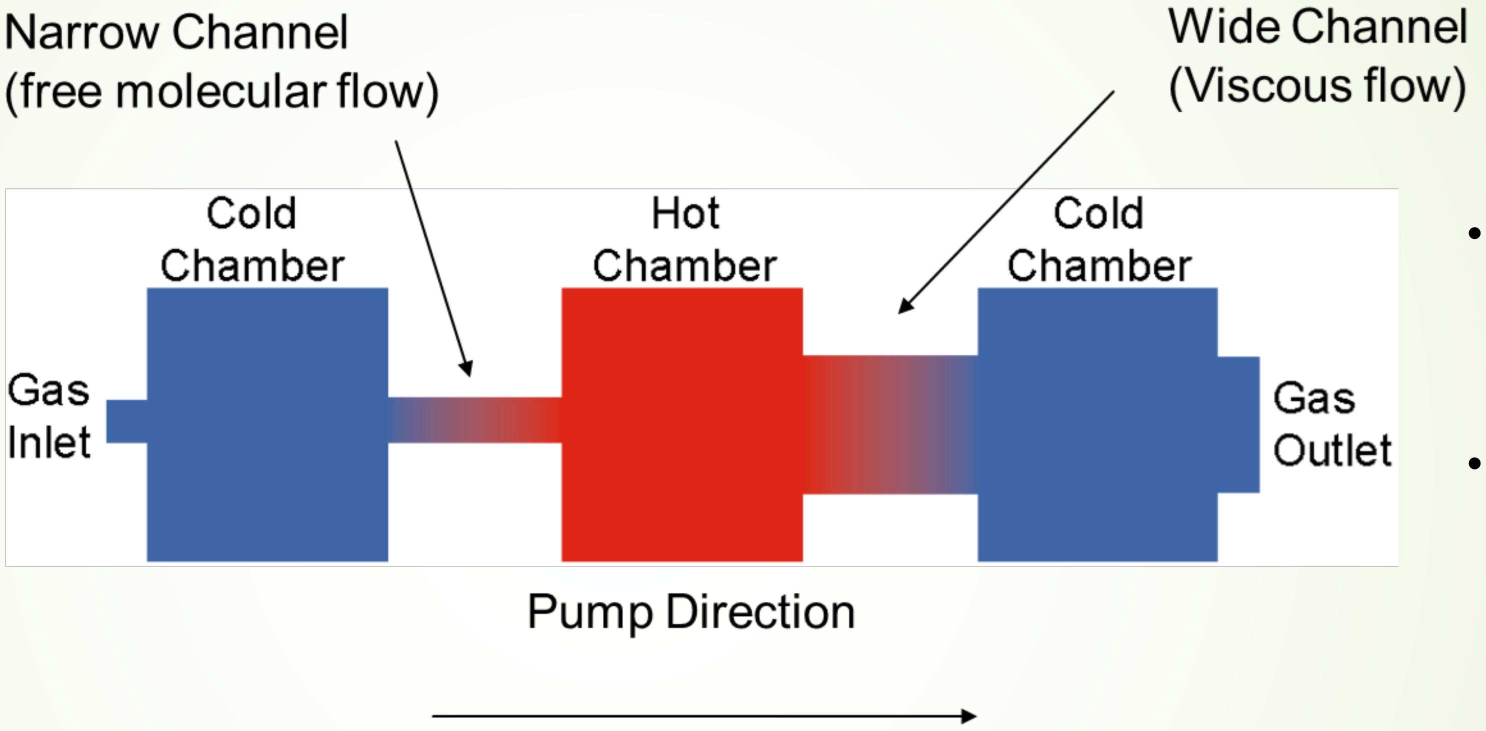
- Why use a Knudsen pump?
    - Gives a very large pressure change, indicating effective pumping



- Viscous flow prevents a back flow of gas
- Kn pump does not work on liquids!

