Thermal Strategies for High Efficiency Thermoelectric Power Generation

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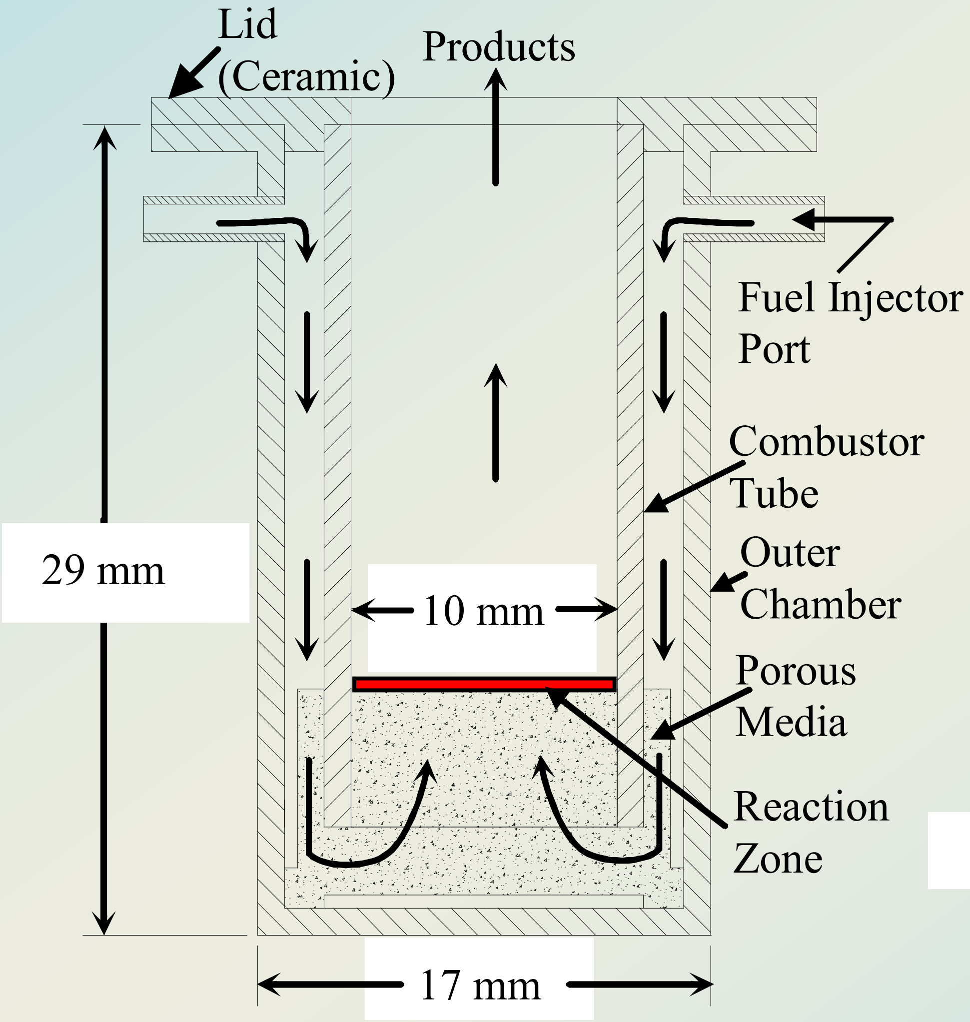
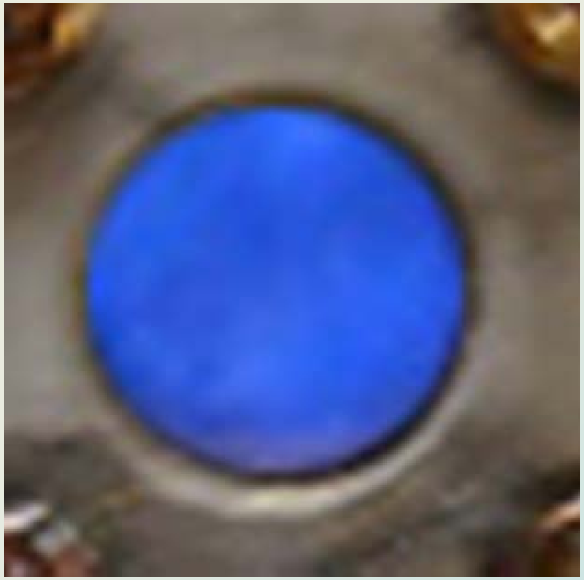
Portable Power Generation





Blue Flame

Kerosene flow rate = 40 g/hr,

Φ = 0.65, Qth = 460 W

Thermoelectric Efficiency

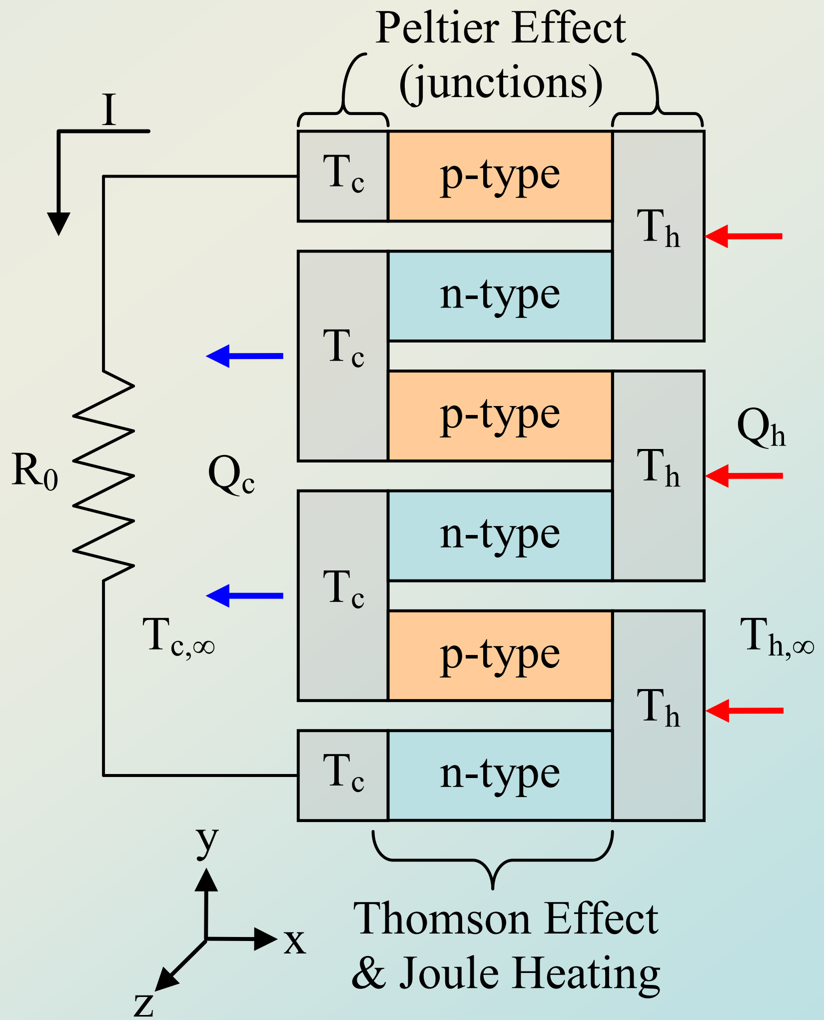
TE Efficiency: $$\eta_{TE} = \frac{W_e}{Q_h} = \eta_c . \gamma$$

