Numerical Investigation of Impinging Surface Enhancement With Copper Inverse Opals (CIOs) For Jet Cooling

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2. Methodology
3. Thermofluidic Characteristics
4. Reduced-order Model for CIO Jet Cooler
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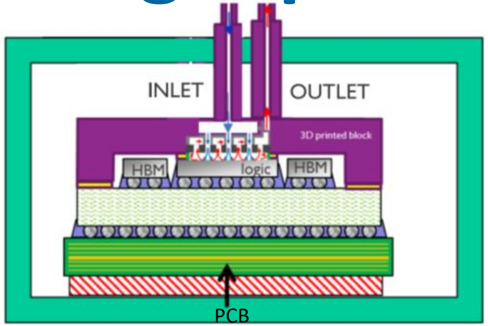
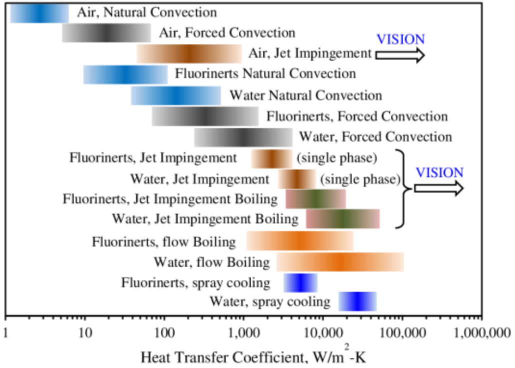
Single-phase Jet cooling



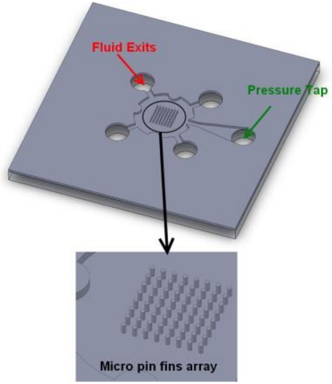
Single-phase impingement jet cooling
Adapted from Pappaterra, Imec



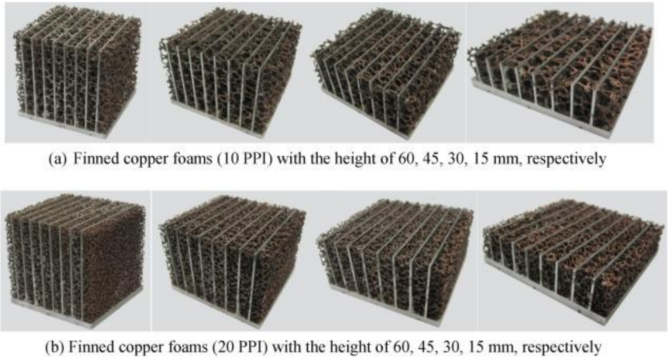
A. Sridhar, PhD thesis, Curtin Univ.

Why single-phase jet impingement?

- Very thin boundary layers
- Much higher htc than conventional forced convection ($\sim 6\times10^4$ W·m^{-2}·K^{-1} for single-phase water)
- Can be enhanced by surface modification



Pillar-like micro fins
Ndao et al., IJHMT, 2012

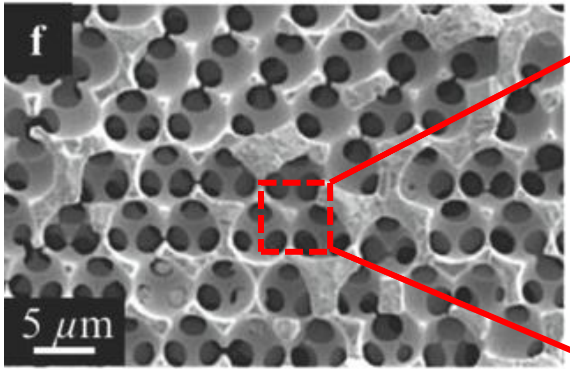


(a) Finned copper foams (10 PPI) with the height of 60, 45, 30, 15 mm, respectively

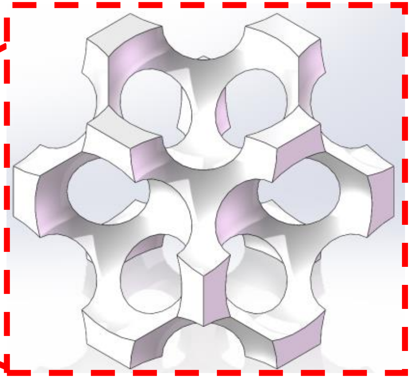
(b) Finned copper foams (20 PPI) with the height of 60, 45, 30, 15 mm, respectively

Finned copper foam heat sinks
Wang et al., Applied Energy, 2019

Copper Inverse Opals (CIOs)



SEM image of CIO structures
Zhang et al., Adv. Funct. Mater., 2018



Unit Cell Schematic
(Face-Centered Cubic)

➢ **Thermofluidic properties of CIOs**

Inverse opal structure:

- High surface area-to-volume ratio

⇒ Strong convective heat transfer

- High fluid permeability

⇒ Low pressure drop

Copper:

- High thermal conductivity

⇒ Good heat spreader

Single-phase Jet Cooler with CIOs

- **3D packages with single-phase jet cooler**

Conventional single-phase jet cooler:

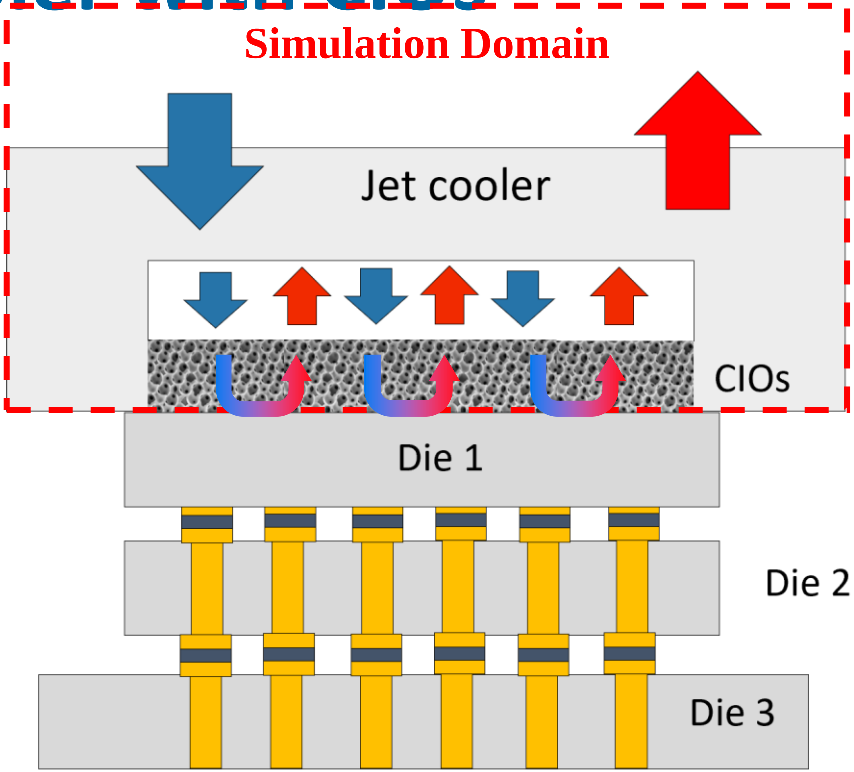
- Jet directly impinges on the die surface

Single-phase jet cooler with CIOs:

- A CIO layer fabricated on the die
- Jet impinges and flows into CIO structure.

