Increasing Heat Transfer in Microchannels with Surface Acoustic Waves*

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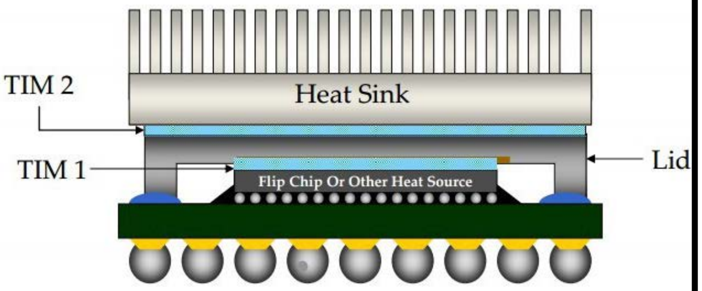
Study Motivation

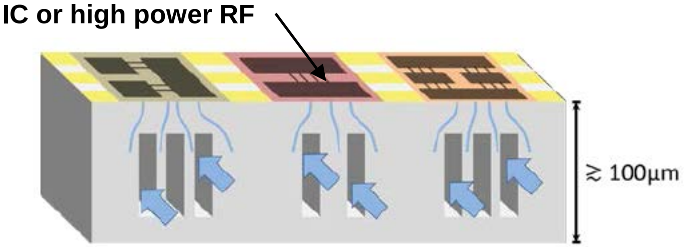
- As the trend in electronics continues towards higher integration density and higher power devices *current remote cooling technology will not be able to handle the predicted levels of heat removal*
  - Increased integration density of electronics, including 3D chip stack will push *localized heat fluxes >1kW/cm^2* and package-level *volumetric heat generation > 1kW/cm^3*
  - New paradigm for embedded cooling required
- Microfluidic cooling holds potential promise and a large amount of research and technology development has been going on (multiple DARPA programs since 2000)
  - Single-phase flow performance in microchannels limited to high flow rates due to laminar flow conditions and fixed thermal boundary layer
- In this numerical study surface acoustic waves (SAWs) are evaluated as a disruptive flow technology
  - SAWs coupled with single-phase microchannel flow
  - Goal is to drive circulating/chaotic flow to disrupt thermal boundary layers

Example of remote cooling for chips w/heat spreaders and thermal interface materials (TIMs)



Thermal management needs be embedded close to heat sources to handle the envisioned heat loads

Microfluidic embedded cooling

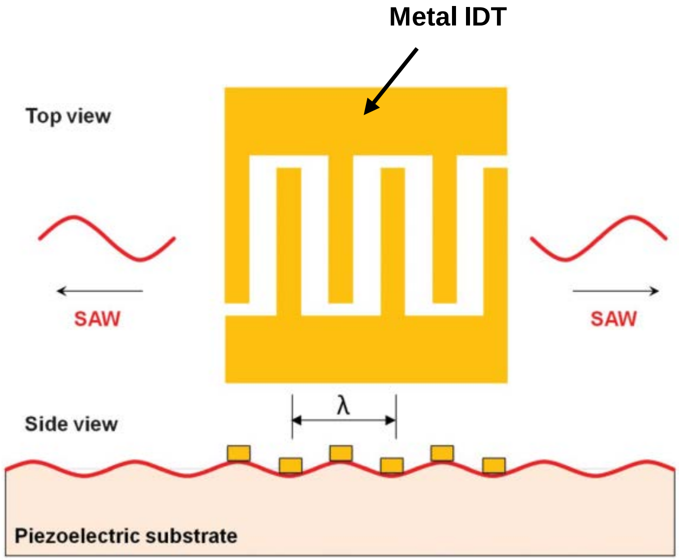


A.B. Cohen et. al. CS MANTECH Conf. 2013.