Carnot Efficiency: $$\eta_c = \frac{T_h - T_c}{T_h}$$

TE Material Parameter: $$\gamma = \frac{\sqrt{1 + Z\,T} - 1}{\sqrt{1 + Z\,T} + T_c / T_h}$$

TE Figure of Merit: $$Z(T) = \frac{\alpha^2(T)}{\rho_e(T) \cdot k(T)}$$

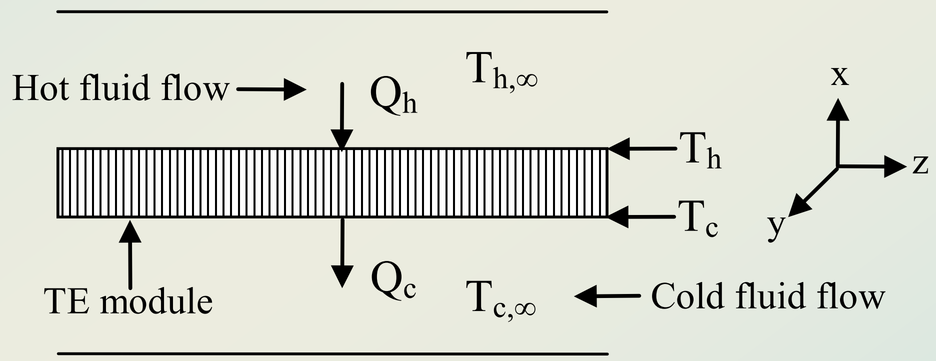
$$T = \frac{T_h + T_c}{2}$$



Thermoelectric Efficiency

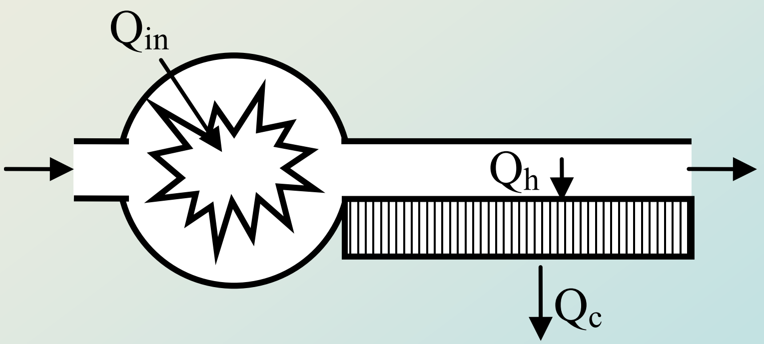
- TE Module Efficiency

$$\eta_m = \frac{\sum W_e}{\sum Q_h}$$



- TE System Efficiency

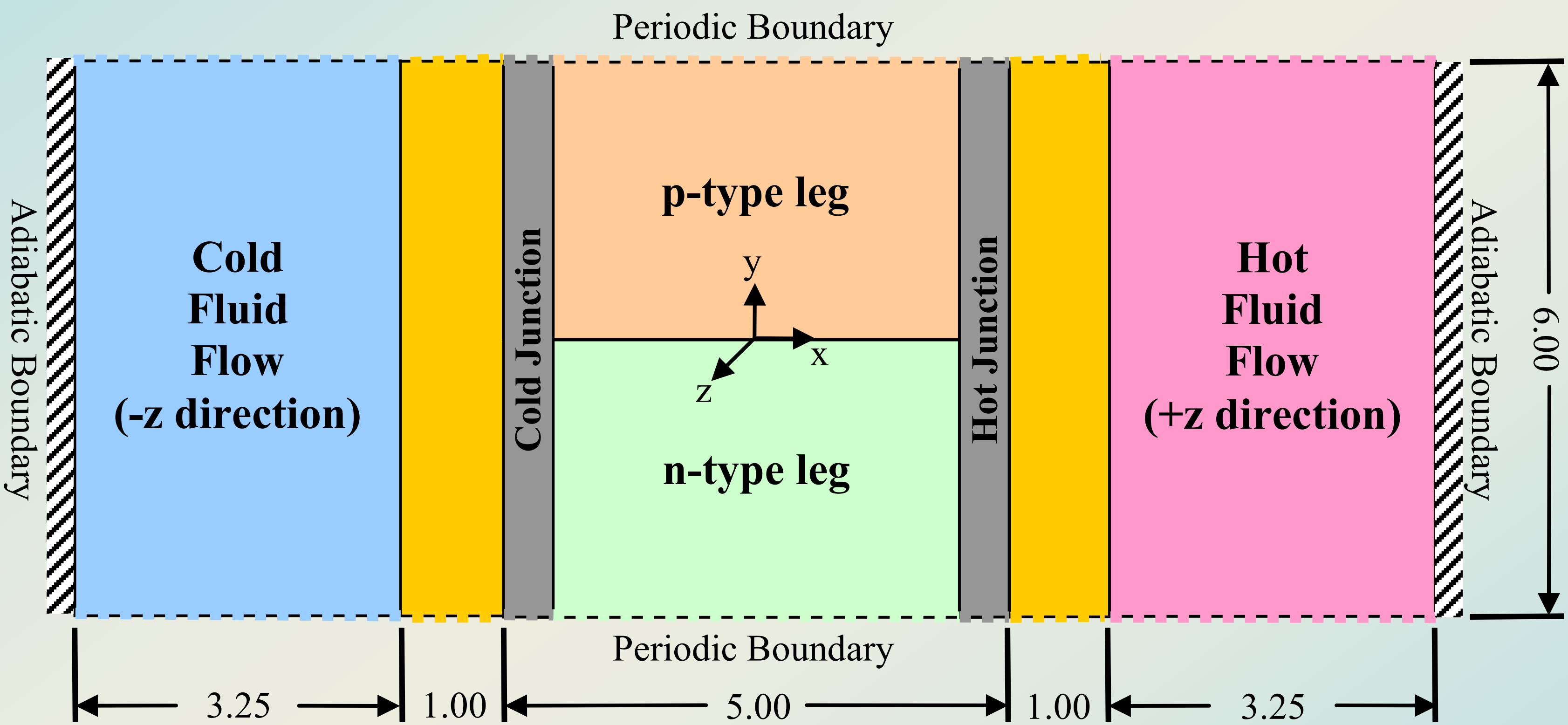
$$\eta_s = \frac{\sum W_e}{Q_{in}} = \frac{\sum Q_h}{Q_{in}} \cdot \frac{\sum W_e}{\sum Q_h}$$