Numerical investigation:

- ❑ Liquid water as working fluid.
- ❑ Flow and heat transfer in the simulation domain are simulated.



Schematic of jet cooler design

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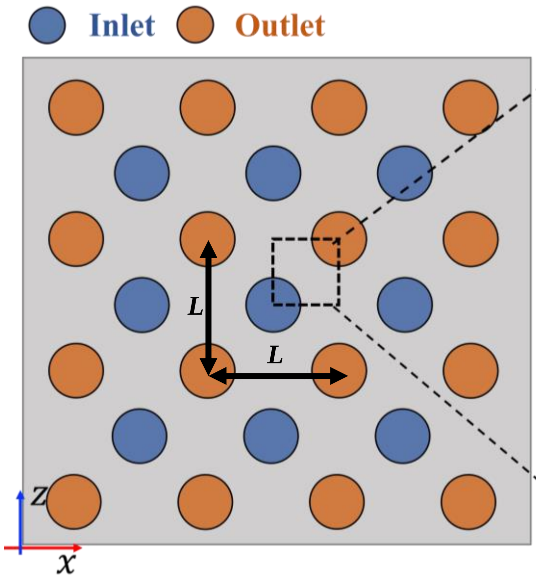
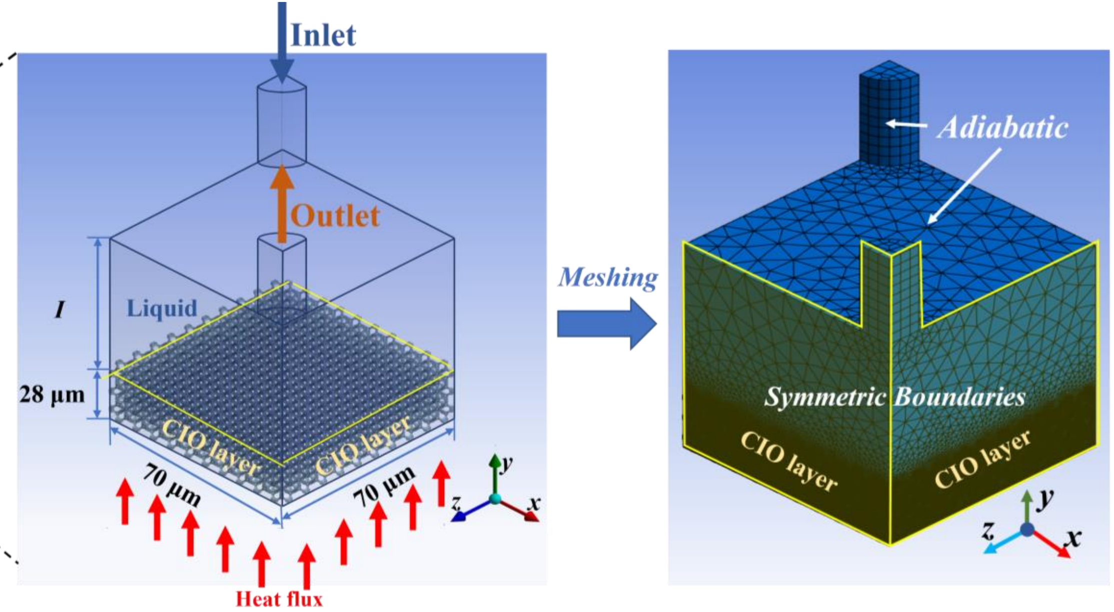
Simulation System



Nozzle Array



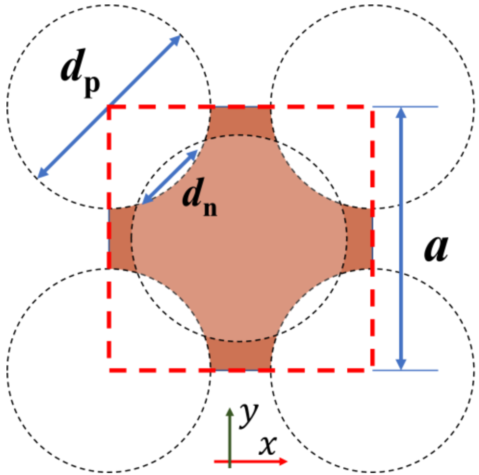
System Setup & Boundary Conditions

Mesh

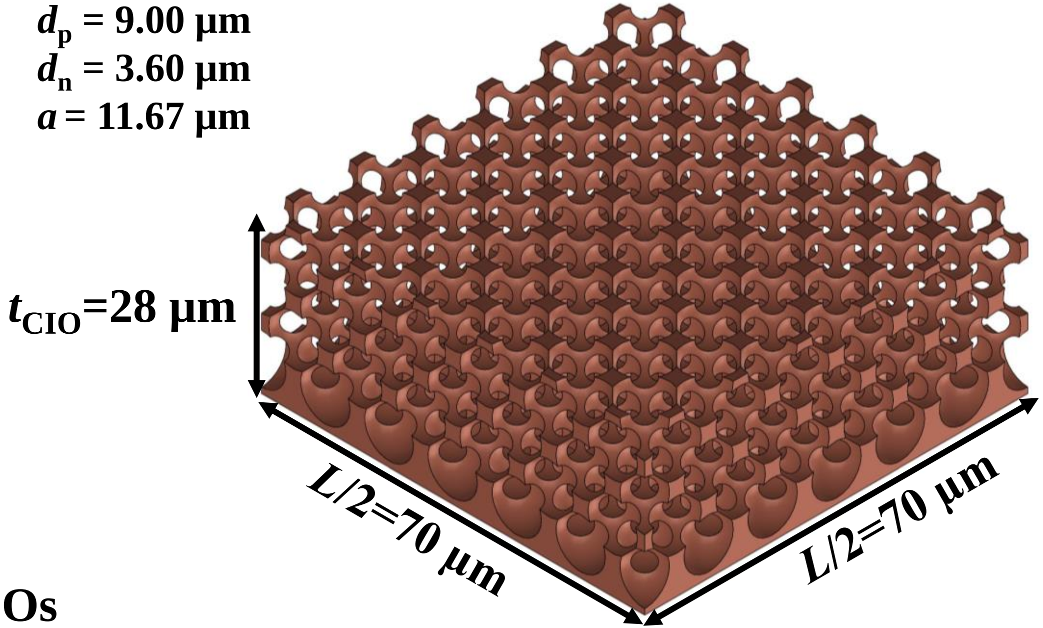
➢ **Unit cell of jet cooler is investigated to reduce computational resource.**