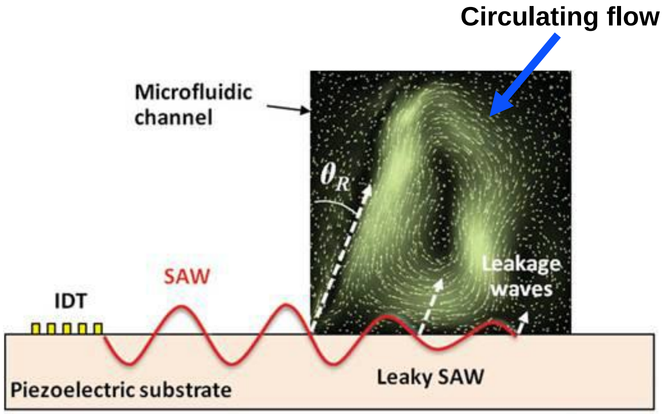
DARPA – Defense Advanced Research Projects Agency

Surface Acoustic Waves (SAWs) and Acoustic Streaming

- SAWs are generated by sinusoidal electrical potential applied to an interdigitated transducer (IDT) on piezoelectric substrate and propagate along the surface
  - Used extensively in telecommunication
    - Signal processing and filtering
- When a SAW traveling along the surface comes in contact with a fluid medium some of SAW’s energy is refracted into the liquid
  - Acoustic streaming (“Leaky SAW”)
- Non-linear acoustic interaction occurs within a thin viscous boundary layer (<1μm for MHz frequencies)
  - Bulk fluid motion arises from viscous interactions with the boundary layer
- Frequency ranges: 1 to 100’s MHz
- Substrate amplitude ranges: 0.1 nm to 10 nm
- Gaining attention in microfluidics
  - Fluid mixing and particle and cell sorting



X. Ding. et. al. Lab Chip, 13, 3626-3649, 2013.



X. Ding. et. al. Lab Chip, 13, 3626-3649, 2013.

Numerical Modeling of Acoustic Streaming

- **Numerical simulation challenges:**
  - **SAW operate in MHz range and behave with harmonic time dependences → $e^{i\omega t}$**
  - **Viscous effects in a fluid occur on msec or larger time scales**
    - **This requires a time-averaged response of the acoustic oscillations**
- **Perturbation expansion is employed on dependent variables u, p, and ρ to solve conservation of mass and momentum**
  - **Acoustic velocity is of first-order (u_1)**
  - **Streaming velocity is assumed to be of second-order (u_2)**
- **Computational methodology:**
  - **Solve the first-order acoustic motion (u_1, p_1, ρ_1)**
  - **Use first-order solution as inputs for second order conservation equations**
    - **Time averaged equations need to be solved**

Mass source term ($\text{kg/m}^2\text{s}$)

Continuity:

$$\rho_o\nabla\cdot\langle\bar{u}_2\rangle=\boxed{-\nabla\cdot\langle\rho_1\bar{u}_1\rangle}$$

Volume force Source terms (N/m^3)

Momentum:

$$-\rho_o\left\langle\frac{\partial\bar{u}_2}{\partial t}\right\rangle+\mu\nabla^2\langle\bar{u}_2\rangle+\left(\mu_B+\frac{\mu}{3}\right)\nabla\left(\nabla\cdot\langle\bar{u}_2\rangle\right)-\langle\nabla p_2\rangle=\boxed{\left\langle\rho_1\frac{\partial\bar{u}_1}{\partial t}\right\rangle+\rho_o\left\langle\left(\bar{u}_1\cdot\nabla\right)\bar{u}_1\right\rangle}$$

COMSOL Modeling

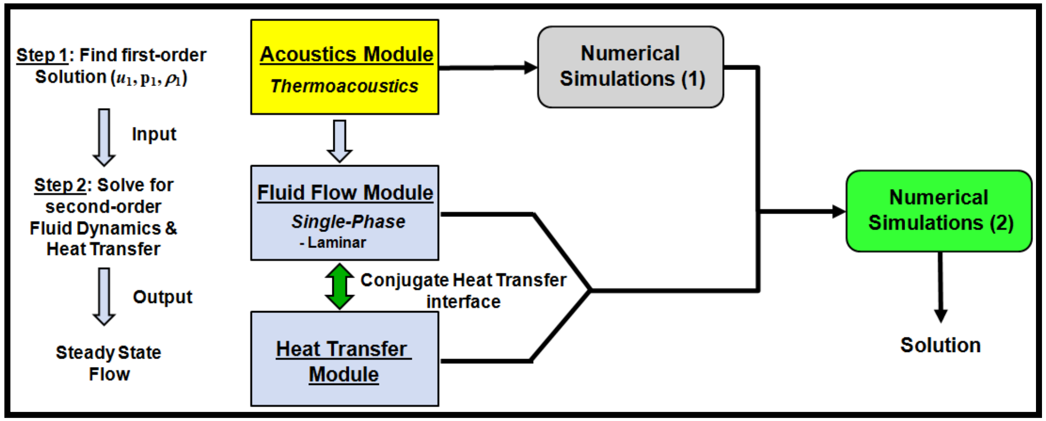
- **COMSOL ver. 4.3b**
- **Step 1: solving first order equations using *Thermoacoustics interface***
  - **Study 1: Frequency Domain**
  - **SAW introduced as velocity on channel walls**
- **Step 2: Solving second order equations using *Conjugate Heat transfer interface***
  - **Study 2: Stationary (steady state)**
  - **Source terms (first-order results) added to mass and momentum equations**
    - **Momentum equation**