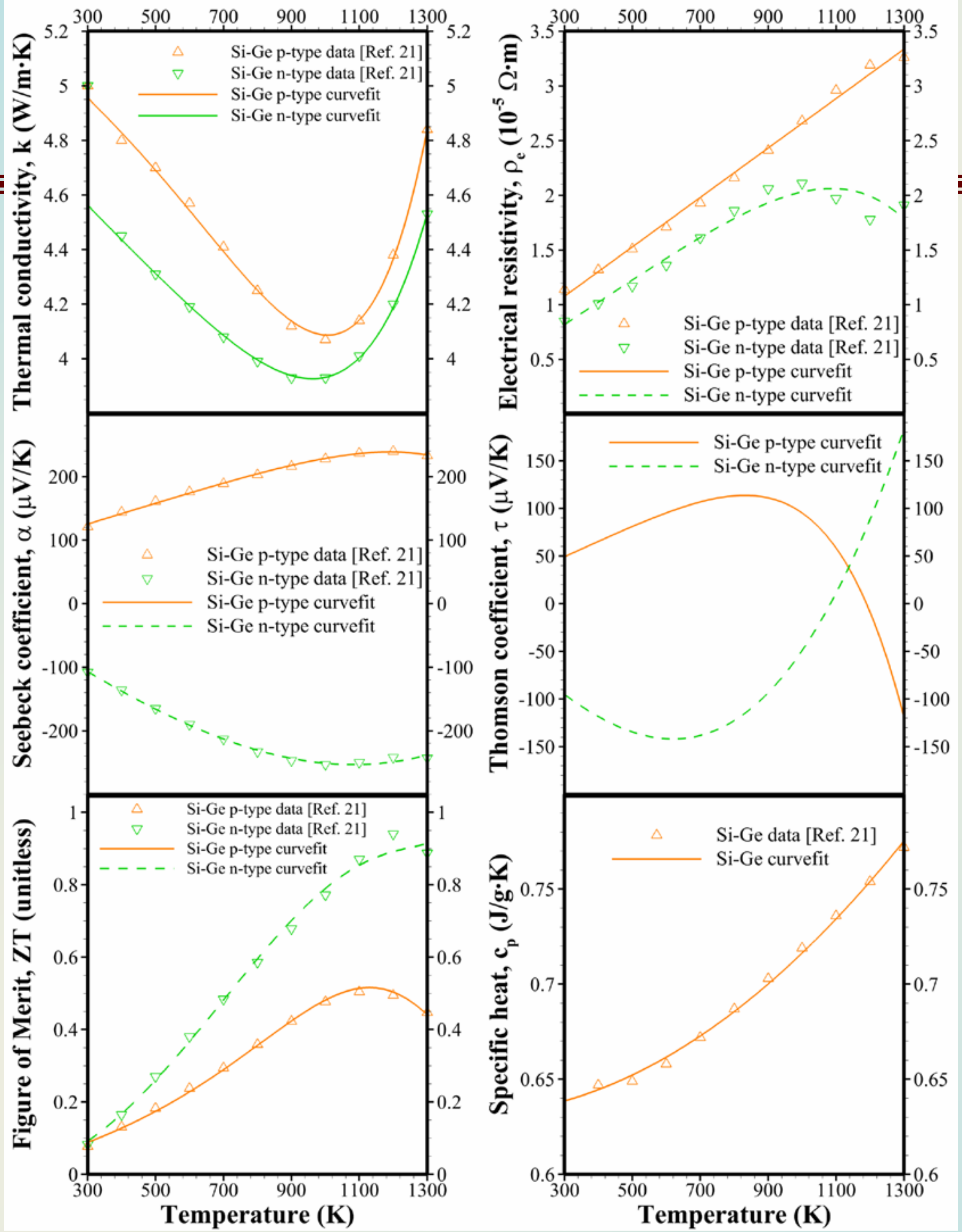
$$\eta_s = Q_R . \eta_m$$

Q_R is the Heat Input Ratio

3D CFD-TE Analysis



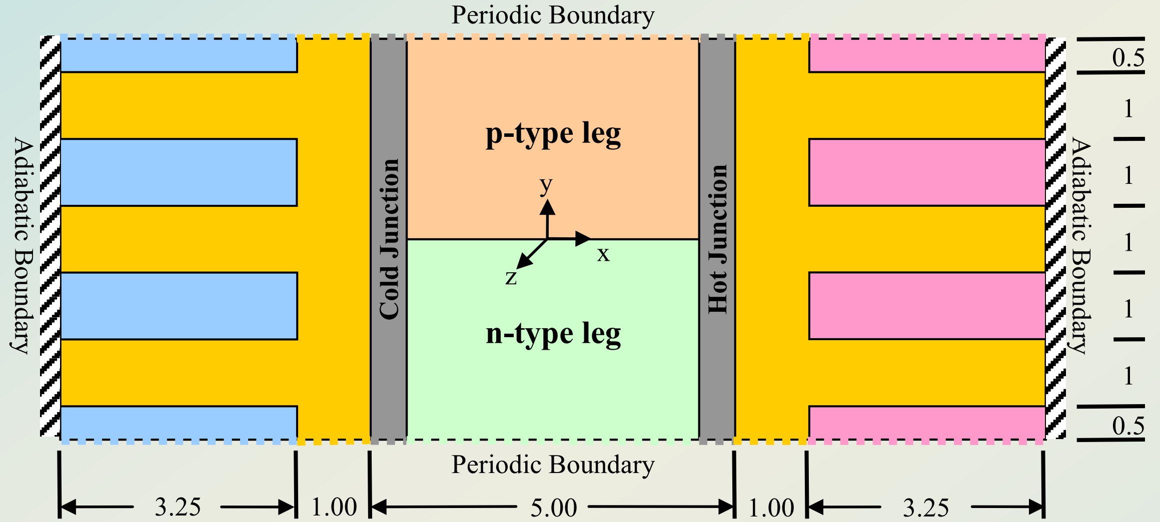
Baseline Configuration



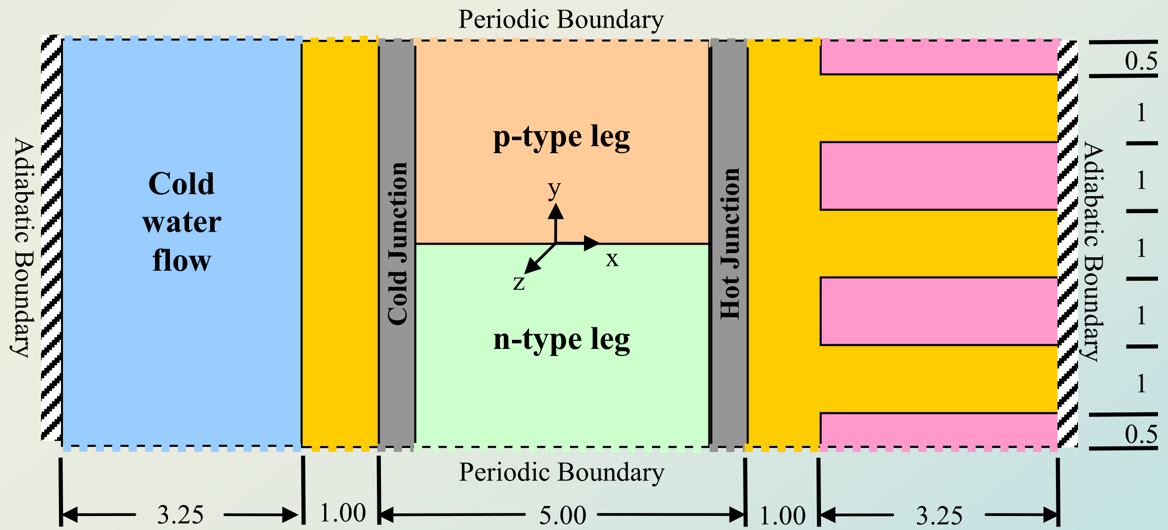
TE Material Properties Of Si-Ge taken from

Handbook of Thermoelectrics

Model Layout



Finned



Water-cooled

CFD Governing Equations

- Conservation of Mass

$$\frac{\partial}{\partial z}(\rho v_z)+\frac{\partial}{\partial r}(\rho v_r)+\frac{\rho v_r}{r}=S_m$$

- Conservation of Momentum

$$\nabla\cdot(\rho v_x\vec{v})=-\frac{\partial P}{\partial x}+\frac{\partial}{\partial x}\left(2\mu\frac{\partial v_x}{\partial x}-\frac{2}{3}\mu\nabla\cdot\vec{v}\right)+\frac{\partial}{\partial y}\left(\mu\frac{\partial v_x}{\partial y}+\mu\frac{\partial v_y}{\partial x}\right)+\frac{\partial}{\partial z}\left(\mu\frac{\partial v_x}{\partial z}+\mu\frac{\partial v_z}{\partial x}\right)+S_x$$