Characterization of CIOs in CFD

d_p = 9.00 µm
d_n = 3.60 µm
a = 11.67 µm



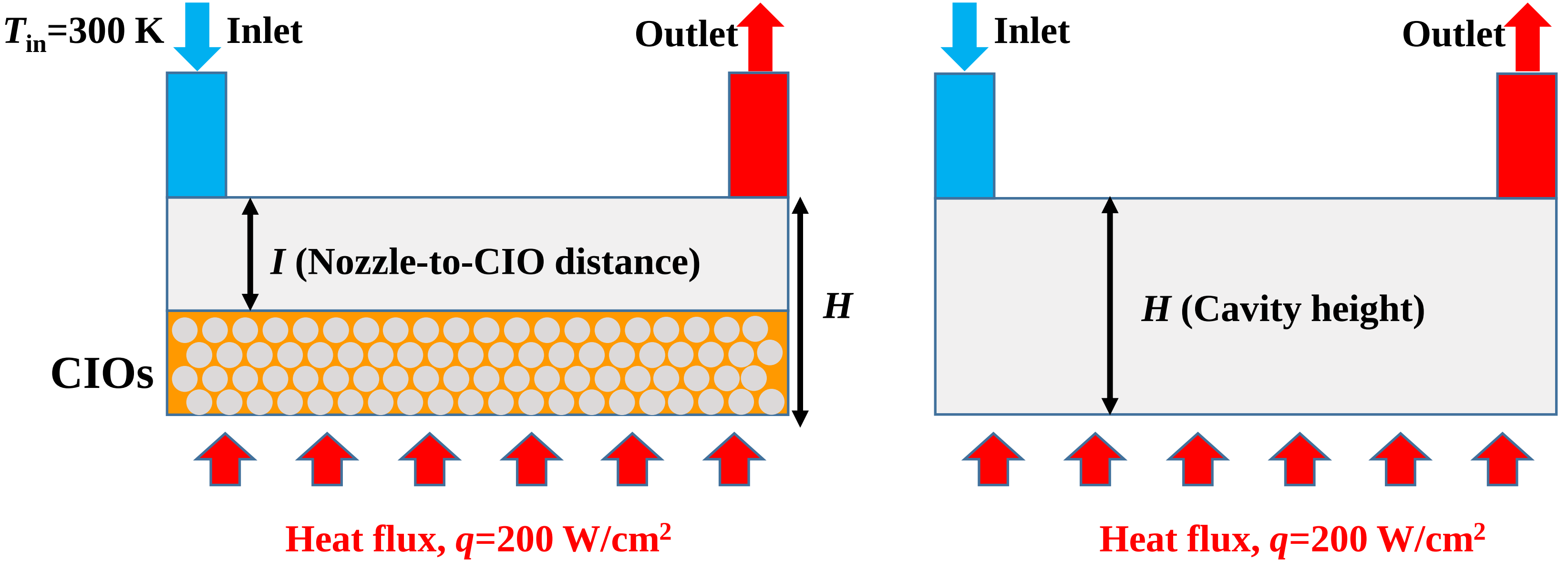
Geometric Parameters of CIOs



70×70×28 µm^3 CIO layer

Benchmark

- Thermofluidic characteristics of jet coolers with and without CIOs are benchmarked.



(a) With CIOs (b) Without CIOs

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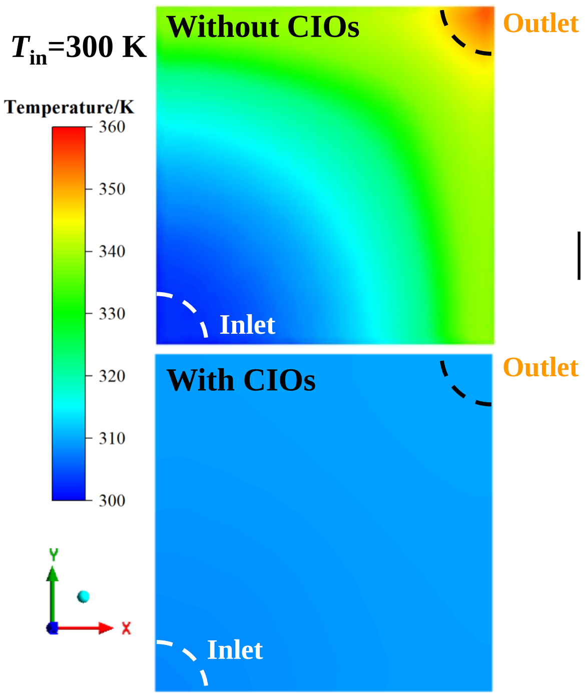
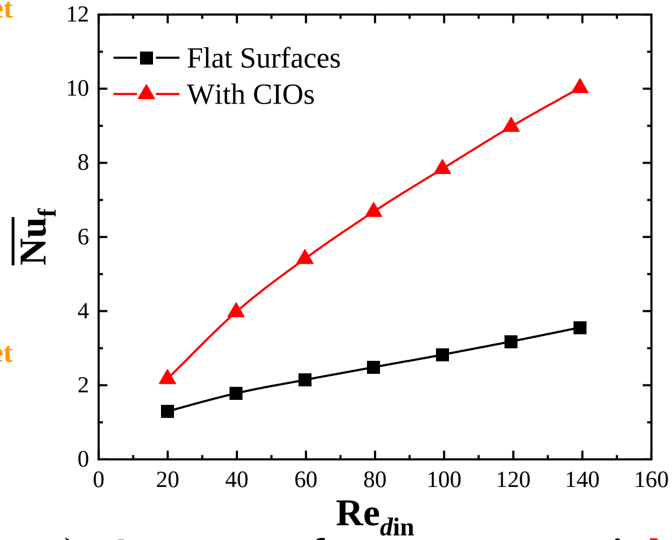
Jet Cooling on CIOs vs. Flat surfaces

Average temperature (Nusselt Number)

