Entropy generation in the woven mesh regenerator filler of cryocoolers

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Introduction

- Regenerators are key components in regenerative cryocoolers. For good performance they should have high heat capacity, low axial thermal conduction, low friction and high porosity. Regenerator fillers come in various geometries, including powders composed of spheres, metal foams, wire mesh, and micro-manufactured structures.
- To optimize a regenerator filler, both first and second laws of thermodynamic must be considered. First law analysis aims to maximize the thermal performance; second law analysis is meant to minimize the entropy generation and exergy destruction and losses.
- In this study, entropy generation is investigated by three-dimensional pore level CFD simulations in a woven mesh regenerator, (wire packing), for steady state and oscillating flow.
- For steady flow, the effects of geometric size, wire diameter, porosity, geometry irregularity and operating conditions are evaluated to optimize the regenerator and minimize exergy destruction.
- For oscillating flow, entropy generation is investigated for one geometry and for different Reynolds numbers.

Physical System

➢ **Geometry**

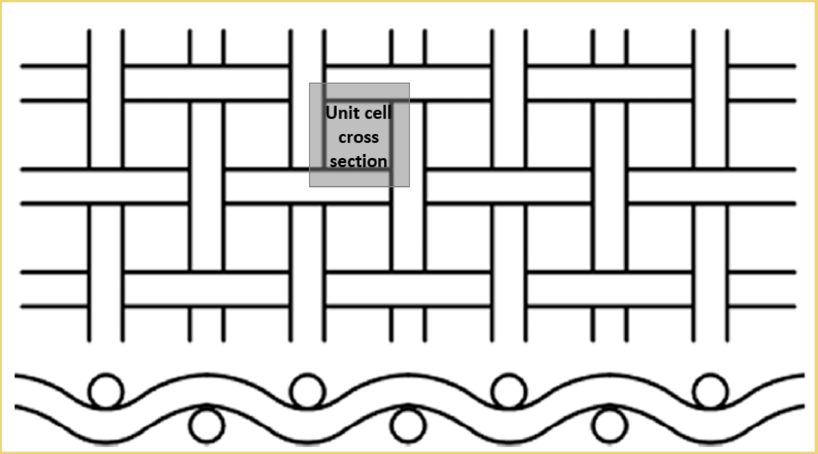

Figure 1. woven mesh regenerator structure

➢ **Unit cell concept as a computational domain**

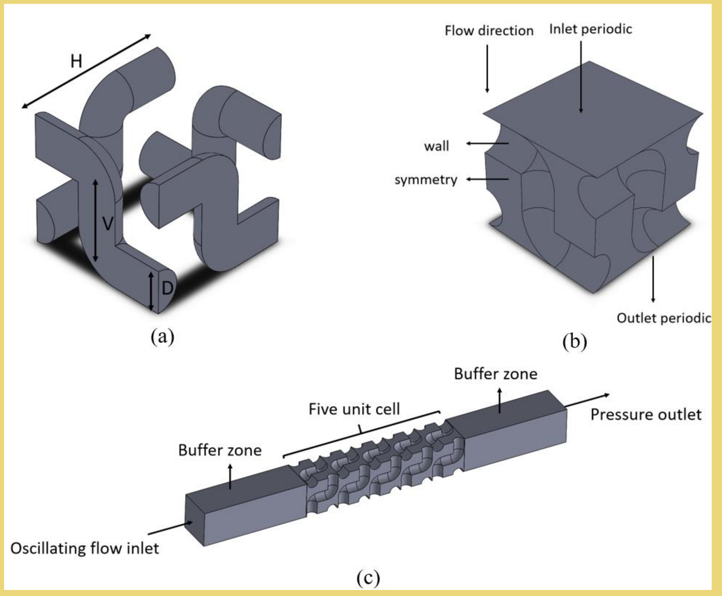

Figure 2. Computational domain and boundary conditions (a) solid part of unit cell for steady state condition, (b) fluid part of unit cell for steady state, (c) fluid part of domain for oscillating flow calculation

➢ **Sensitivity analysis on the unit cell**

Table 1. Unit cell geometry configurations for steady state analysis

Case number	D (µm)	H(µm)	V(µm)	Porosity	D_h(µm)
1	30	100	60	0.76	110
2	20	100	60	0.88	153
3	40	100	60	0.64	71
4	30	70	60	0.62	50
5	30	130	60	0.83	156
6	30	100	40	0.74	87
7	30	100	80	0.78	109
8	Geometry irregularity, case 1 partially blocked by particle with diameter 10 µm				
9	Geometry irregularity, case 1 partially blocked by particle with diameter 20 µm				