$$\nabla\cdot(\rho v_y\vec{v})=-\frac{\partial P}{\partial y}+\frac{\partial}{\partial x}\left(\mu\frac{\partial v_y}{\partial x}+\mu\frac{\partial v_x}{\partial y}\right)+\frac{\partial}{\partial y}\left(2\mu\frac{\partial v_y}{\partial y}-\frac{2}{3}\mu\nabla\cdot\vec{v}\right)+\frac{\partial}{\partial z}\left(\mu\frac{\partial v_y}{\partial z}+\mu\frac{\partial v_z}{\partial y}\right)+S_y$$

$$\nabla\cdot(\rho v_z\vec{v})=-\frac{\partial P}{\partial z}+\frac{\partial}{\partial x}\left(\mu\frac{\partial v_z}{\partial x}+\mu\frac{\partial v_x}{\partial z}\right)+\frac{\partial}{\partial y}\left(\mu\frac{\partial v_z}{\partial y}+\mu\frac{\partial v_y}{\partial z}\right)+\frac{\partial}{\partial z}\left(2\mu\frac{\partial v_z}{\partial z}-\frac{2}{3}\mu\nabla\cdot\vec{v}\right)+S_z$$

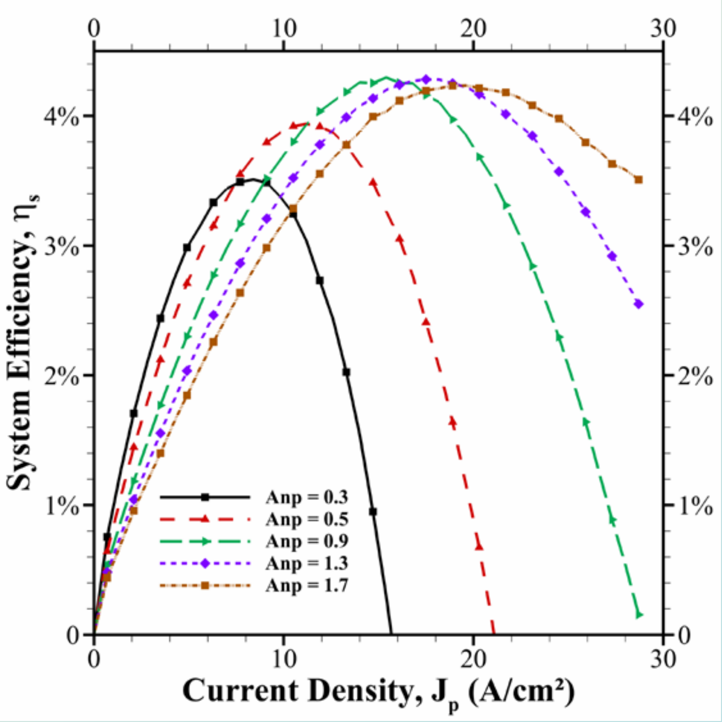
- Conservation of Energy

$$\frac{\partial}{\partial x}(\rho v_x c_p T)+\frac{\partial}{\partial y}(\rho v_y c_p T)=\frac{\partial}{\partial x}\left(k_x\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_y\frac{\partial T}{\partial y}\right)+S_E$$