❑ **Temperature contour of chip interface**



❑ **Nu_f at I/L=0.1765 and different inlet velocities**



$$Re_{din} = \frac{\rho u_{in} d_{in}}{\mu_f}$$

$$\overline{Nu_f} = \frac{q d_{in}}{(T_s - T_{in}) k_f}$$

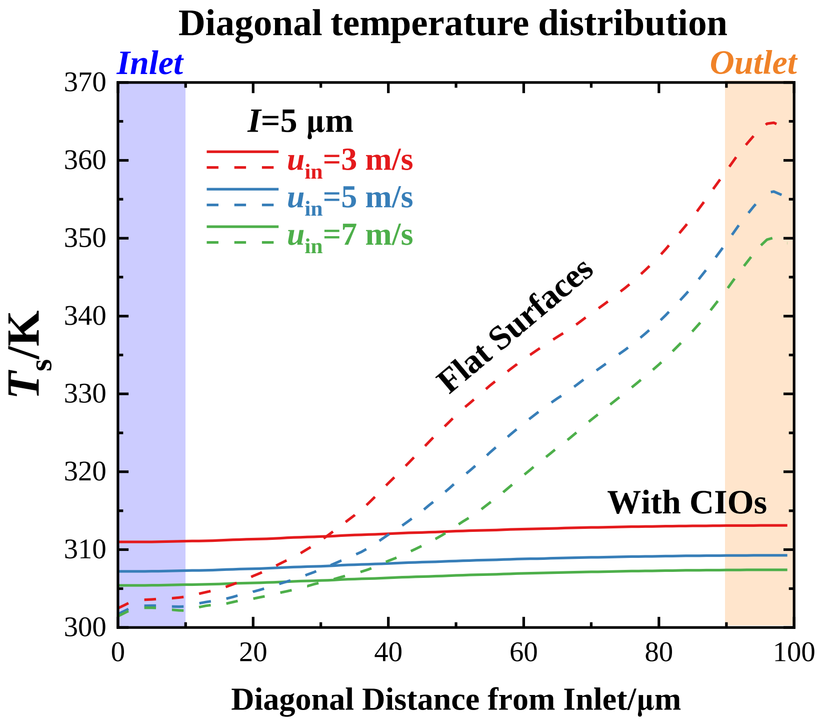
k_f	Fluid thermal conductivity
ρ	Fluid density
μ_f	Viscosity
u_{in}	Inlet velocity
d_{in}	Inlet diameter
q	Heat flux on chip
T_s	Mean temperature of chip
T_{in}	Inlet fluid temperature

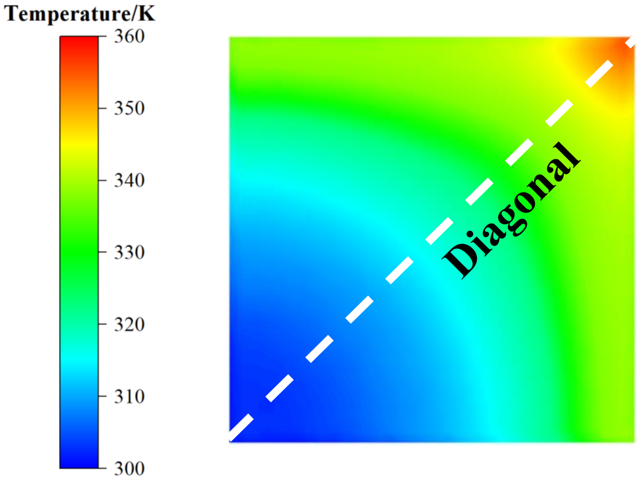
- **Average surface temperature is largely decreased by using CIOs.**
- **Nusselt number is significantly larger in systems with CIOs.**

❖ **Strong convective heat transfer in CIOs**

Jet Cooling on CIOs vs. Flat surfaces

Temperature uniformity

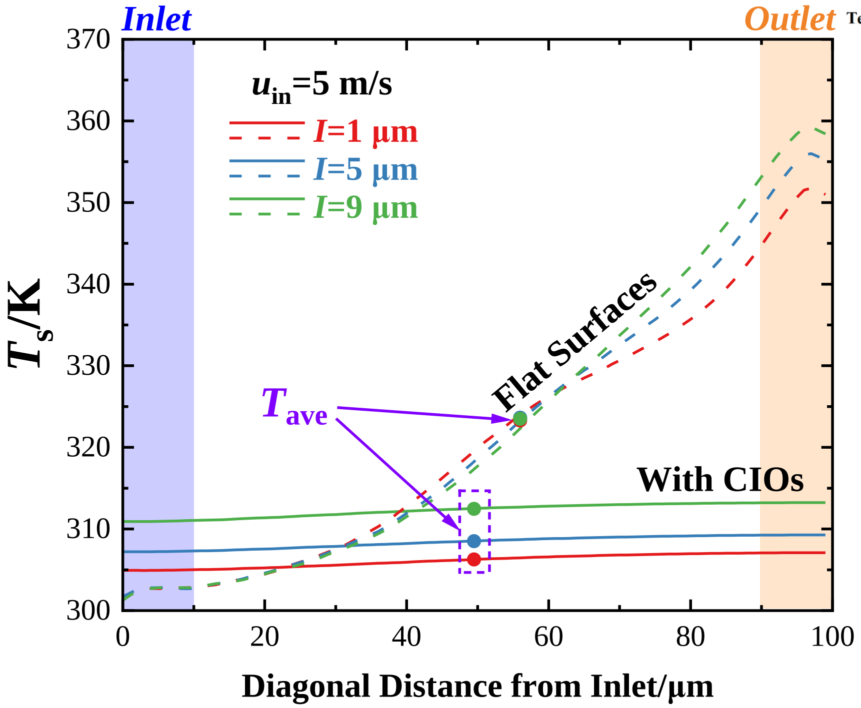


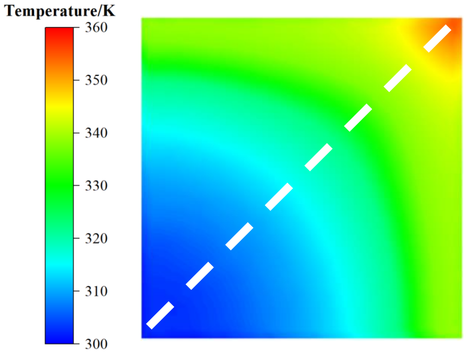


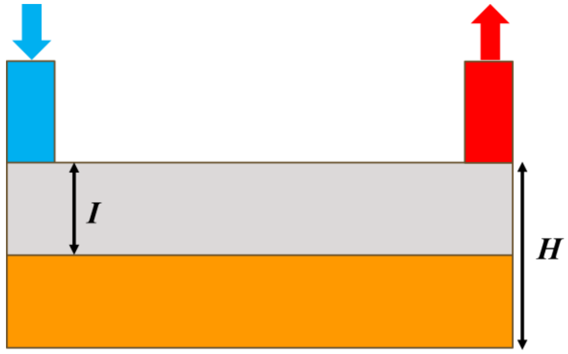
- ❑ Temperature uniformity is evaluated at different inlet velocities
- ➢ Jet coolers with CIOs show a much more uniform surface temperature.
- ❖ Good heat spreading in CIO structure

Jet Cooling on CIOs vs. Flat surfaces

Temperature at different nozzle-to-CIO distances(I)







- Effects of nozzle-to-CIO distance (I) are studied:
  - Impact of I is almost negligible for flat surfaces.
  - T_s in system with CIOs decreases with increasing I.