      Volume force, F directly added
    - **Mass**

      Constitutive equation needs to be altered

      Use “weak contribution”
  - **No coupling of first-order terms to Energy equation**
  - **Time-averaged response of complex-values**

Ex: Mass source term $= -\nabla \cdot \langle \rho_1 \bar{u}_1 \rangle \Rightarrow \langle \rho_1 u_{1x} \rangle = \frac{1}{2} Re[conj(\rho_1) \cdot u_{1x}]$



Step 1: Find first-order Solution (u_1, p_1, ρ_1)

Input

Step 2: Solve for second-order Fluid Dynamics & Heat Transfer

Output

Steady State Flow

Acoustics Module
Thermoacoustics

Fluid Flow Module
Single-Phase
- Laminar

Conjugate Heat Transfer interface

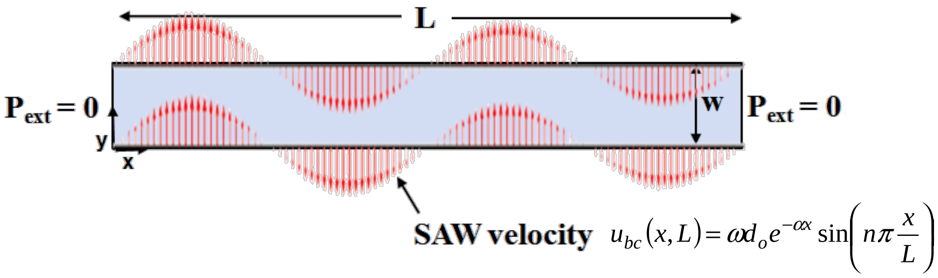
Heat Transfer Module

Numerical Simulations (1)

Numerical Simulations (2)

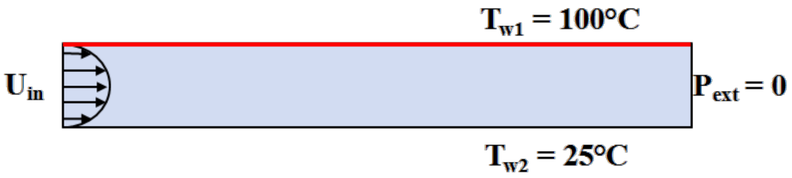
Solution

Step 1: First-Order boundary conditions



$u_{bc}(x,L) = \omega d_o e^{-\alpha x} \sin\left(n\pi \frac{x}{L}\right)$

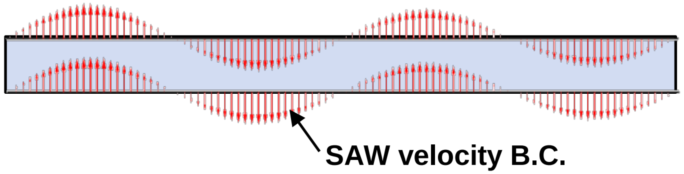
Step 2: Second-Order boundary conditions



Model 1 Simulation Results: Laminar Flow Only

Model parameters:

L = 1000 μm
w = 50 μm
f = 15 MHz
d_o = 0.1 nm
U_{in} = no inlet flow

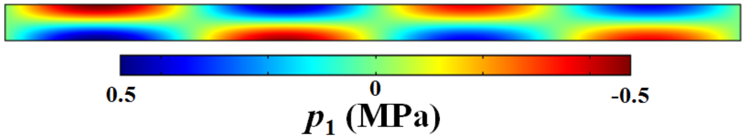


Water filled channel

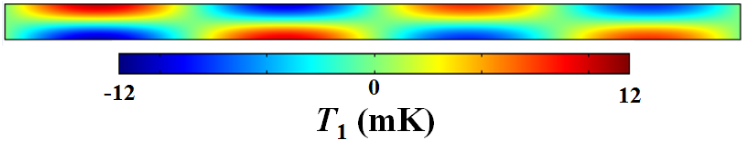
SAW velocity B.C.