How a Knudsen Pump works

S. McNamara, *Thermally Driven Gas Micropumps*, University of Louisville, KY (2017)

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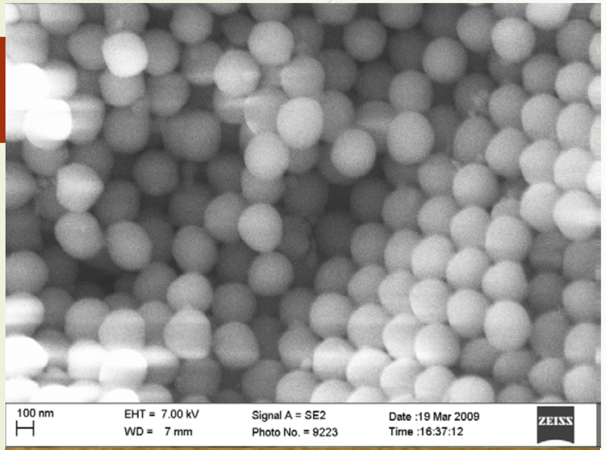
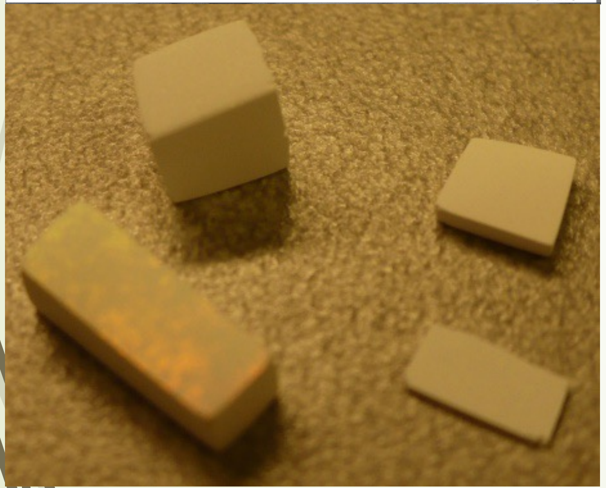
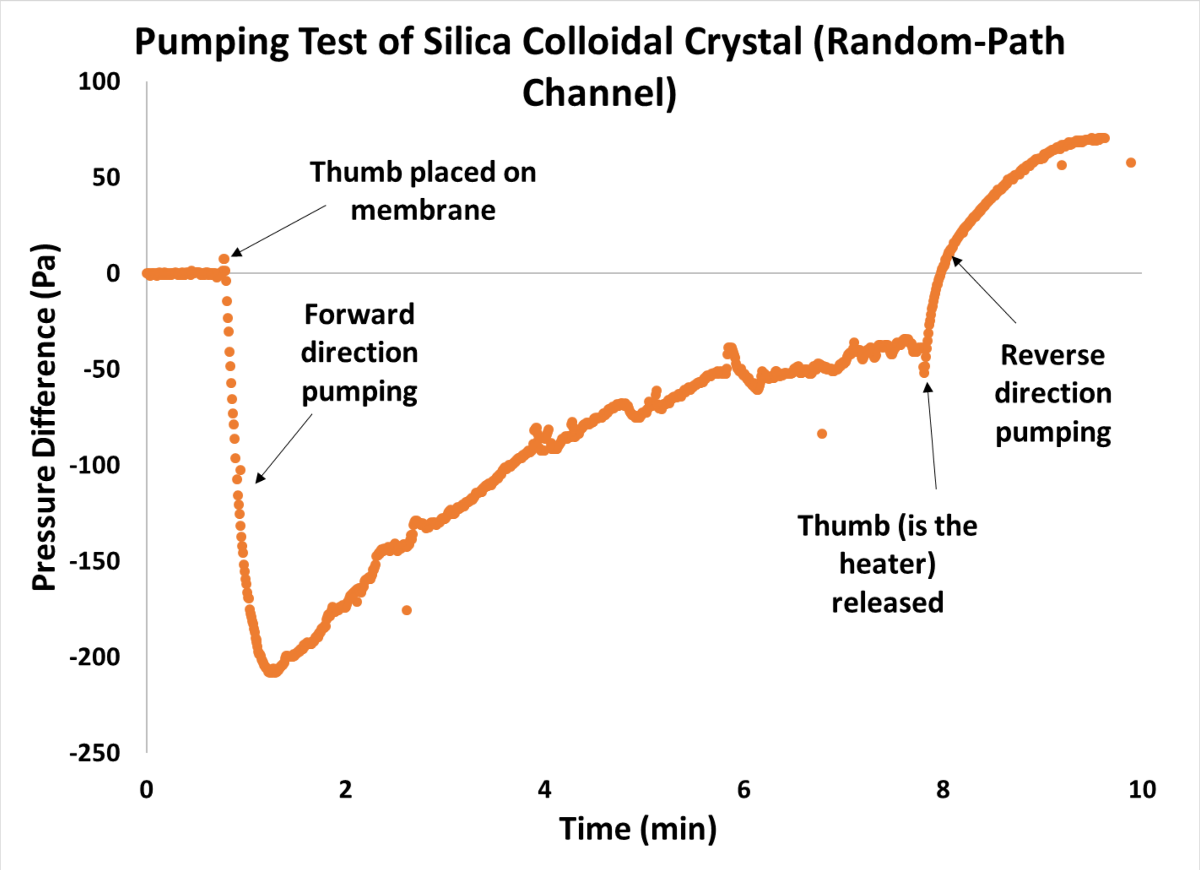
Why is air pumping better through random-path membranes instead of straight-channel membranes?