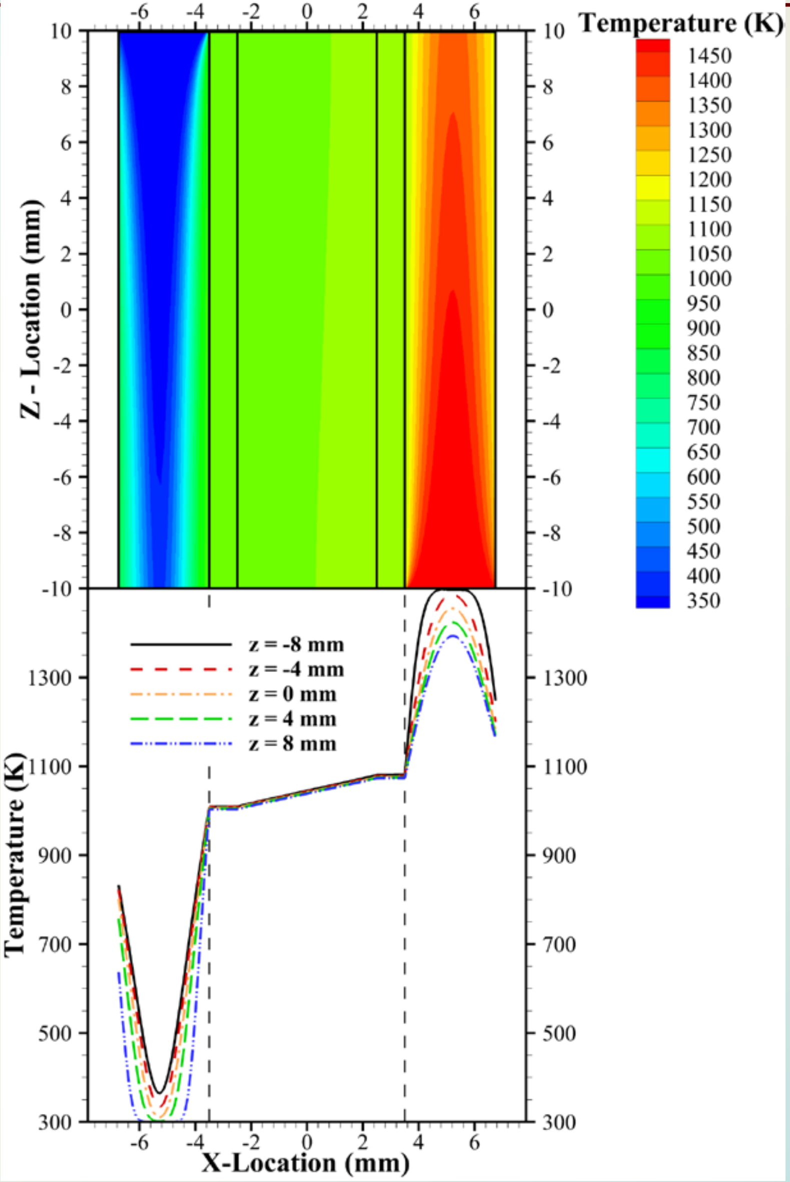
- Source Terms
  - Mass - S_m; Momentum - S_x, S_y & S_z; Energy - S_E

Thermoelectric Equations

- Thermoelectric junctions
  - Hot junction $$S_{E,h} = \frac{1}{1+A_{np}}\left[\left(\rho_{e,p} + \frac{\rho_{e,n}}{A_{np}}\right)J_p^2 - \frac{J_p \cdot T \cdot (\alpha_p - \alpha_n)}{t_h}\right]$$
  - Cold junction $$S_{E,c} = \frac{1}{1+A_{np}}\left[\left(\rho_{e,p} + \frac{\rho_{e,n}}{A_{np}}\right)J_p^2 - \frac{J_p \cdot T \cdot (\alpha_n - \alpha_p)}{t_h}\right]$$
- Thermoelectric legs
  - p-type $$S_{E,p} = \rho_{e,p} J_p^2 - J_p \cdot \tau_p \cdot \frac{\partial T_p}{\partial x}$$
  - n-type $$S_{E,n} = \rho_{e,n}\frac{J_p^2}{A_{np}^2} + \frac{J_p}{A_{np}} \cdot \tau_n \cdot \frac{\partial T_n}{\partial x}$$
- $J_p = I/A_p$; $A_{np} = A_n/A_p$
- J_p and A_{np} optimized for η_s