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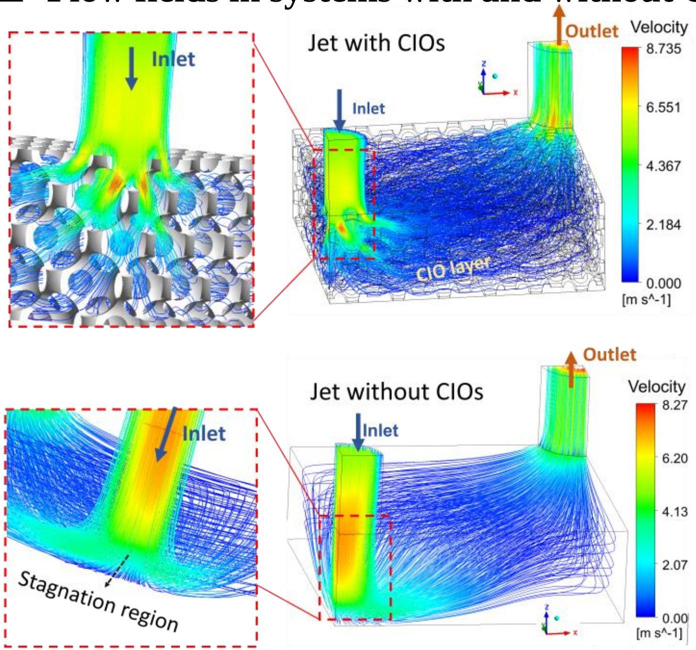
Jet Cooling on CIOs vs. Flat surfaces

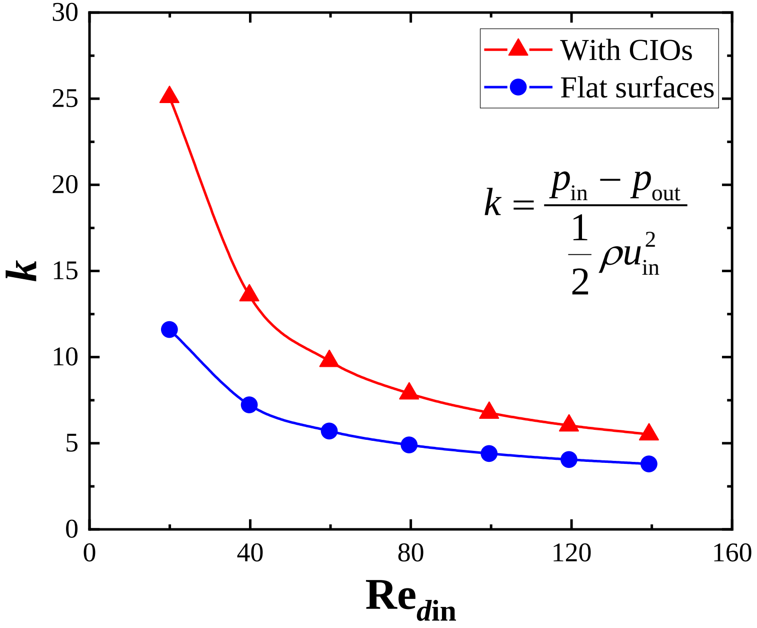
Pressure drop

- Flow fields in systems with and without CIOs



➢ Part of inlet flow is **redistributed** among CIOs.

- Pressure drop at **different inlet velocities**



➢ CIOs **increase** the system pressure drop.

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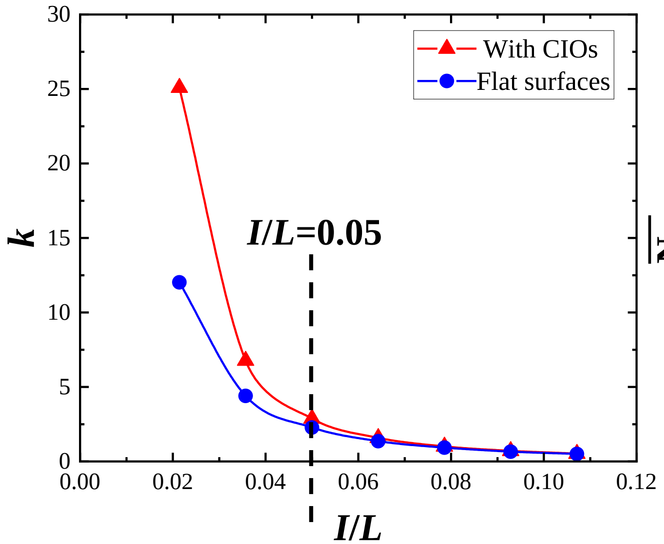
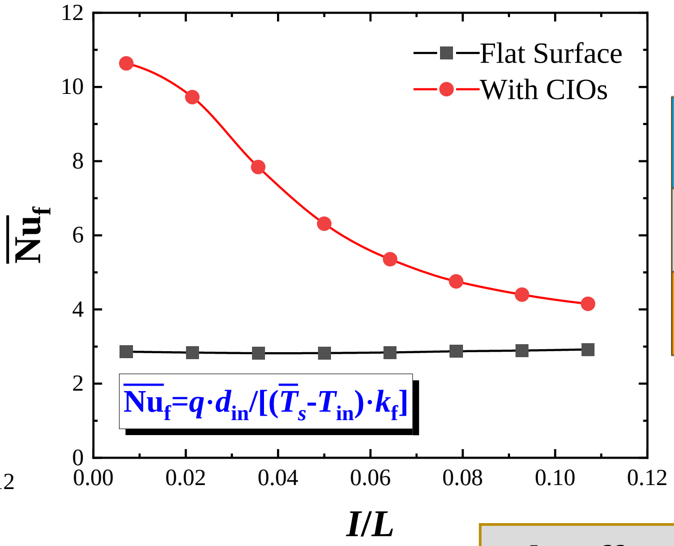
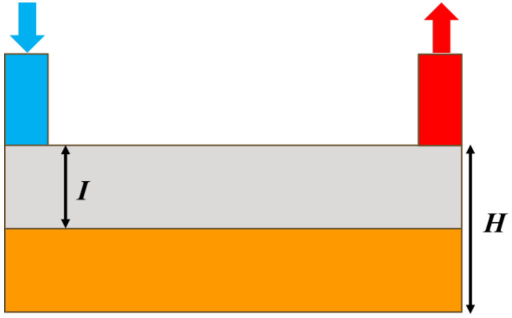
Impact of nozzle-to-CIO distance (I)

❑ ***k* at different *I* (Re_{din}=99.50)**



❑ **Nu_f at different *I* (Re_{din}=99.50)**





- **Effects of CIOs on pressure drop reduced by increasing *I*.**
- ***I/L*<0.05: *k* is obviously enlarged due to CIO structure.**
- ***I/L*>0.05: *k* is almost the same for systems with flat surfaces and CIOs.**
- **Heat transfer coefficient is also close to that without CIOs at large *I*.**

Why effects of CIOs on thermofluidic characteristics are suppressed at large I?