- Big pressure drop is a sign of good pumping
- Uses only the heat of your thumb
  - 33°C; minimal effort
- Total test time 10 minutes

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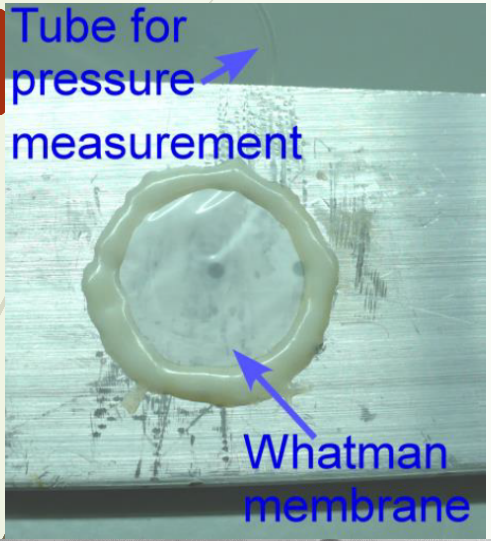
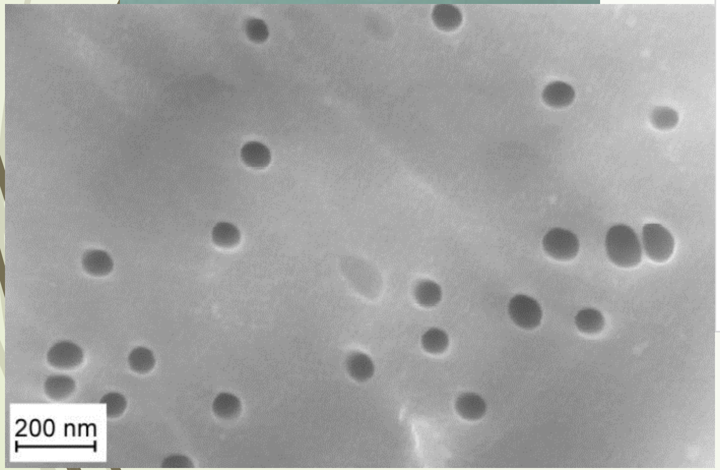
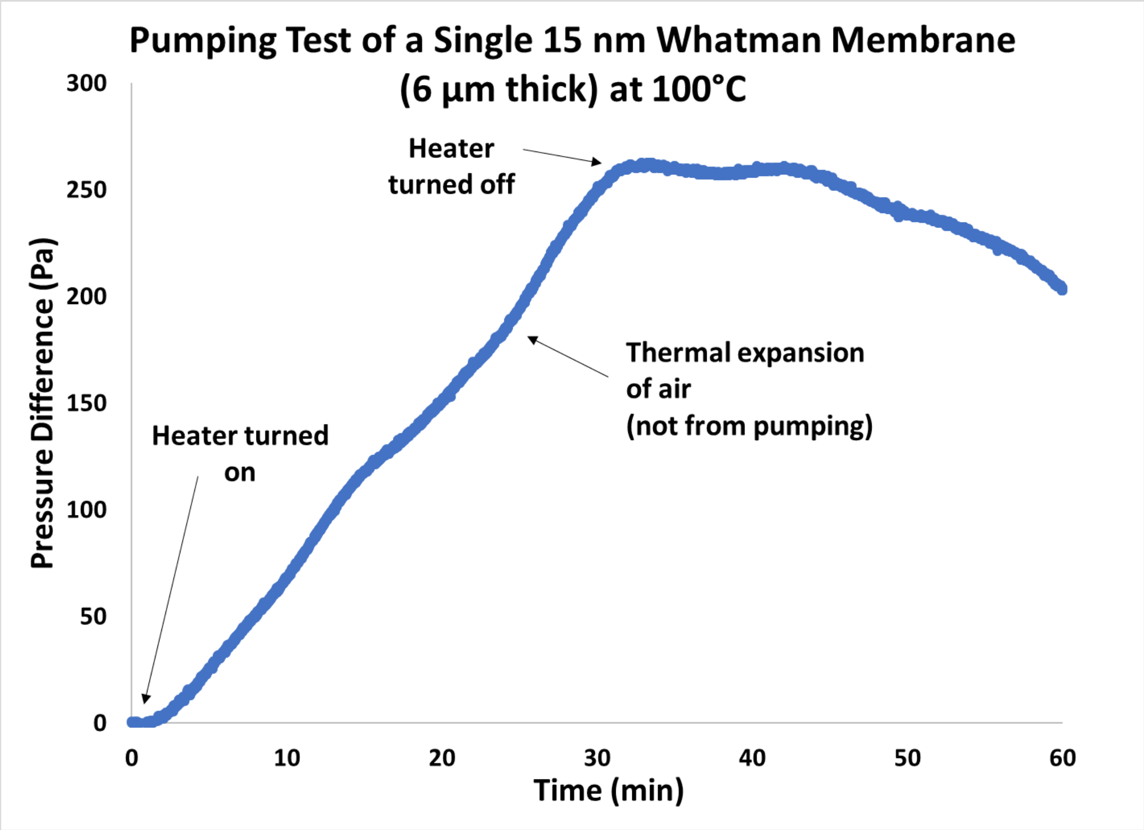
Why is air pumping better through random-path membranes instead of straight-channel membranes?