Contour Plots of First-Order Fields

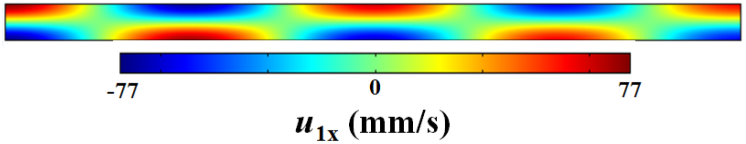
Pressure



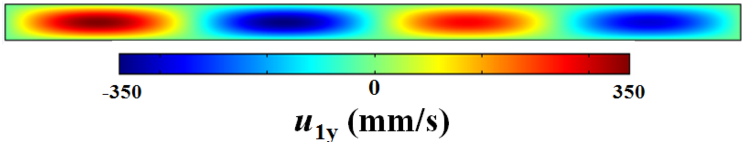
Temperature



Horizontal velocity

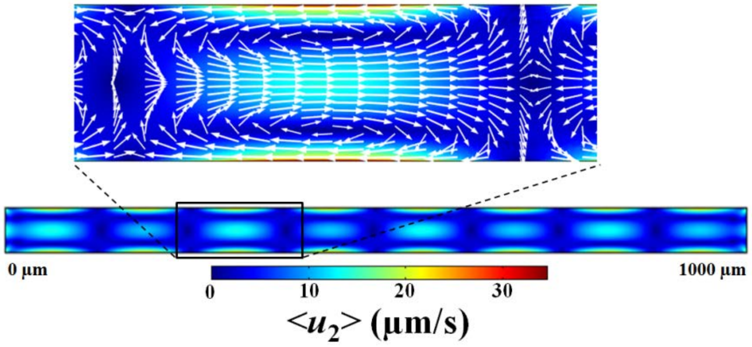


Vertical velocity

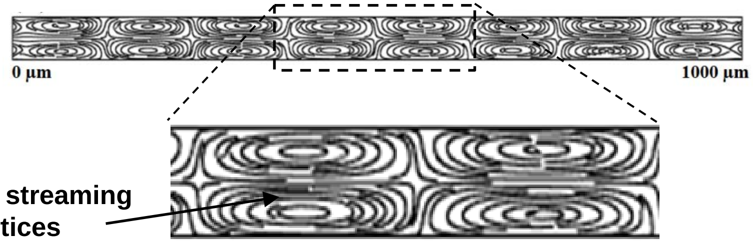


Time-averaged Second-order Results

Velocity contour plot



Streamlines

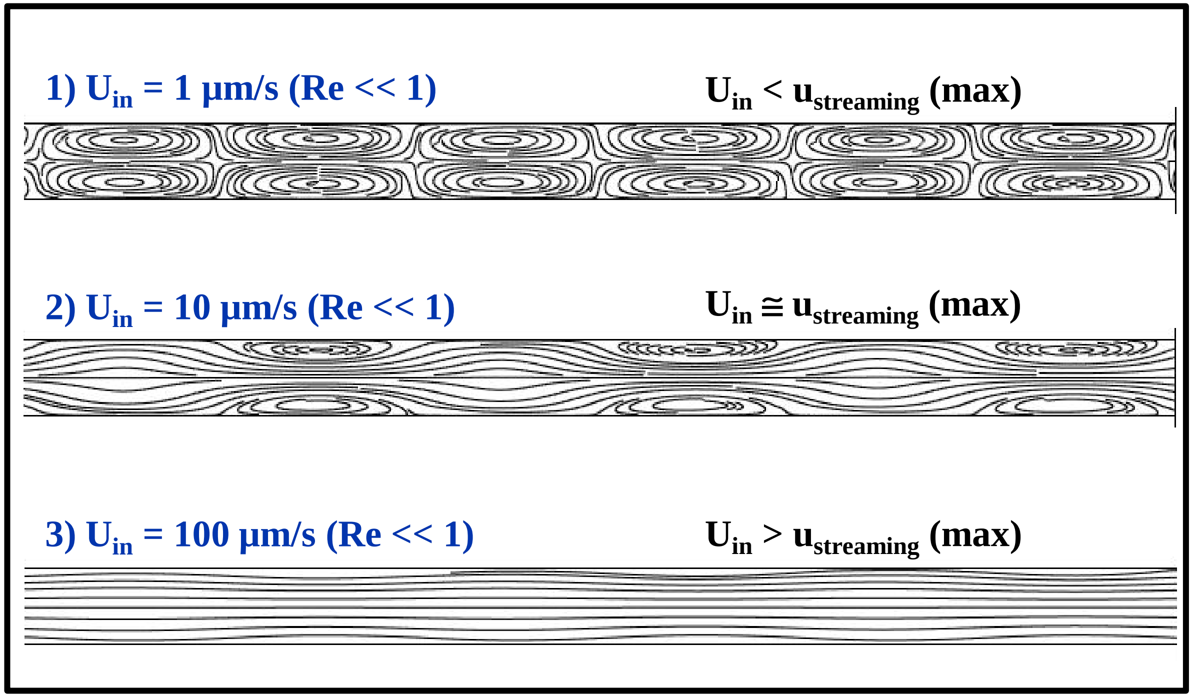


Rayleigh streaming vortices

Model 1: Effect of Inlet Velocity

- **Inlet flow included in 2nd order simulations**
  - **1st order results the same for all cases**