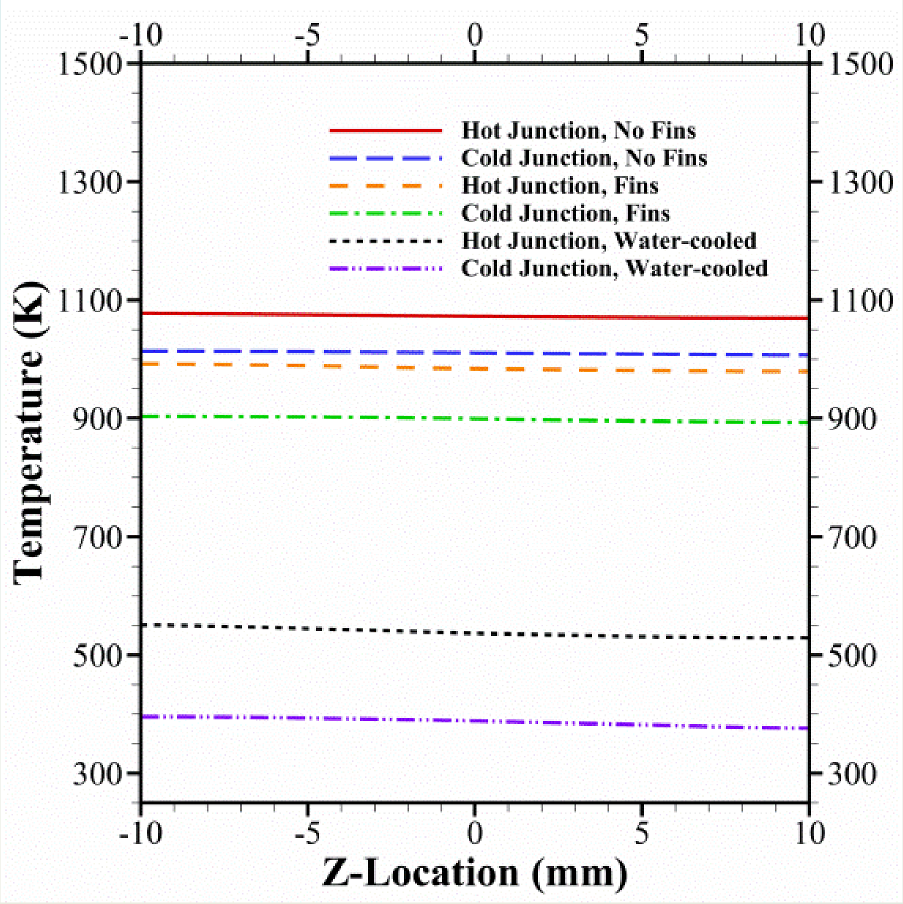


Temperature Contours

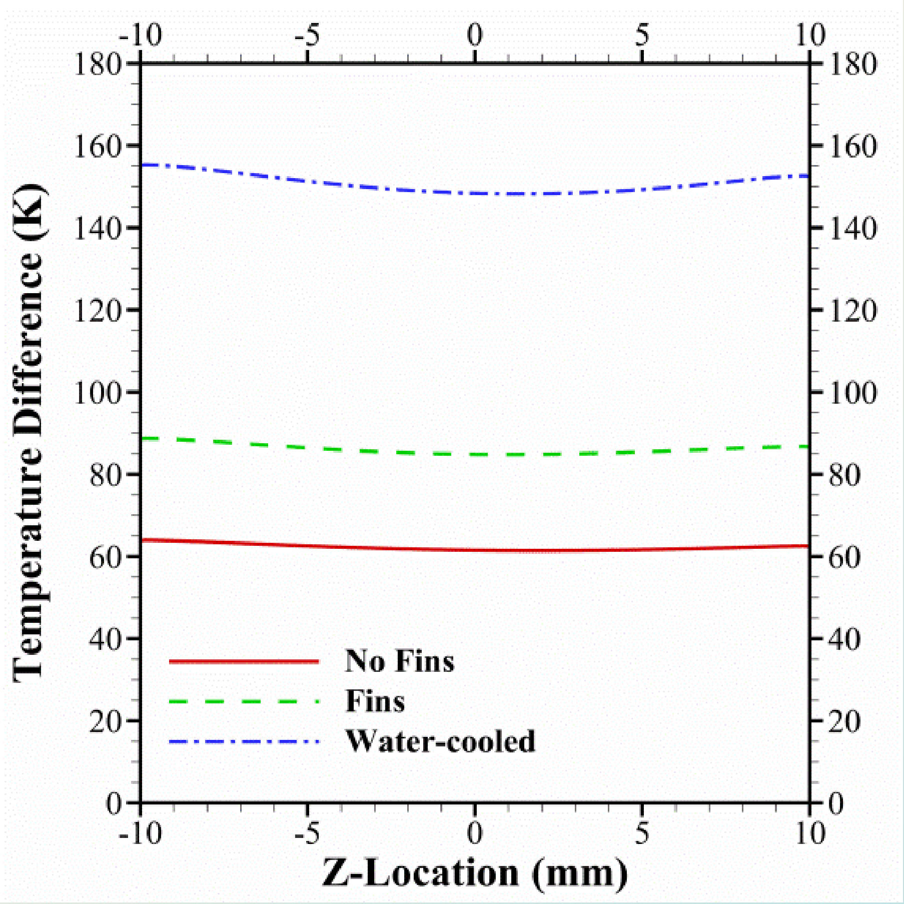


No fins

Axial Mean Temperature Profile

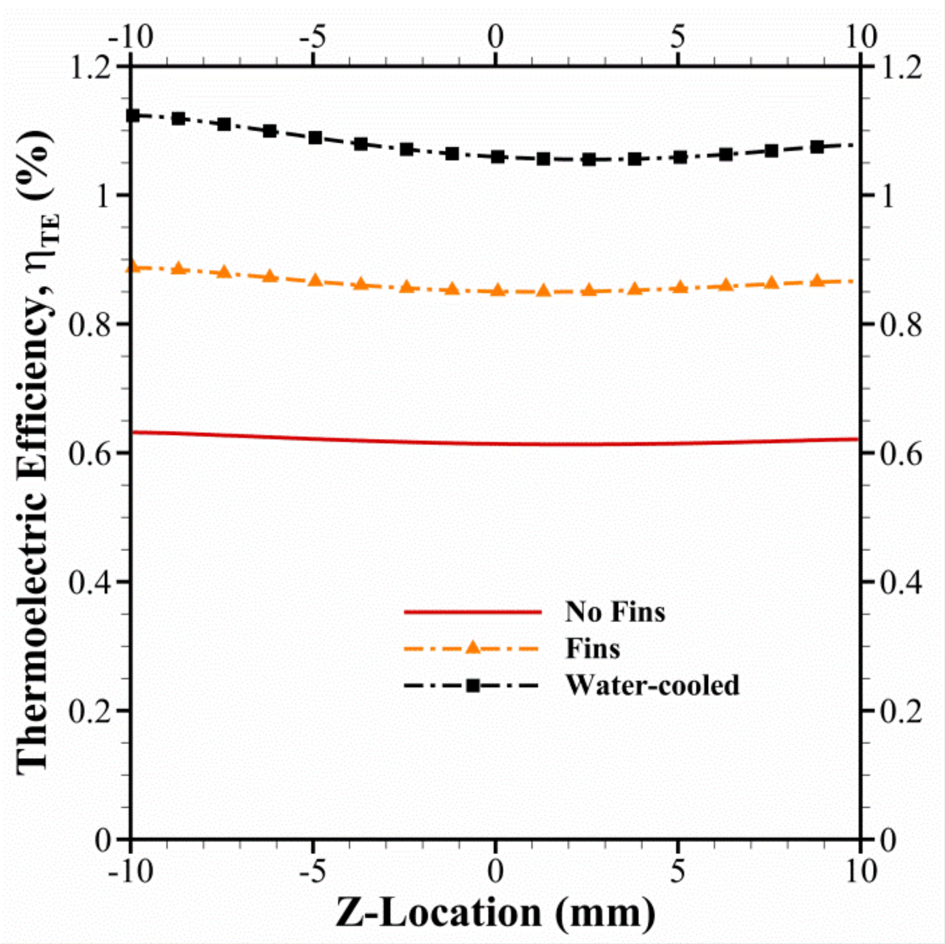