- Can't get a signal
- No pumping because no pressure drop
- Gas expansion contributing to large pressure because membrane is too thin

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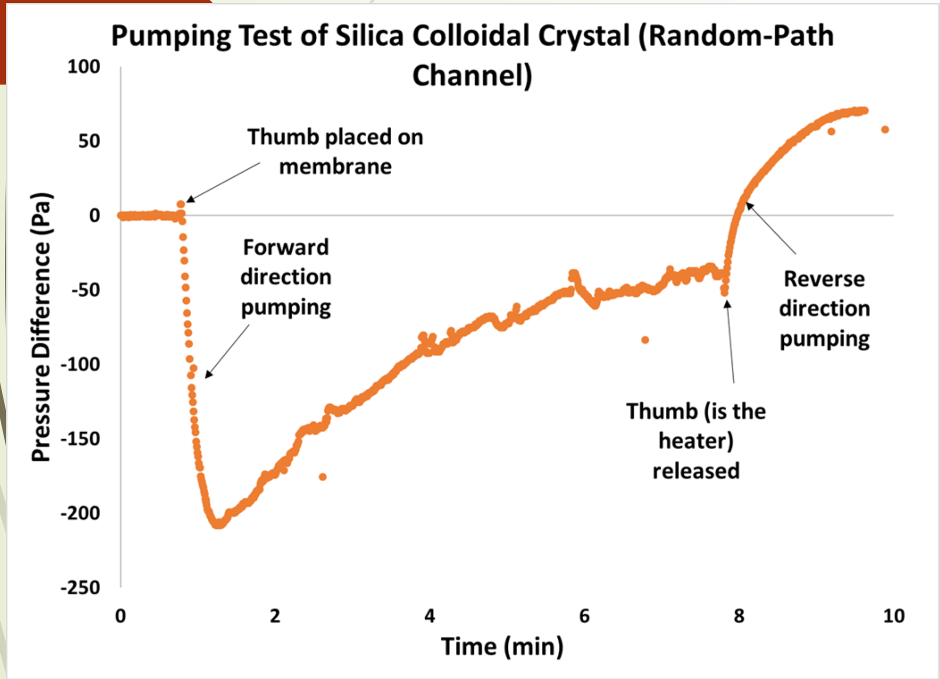
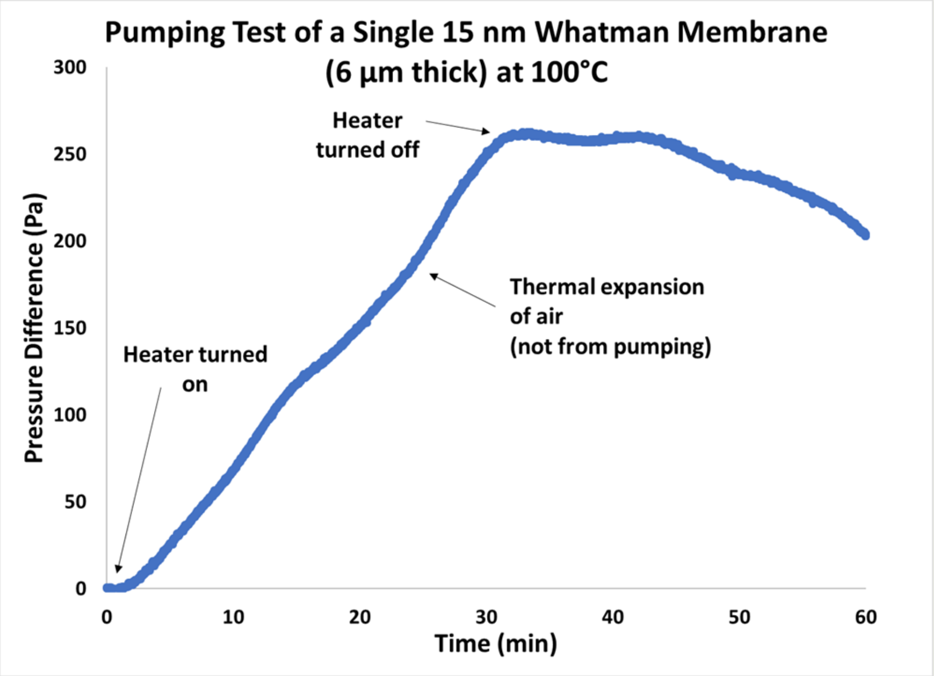
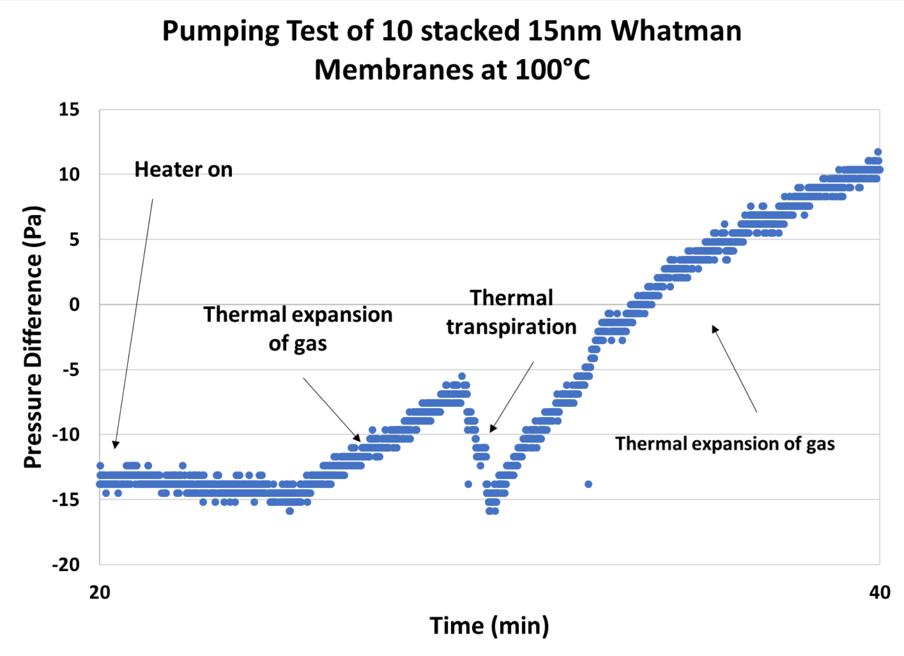
Comparison between random and straight-path membranes