- **U_{in} <= Max acoustic streaming velocity**
  - **Circulating flow in the microchannel is created**
- **U_{in} > Max acoustic streaming velocity**
  - **Advection dominates flow and vortices are not generated**
- **Need to increase acoustic streaming velocity to have higher Reynolds number flows**

Time-averaged 2nd Order Results: Streamlines for <u_2>



1) U_{in} = 1 µm/s (Re << 1) $U_{in} < u_{streaming}$ (max)

2) U_{in} = 10 µm/s (Re << 1) $U_{in} \cong u_{streaming}$ (max)

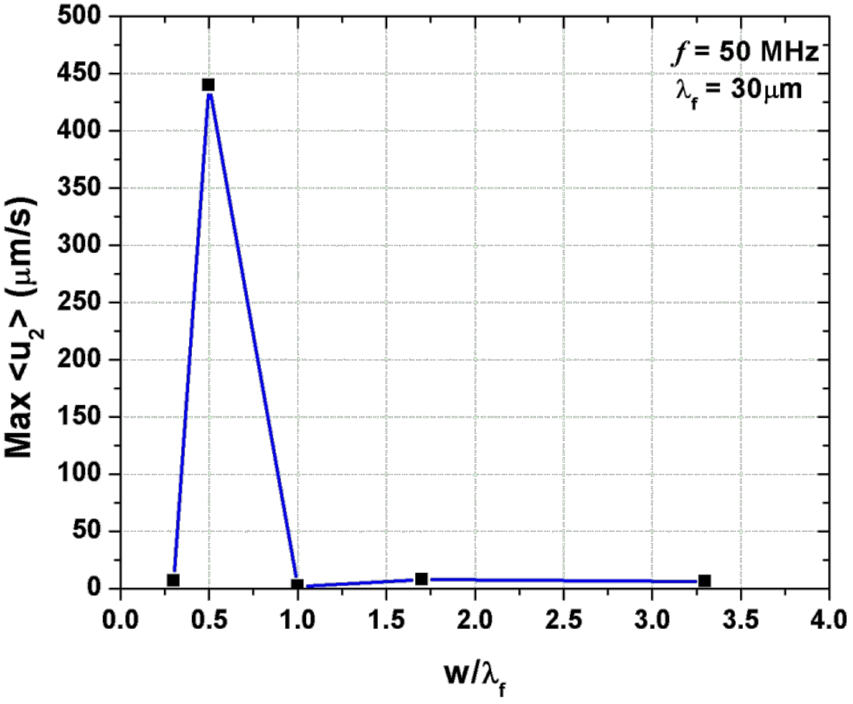
3) U_{in} = 100 µm/s (Re << 1) $U_{in} > u_{streaming}$ (max)