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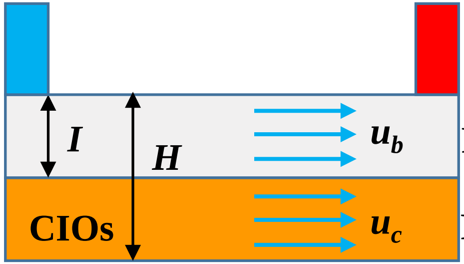
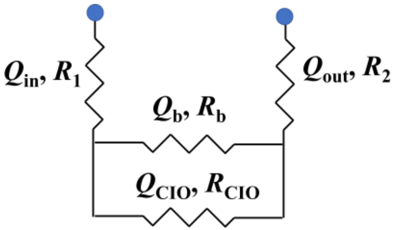
Definition of Bypass Ratio



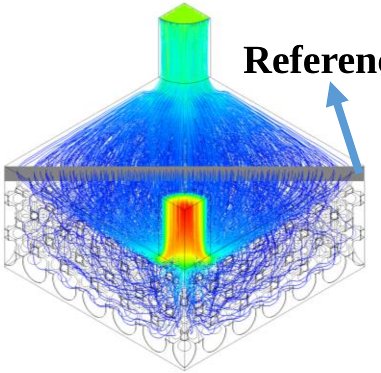
Flow in channel

Flow in CIOs

Flow resistance network



- Flow distribution due to resistance.
- Channel resistance affected by *I*.
- Variation of flow rate leads to different thermofluidic characteristics.



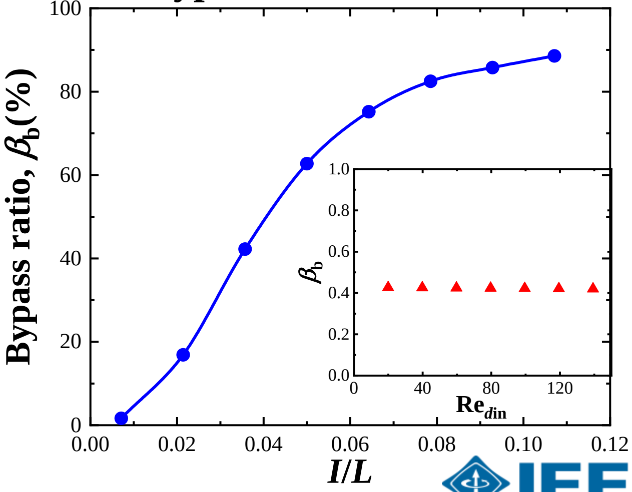
Reference Plane A_{ref}

Bypass ratio:

$$\beta_b = \frac{\text{Flow rate in channel}}{\text{Total flow rate}}$$

$$\beta_b = \frac{\int_{A_{ref}} \vec{u} \cdot d\overrightarrow{A_{ref}}}{A_{in} u_{in}}$$

Bypass ratio at different *I*



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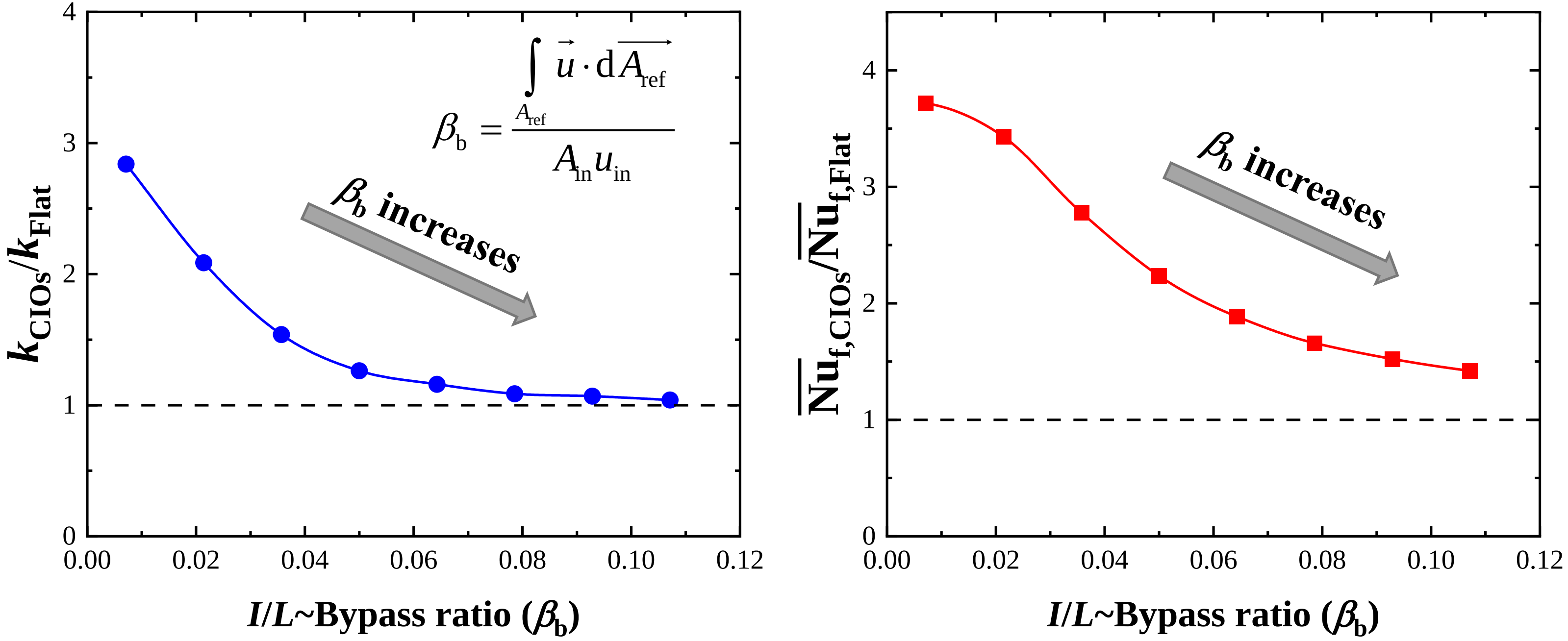
Effects of Bypass Ratio

- Comparison between thermofluidic characteristics of jet coolers with and without CIOs



- As bypass ratio increases, flow rate in CIOs is decreased, reducing the effects of CIOs.