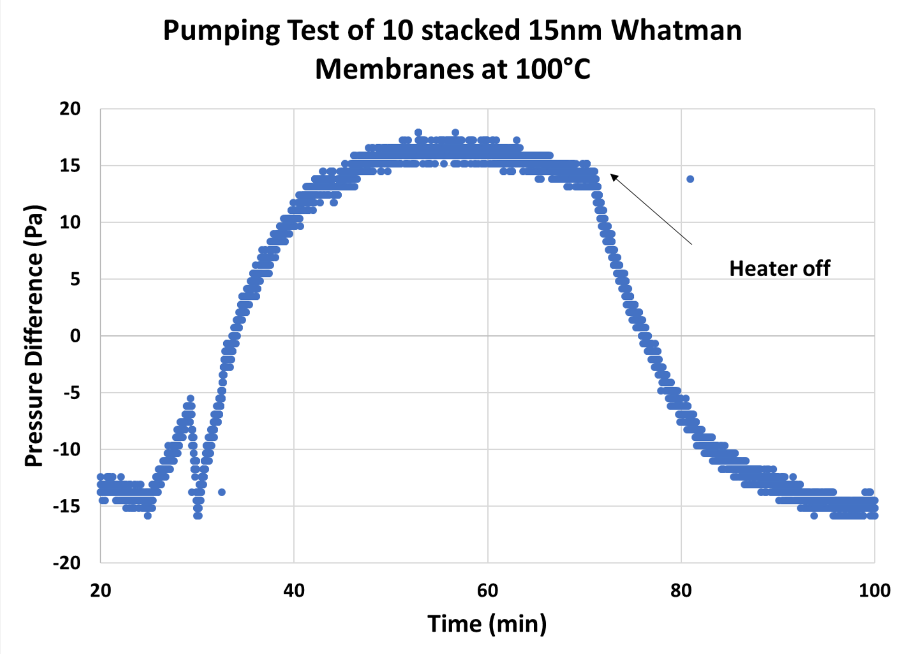




- Silica crystal 3 mm thick, 1000 times thicker than the Whatman
- Takes no effort to power the silica and get a pressure drop
  - 8x smaller ΔT
- More heat placed into the Whatman and can't get a signal
- Straight-channels in theory, should provide better pump performance than random-path

Increasing thickness of straight-channel membranes





- Thickness increased by 10
- Received a signal
- Gas expansion and thermal transpiration competing
- Need to reduce gas expansion, improve the signal, and reduce experimental runtime

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Factors addressed in Experimental Setup

- 1. thickness of membrane
- 2. thermal mass
- 3. thermal insulation
- 4. cooling

- Try to increase ΔT across the membrane to improve the pressure drop
- Reduce the thermal expansion to get a better signal
- Reduce the time needed to run an experiment