Mean Junction Temperature



Hot Junction - Cold Junction

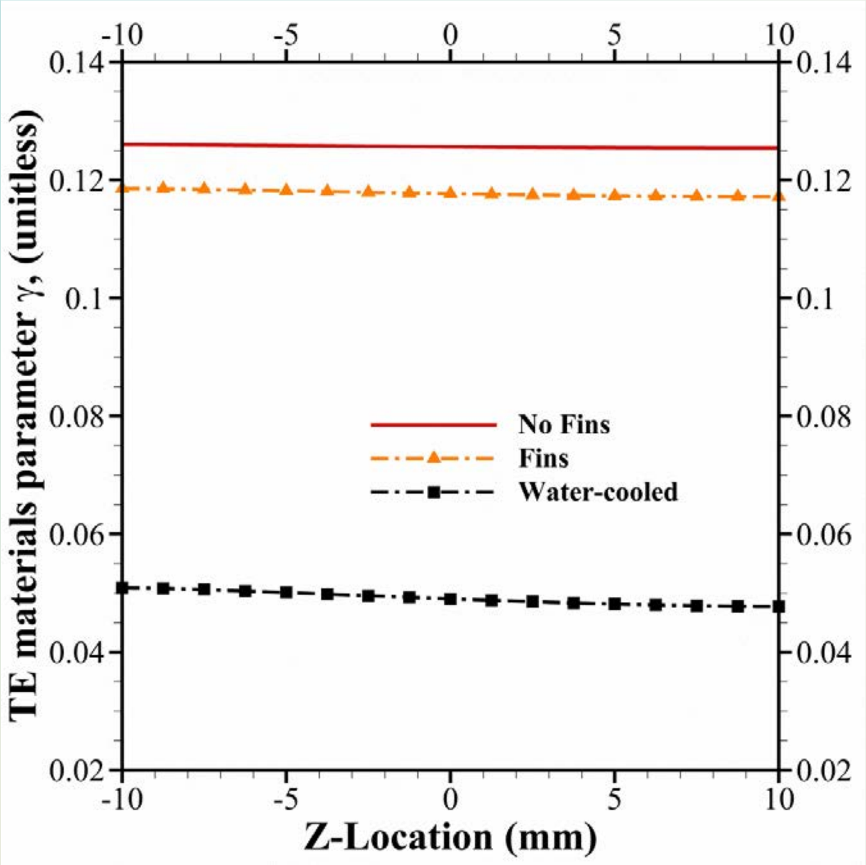
TE Module Performance



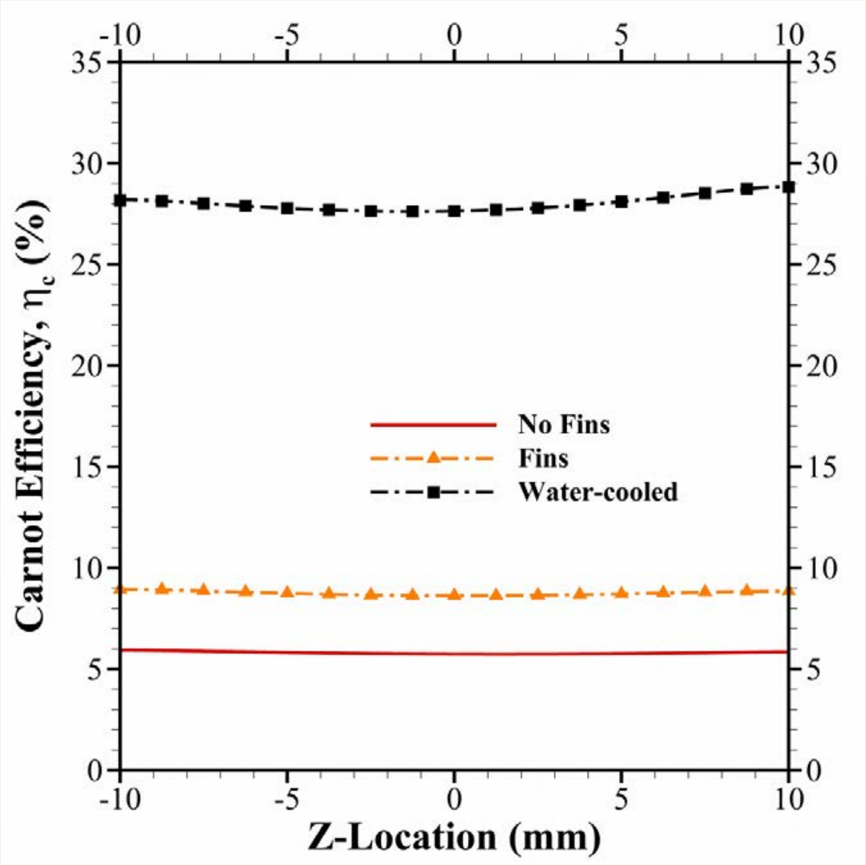
$$\eta_{TE} = \frac{W_e}{Q_h} = \eta_c . \gamma$$