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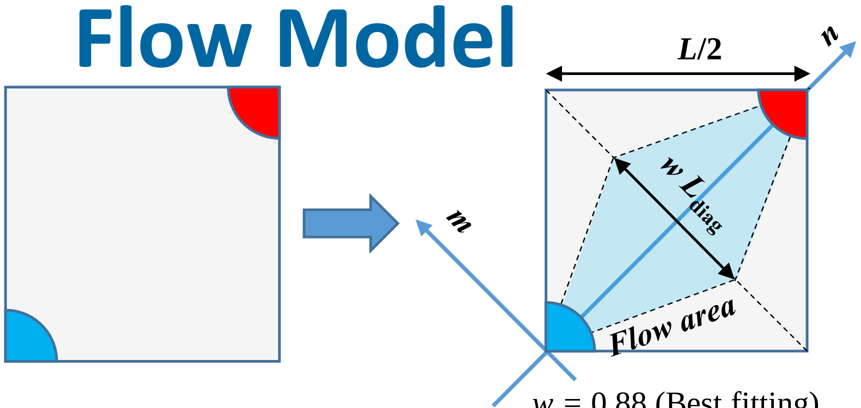
Flow Model



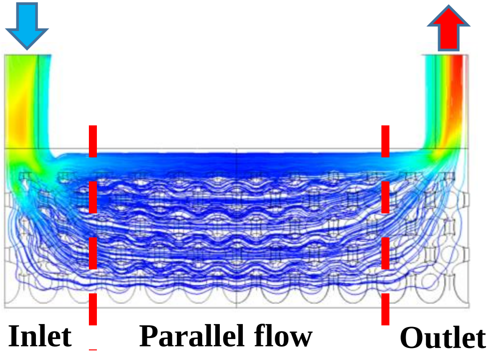
$w = 0.88$ (Best fitting)

Bypass Ratio $\left(\frac{\mathrm{d}p}{\mathrm{d}n}\right)_{\mathrm{CIO}} = \left(\frac{\mathrm{d}p}{\mathrm{d}n}\right)_{\mathrm{bypass}}, u_b A_b + u_c A_c = Q_{\mathrm{in}}$

Flow between parallel plates: $\left(\frac{\mathrm{d}p}{\mathrm{d}n}\right)_{\mathrm{bypass}} = \frac{3\mu}{(I/2)^2} u_b$

Dietrich et al. 2009: $\left(\frac{\mathrm{d}p}{\mathrm{d}n}\right)_{\mathrm{CIO}} = 110 \frac{\mu}{\psi d_h^2} u_c + 1.45 \frac{\rho}{\psi^2 d_h} u_c^2$

$\Rightarrow u_b \,\&\, u_c \Rightarrow \beta_b = \frac{u_b A_b}{u_b A_b + u_c A_c}$



- Parallel flow regime
- Inlet regime
- Outlet regime

Pressure Drop

$$\Delta p = \boxed{\frac{1}{2} k \rho u_{\mathrm{in}}^2} + \boxed{2 \int_{R_{\mathrm{in}}}^{L_{\mathrm{diag}}/2} \left(\frac{\mathrm{d}p}{\mathrm{d}n}\right)_{\mathrm{CIO}} \mathrm{d}n}$$

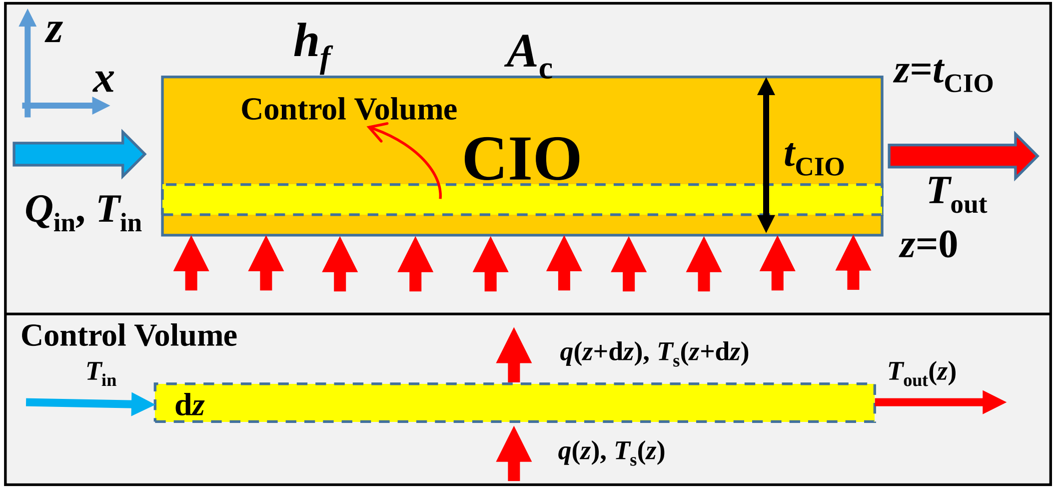
Δp near inlet and outlet **Δp_{para} from parallel flow**

$$k = \left(21.2 \frac{d_{\mathrm{in}}}{L} + 14.5\right) \mathrm{Re}_{din}^{-0.73 \frac{d_{\mathrm{in}}}{L} - 0.26} \left(2.26 \frac{t}{L} + 0.89\right) \left(0.37 \left(\frac{I}{L}\right)^{0.15} + 0.55\right) + 0.8$$

$$\left(0.05 \le \frac{d_{in}}{L} \le 0.6; 0.5 \le \frac{I}{d_{in}} \le 20; 32 \le \mathrm{Re}_{din} \le 1024; \frac{t}{L} \ge 0.1\right)$$

Wei et al., *Int. J. Heat Mass Transf.*, 2022, 182, 12865

Heat Transfer Model



- Solution for temperature distribution

$$T_s - T_{in} = Ae^{-rz} + Be^{rz}, r = \sqrt{\frac{1}{k_{eff}} \frac{\dot{m}c_p\left(1-\exp\left(-\frac{h_{CIO}A_{CIO}}{\dot{m}c_p}\right)\right)}{A_c t_{CIO}}}$$

Heat transfer coeff. in CIOs

Boundary Conditions

(1) $z = 0, q = q_{in}$

$q_{in} = -k_{eff}\left(-Ar + Br\right)$

(2) $z = t_{CIO}, q = q_c$

$q_c = -k_{eff}\left(-Are^{-rt_{CIO}} + Bre^{rt_{CIO}}\right)$

(3) $z = t_{CIO}, \theta_s = \theta_{top}$

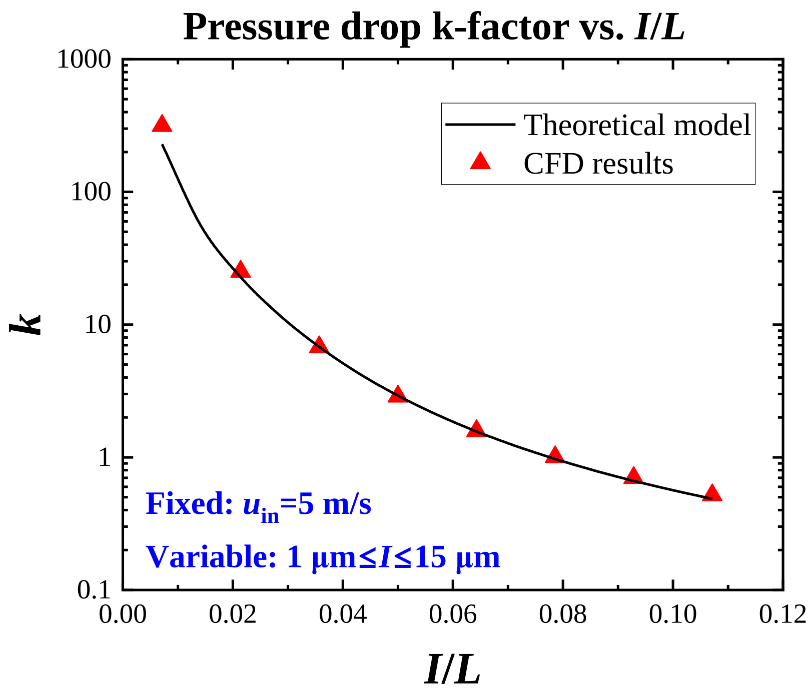
$\theta_{top} = -Ae^{-rt_{CIO}} + Be^{rt_{CIO}}$