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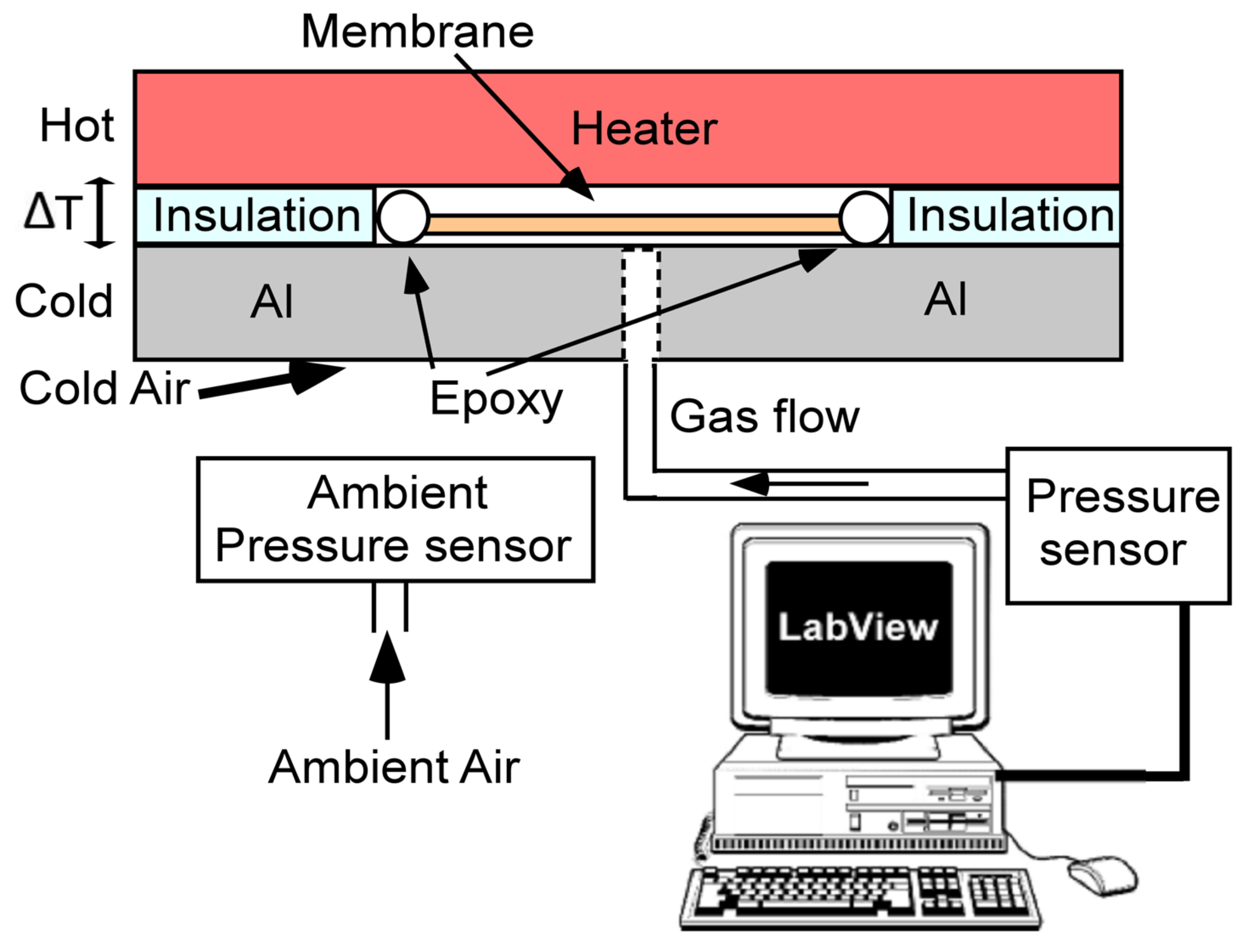
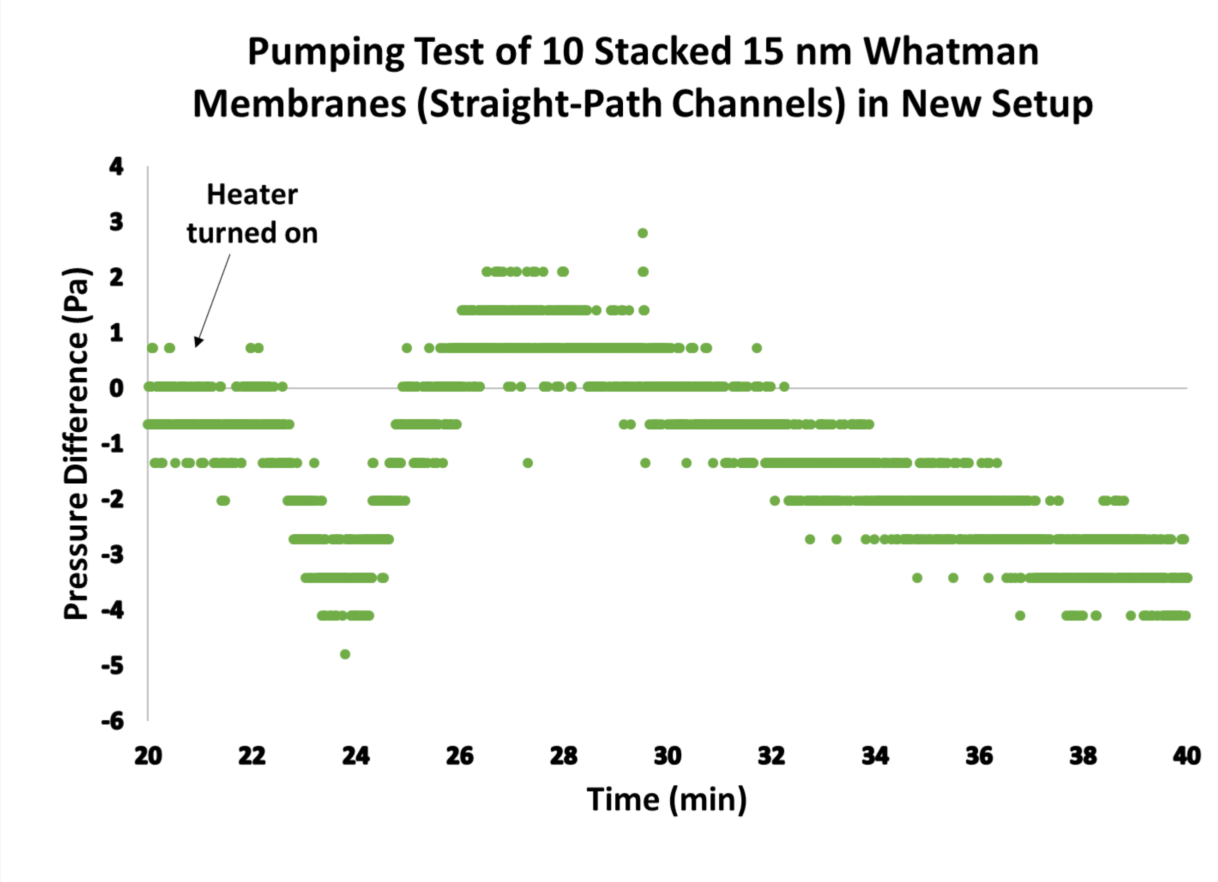
Experimental Setup