➢ **Operation Conditions**

Table 2. Operation conditions

Temperature (K)	300
Heat flux from walls range (W/m^2)	250-1000
Mean pressure (MPa)	3.87
Reynolds number range	2-40
Working fluid	Helium
Wire material	Stainless steel
Frequency in oscillating flow (Hz)	20

Set of Equations

- continuity, momentum and energy equations

$$\frac{\partial u_j}{\partial x_j} = 0$$

$$\frac{\partial u_i}{\partial t} + \frac{\partial}{\partial x_j} u_j u_i = -\frac{1}{\rho_f}\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\nu_f\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)$$

$$\rho_f c_f\left(\frac{\partial T}{\partial t} + \frac{\partial}{\partial x_j}u_j T\right) = \frac{\partial}{\partial x_j}\left(k_f \frac{\partial T}{\partial x_j}\right)$$

$$\rho_s c_s\left(\frac{\partial T}{\partial t}\right) = \frac{\partial}{\partial x_j}\left(k_s \frac{\partial T}{\partial x_j}\right)$$

- Volume average and volume-cycle average variable

$$\langle\beta\rangle = \frac{1}{V_f}\int_{V_f}\beta dV \qquad \langle\beta\rangle_{cycle} = \frac{1}{t_{cycle}}\int_{t_{cycle}}\langle\beta\rangle\, dt$$

- Local entropy generation

$$\dot{S}_{gen} = \dot{S}_{g,FF} + \dot{S}_{g,HT}$$

$$\dot{S}_{g,FF} = \frac{\mu_f}{T}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\frac{\partial u_i}{\partial x_j}$$

$$\dot{S}_{g,HT} = \frac{k_f}{T^2}\left[\left(\frac{\partial T}{\partial x}\right)^2 + \left(\frac{\partial T}{\partial y}\right)^2 + \left(\frac{\partial T}{\partial z}\right)^2\right]$$

- Dimensionless numbers

$$Re = \frac{\rho_f|\langle\vec{u}\rangle|D_h}{\mu_f}, \qquad Nu = \frac{\frac{q''}{T_{wall} - \langle T_f\rangle}D_h}{k_f}, \qquad Be = \langle\frac{\dot{S}_{g,HT}}{\dot{S}_{g,FF} + \dot{S}_{g,HT}}\rangle$$

$$S_n = \dot{S}_{gen}\frac{D_h^2}{k_f} \qquad S_t = \langle S_n\rangle = \frac{1}{V_f}\int_{V_f} S_n dV$$

- Performance evaluation criterion

$$PEC = \frac{Nu}{S_t}$$

Results

➢ **Steady state flow**

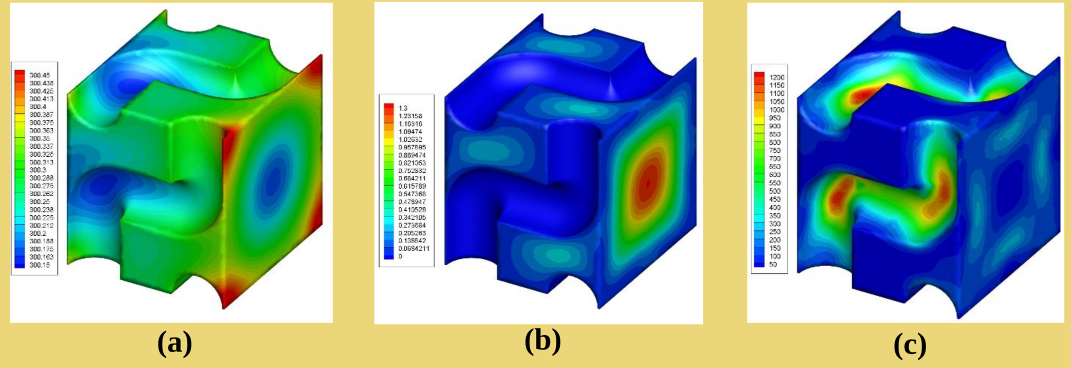

Figure 3. Contour plots of case number 1 at Re= 18 and q" = 750 W/m^2, (a) temperature (K), (b) velocity magnitude (m/s), (c) local total volumetric entropy generation rate (W/m^{3}K).