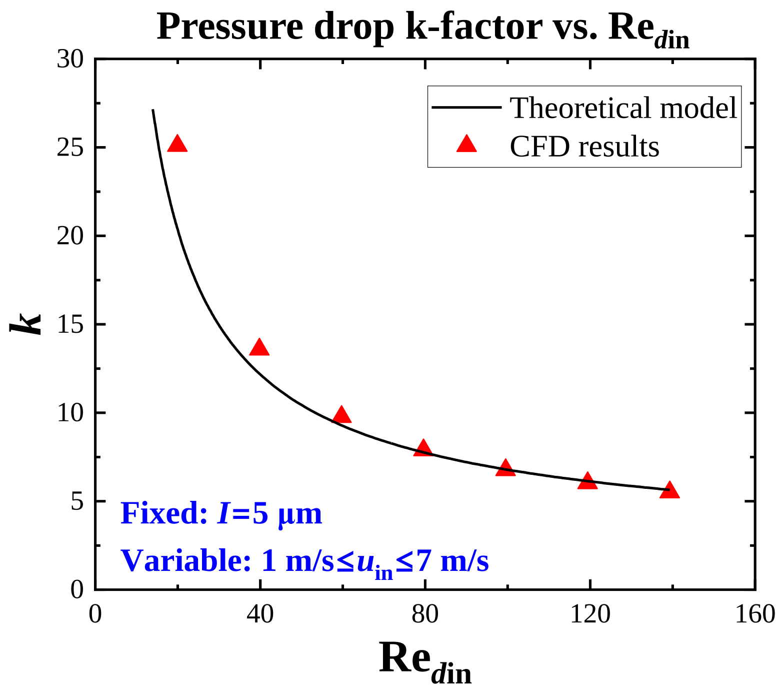
(4) Convection at $z = t_{CIO}$

$q_c = h_f \theta_{top}$

Heat transfer coeff. on the top surface of CIOs

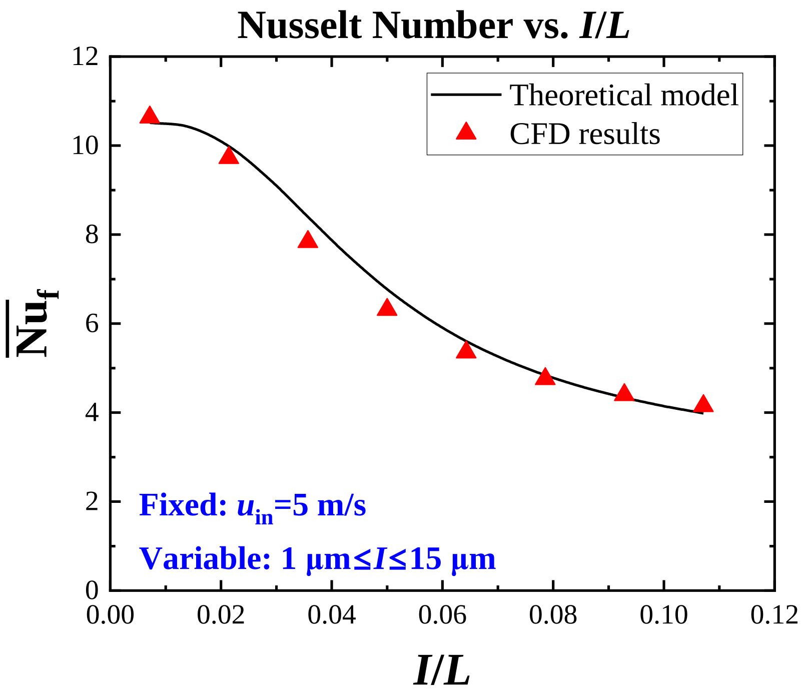
Results

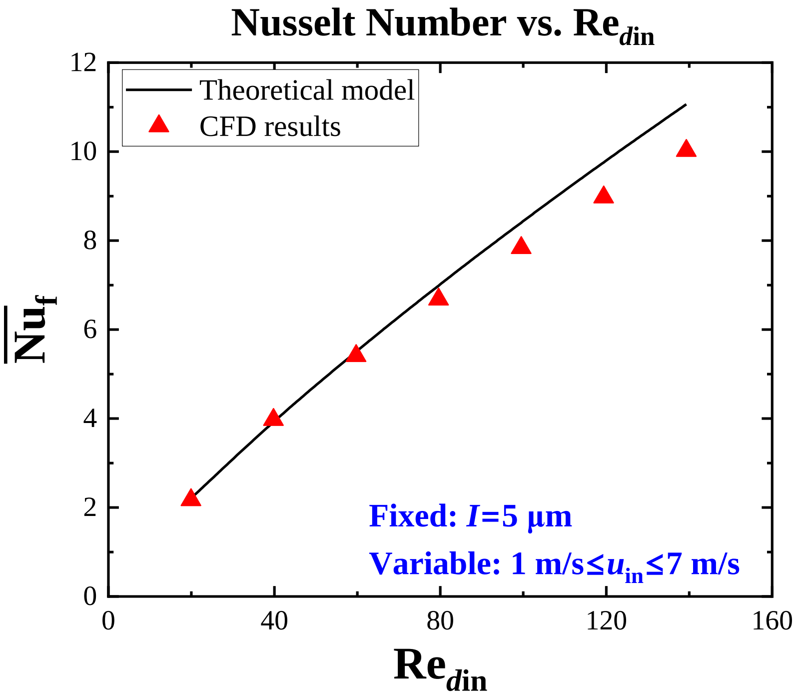




- **Flow characteristics at different inlet velocities and nozzle-to-CIO distances are well modeled.**

Results





- **Well capture Heat transfer characteristics at different inlet velocities and nozzle-to-CIO distances.**

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Conclusions

We perform CFD simulations to explore the possibility of integrating CIOs in single-phase impingement jet cooling solutions.

- Utilization of CIOs in single-phase jet coolers enables a lower and more uniform temperature on the chip interface.
- However, large flow resistance in CIOs will increase the total pressure drop of jet cooler.
- Increasing the nozzle-to-CIO distance results in a stronger bypass flow and thus decreases the pressure drop and Nusselt number.
- A reduced-order model is proposed to describe the flow and heat transfer characteristics of jet coolers with CIOs, showing a good accuracy.

Thank you!