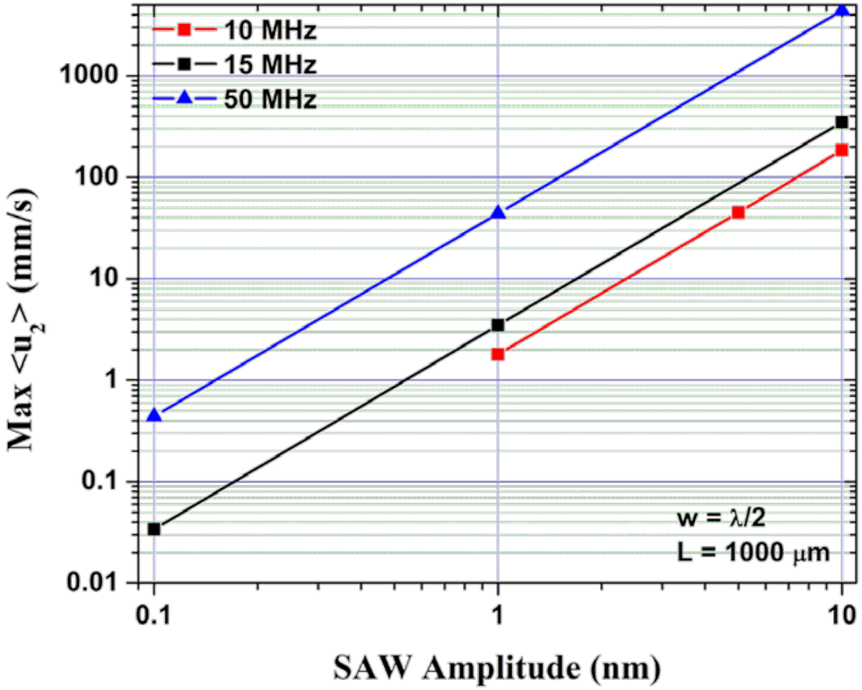
L = 1000 µm
w = 50 µm
f = 15 MHz
d_o = 0.1 nm
U_{in} = varied

Effects on Acoustic Streaming Velocity

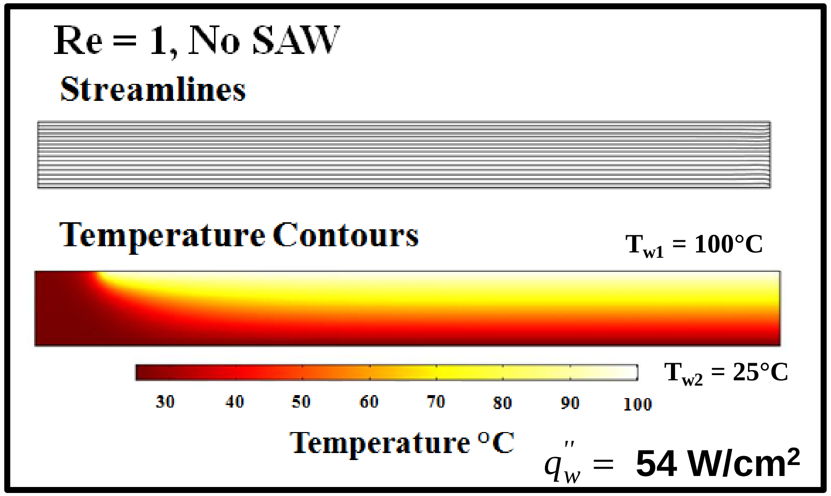
- Maximum acoustic streaming velocity occurs when:
  - Channel width w = λ/2
    - Wave length determined from fluid properties

- Acoustic streaming velocity dependent on SAW amplitude d_o
- Streaming velocity is quadratic in SAW amplitude for all frequencies