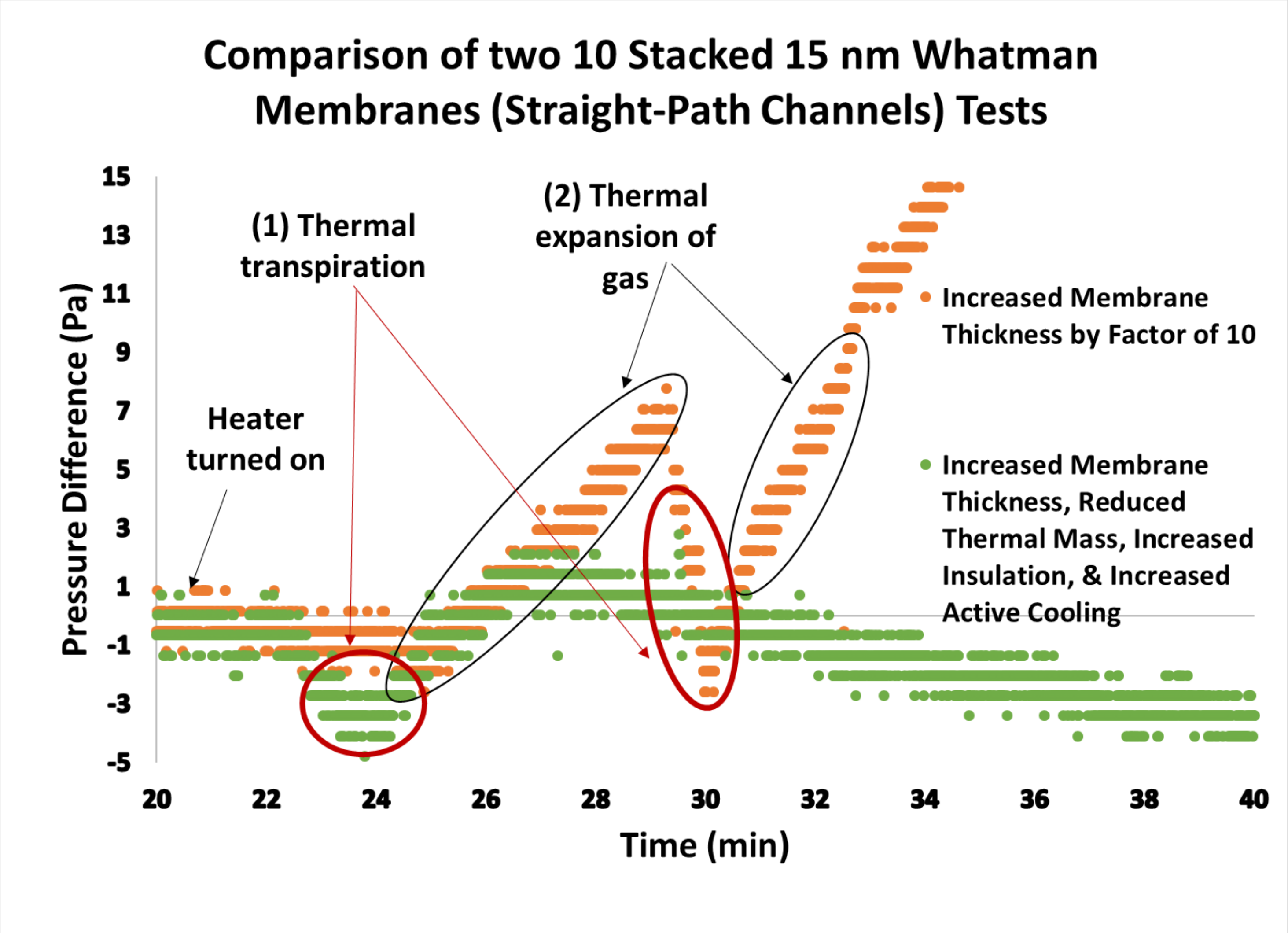


Got a signal!