Thermoelectric Efficiency, η_{TE}

TE Module Performance



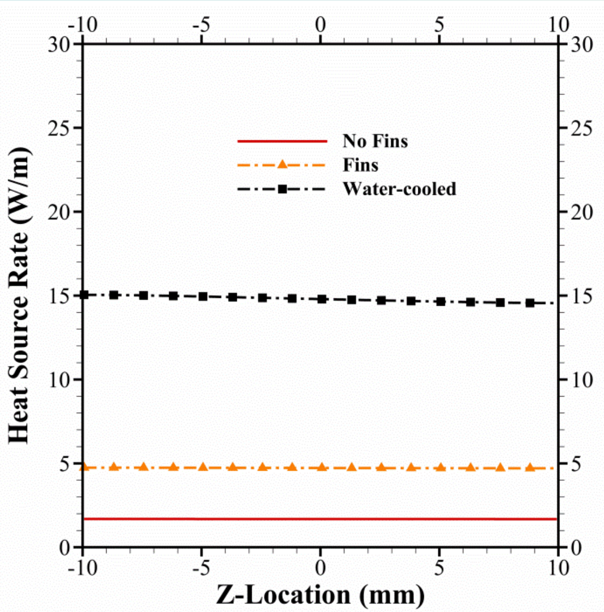
TE material parameter, γ



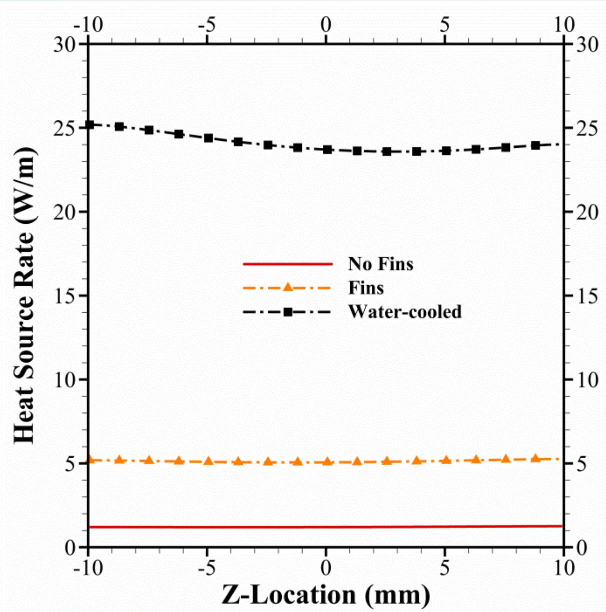
Carnot Efficiency

$$\eta_{TE} = \frac{W_e}{Q_h} = \eta_c . \gamma$$

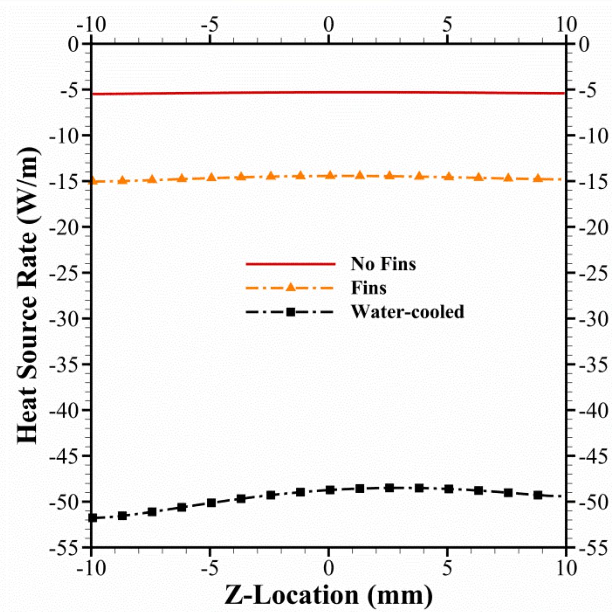
Individual Thermoelectric Effects



Joule Heating



Thomson Effect

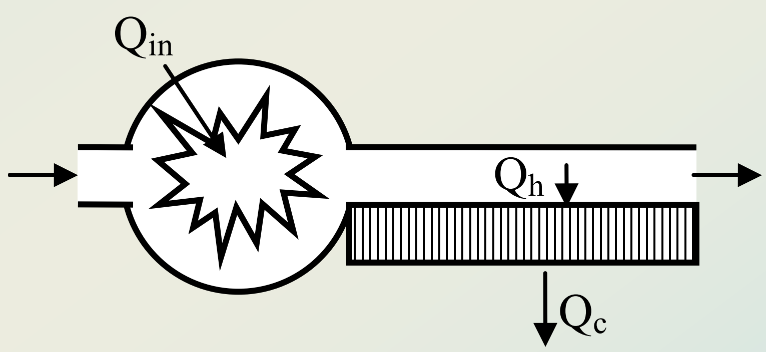


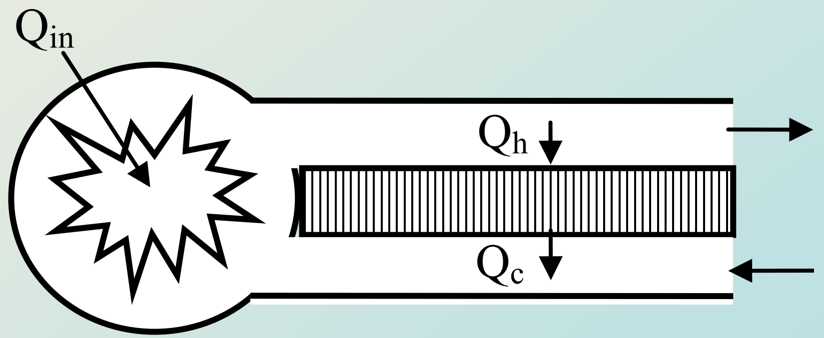
Peltier Effect

- Heat source rate of individual TE effects
  - Joule heating always causes power loss
  - Thomson effect is also causing power loss in this case
  - Peltier effect absorbs heat to generate power

TE Module Performance

	No Fins	Finned	Water-cooled
Thermoelectric efficiency, η_m	0.62 %	0.86 %	1.08 %
Heat Input Ratio, Q_R	0.17	0.46	0.81
System efficiency, η_s	0.10 %	0.40 %	0.87 %
With Heat Recirculation			
Heat Input Ratio, Q_R	0.20	0.84	4.05
System efficiency, η_s	0.13 %	0.72 %	4.36 %





Summary Remarks

- The system efficiency increases by an order of magnitude even though the TE material and fluid inlet temperatures are the same.

- High ZT does not translate into high TE system efficiency without the thermal considerations.

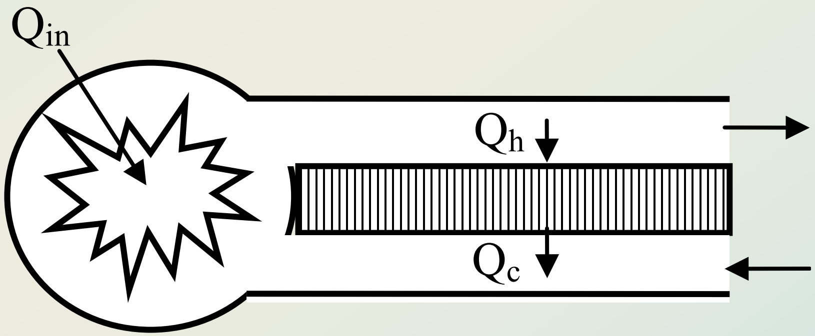
- Heat recirculation offers an opportunity to greatly increase TE system efficiency (factor of 44 in present study).

- Thermal strategy is extremely important.

Heat Exchange Effectiveness

- Define heat exchange effectiveness of the TE module with heat recirculation:

$$\varepsilon = \frac{\dot{m}(h_{h,in} - h_{h,out})}{\dot{m}(h_{h,in} - h_{c,in})} = \frac{\sum Q_h}{Q_{in} + \sum Q_c}$$



- Heat exchange effectiveness of 1.0 will require infinite surface area, but a value of 0.8 is plausible in modern heat exchange systems.

Heat Recirculation

$$\eta_s = \frac{\sum W_e}{Q_{in}} = \frac{\sum Q_h}{Q_{in}} \cdot \frac{\sum W_e}{\sum Q_h}$$

$$\eta_s = Q_R . \eta_m$$

$$Q_R = \frac{1}{\frac{1-\varepsilon}{\varepsilon} + \eta_m}$$

η_m	$\varepsilon=0.6$		$\varepsilon=0.7$		$\varepsilon=0.8$	
	Q_R	η_s	Q_R	η_s	Q_R	η_s
5%	1.4	7.0	2.1	10.5	3.33	16.0
10%	1.3	13.0	1.9	19.0	2.86	28.6
20%	1.2	24.0	1.6	32.0	2.22	44.4

Summary

- Thermal resistance between TE module and fluids can significantly reduce the TE system efficiency.
- Thermal strategies can lead to high TE system efficiency, even with poor TE material performance.
- Improved understanding of the interaction of heat transfer, fluid flow, TE materials, and TE power generation is feasible with our 3D CFD-TE model.
- TE system efficiency can be increased significantly by employing heat recirculation.
- We are developing integrated TE system configurations that can achieve high heat exchange effectiveness and thus, high TE system efficiency.

Acknowledgments

Troy Dent

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Putting the heat on Thermoelectrics

Questions ?