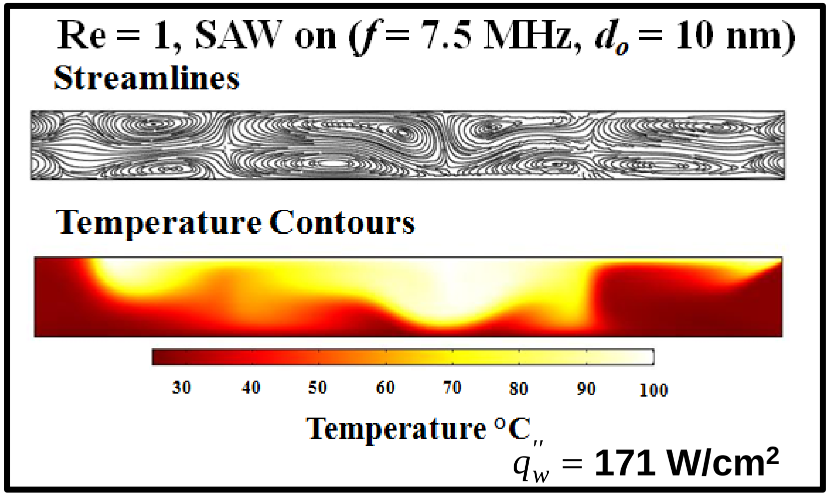




Heat Transfer Results



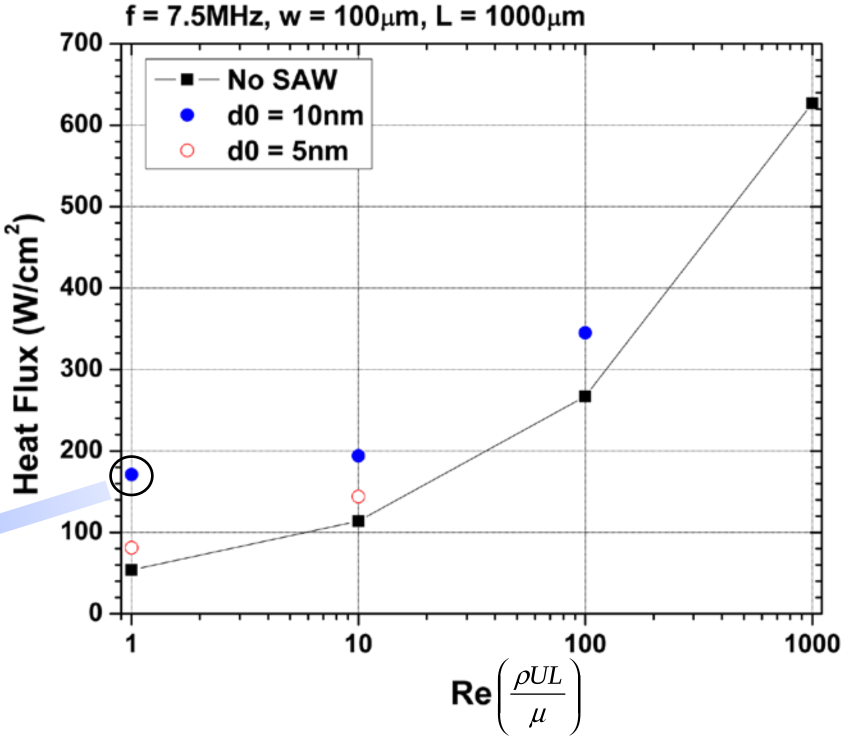
q''_w = 54 W/cm²



q''_w = 171 W/cm²

Model parameters:

L = 1000 µm
w = 100 µm
f = 7.5 MHz
d_o = 10 nm
U_{in} = 0.01 m/s (Re = 1)



- **Results show under the right condition there is an increase in heat transfer due to SAWs**
  - **Stream velocity < Acoustic streaming velocity**

Summary

- Developed the framework to numerically simulate Acoustic Streaming in microchannels from surface acoustic waves
- Coupled three physics together
  - Acoustics, fluid flow and heat transfer
- Results indicate that SAW can enhance heat transfer
  - Bulk stream velocity < Acoustic streaming velocity
- Considerably more analysis work needs to be done
  - Need to increase vorticity strength in order for concept to be useful in microfluidic cooling
  - Identified potential ways to achieve this condition
    - Pulse the SAW and frequency or amplitude modulate
    - Pulse the inlet velocity
    - Explore different frequencies and geometries
    - Launch SAW from different locations in channel

      Perpendicular to the flow

Thank you!