- Accounting for:
  - Increased membrane thickness
  - Reduced total thermal mass
  - Increased thermal insulation around the membrane
  - Active cooling on cold side of the membrane to keep it cold, maximize ΔT while keeping thermal gas expansion down

- Reduced experimental runtime significantly and signal has improved





- Comparison shows (green) has a greater pressure drop
- (Green) thermal transpiration remains dominate effect shortly after 26 minutes
- (Green) significantly lower runtime than (orange)

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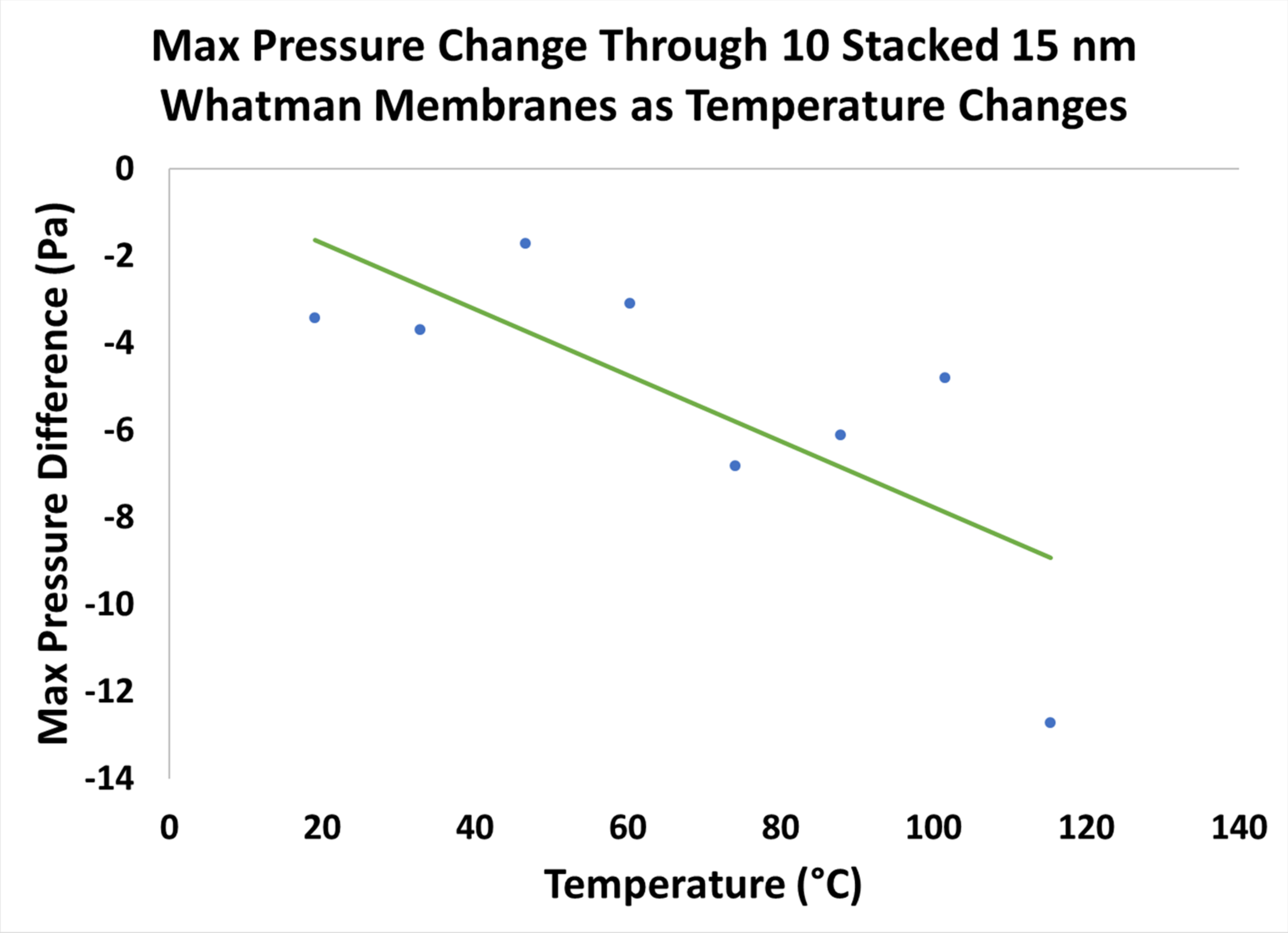
Conclusions

- Successfully demonstrated pumping with a straight-channel membrane
- Reduced parasitic heating on the cold side of the membrane
- Pressure change for T greater than 100°C shows significantly improved pumping (right)
  - Possibly due to the removal of adsorbed molecules
  - Straight-channel pumping maybe comparable to random-path channels after 100°C



Applications of this Experiment

- Lab-on-a-Chip (most notable)
- micropropulsion in spacecraft
- Medicinal pumps

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- K. Pharas, S. Miles, and S. McNamara, *Thermal transpirational flow in the transitional flow regime*, *J. Vac. Sci. Technol. A 30(5), Sep/Oct* (2012)
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