Questions?

Backup Material

Model Material Parameters

Water @25°C			
Density	ρ_f	**998**	**kg/m^3**
Speed of sound	c_f	**1495**	**m/s**
Dynamic viscosity	μ	**8.90e-4**	**Ps s**
Thermal diffusivity	D	**1.43e-7**	**m^2/s**
Solid*			
Density	ρ_s	**4650**	**kg/m^3**
Speed of sound	c_s	**3990**	**m/s**

*Single crystal Lithium Niobate

Physics

First-order equations

a) Thermodynamic heat transfer equation for T_1

$$\frac{\partial T_1}{\partial t} = D\nabla^2 T_1 + \frac{\alpha T_0}{\rho_o C_p}\frac{\partial p_1}{\partial t}$$

b) Kinematic continuity equation in terms of p_1

$$\frac{\partial p_1}{\partial t} = \frac{1}{\gamma\kappa}\left[\alpha\frac{\partial T_1}{\partial t} - \nabla\cdot u_1\right]$$

c) Momentum equation for velocity field $\mathbf{u}_1$

$$\rho_o\frac{\partial u_1}{\partial t} = -\nabla p_1 + \mu\nabla^2 u_1 + \left(\mu_B + \frac{\mu}{3}\right)\nabla(\nabla\cdot u_1)$$

Equations solved with *Thermoacoustics Physics* interface in COMSOL

Second-order equations

a) Continuity equation

$$\rho_o\nabla\langle u_2\rangle = -\nabla\cdot\langle\rho_1 u_1\rangle$$

b) Momentum equation

$$\mu\nabla^2\langle u_2\rangle + \left(\mu_B + \frac{\mu}{3}\right)\nabla\nabla\cdot\langle u_2\rangle - \nabla\langle p_2\rangle = \langle\rho_1\frac{\partial u_1}{\partial t}\rangle + \rho_o\langle(u_1\cdot\nabla)u_1\rangle$$

c) Energy equation

$$\rho_o C_p\langle u_2\rangle\nabla T_2 = \nabla\cdot\left(K\nabla T_2\right) + Q$$

<x> = time average quantity over full oscillation period

Equations solved with *Conjugate Heat Transfer* interface in COMSOL

Time Averaging of Complex Variables

- **For complex-valued fields *A(t)* and *B(t)* with harmonic time dependence, the time average is the real part:**

$$\langle A(t)B(t)\rangle = \frac{1}{2} Re\left[conj\left(A(0)\right) * B(0)\right]$$

Ex: Mass source term: $= -\nabla \cdot \langle \rho_1 \overline{u}_1 \rangle$

$$= -\left(\frac{\partial \langle \rho_1 u_{1x} \rangle}{\partial x} + \frac{\partial \langle \rho_1 u_{1y} \rangle}{\partial y} \right)$$

$$\langle \rho_1 u_{1x} \rangle = \frac{1}{2} Re\left[conj\left(\rho_1\right) \cdot u_{1x}\right]$$

$$\langle \rho_1 u_{1y} \rangle = \frac{1}{2} Re\left[conj\left(\rho_1\right) \cdot u_{1y}\right]$$

SAW Streaming Analysis

- SAW can be generalized as periodic i.e. harmonic
- The fluid motion induced by harmonic forcing in general has two components
  - Harmonic component
    - This is the motion of the fluid from the acoustic response
  - Steady component
    - This is the streaming response
- The computational challenge is how to separate the two components
- To solve for the conservation of mass and momentum a perturbation expansion is done on dependent variables u, p, ρ

$$u = u_o + \varepsilon u_1 + \varepsilon^2 u_2 + O\left(\varepsilon^3\right)$$
$$p = p_o + \varepsilon p_1 + \varepsilon^2 p_2 + O\left(\varepsilon^3\right)$$
$$\rho = \rho_o + \varepsilon \rho_1 + \varepsilon^2 \rho_2 + O\left(\varepsilon^3\right)$$

$$\varepsilon = \frac{U}{c_o}$$

Smallness factor (acoustic Mach #)

$$\varepsilon << 1$$