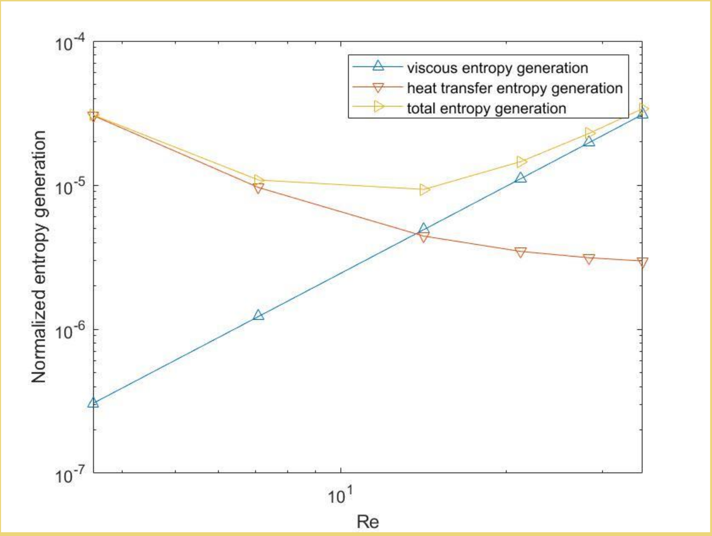

Figure 4. Viscous, heat transfer and total volume average volumetric entropy generation rate in case 1 for q"= 750 W/m^2.

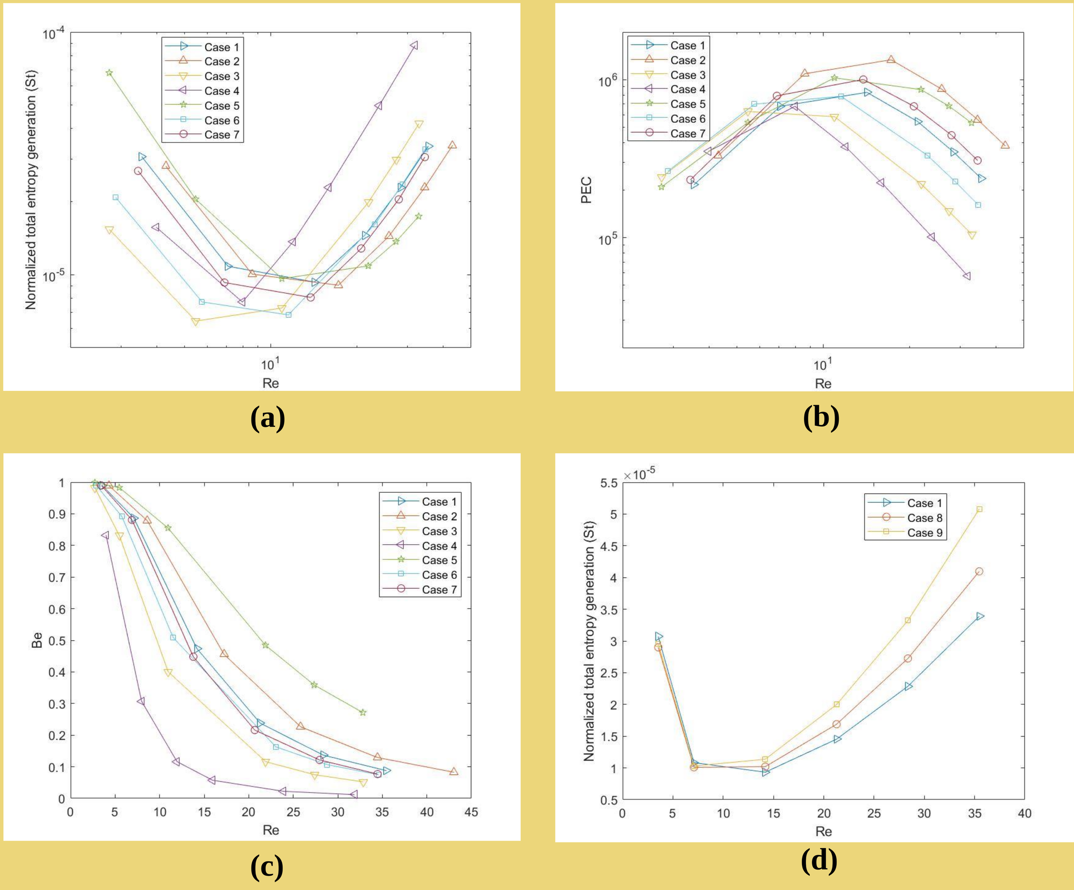

Figure 5. Comparison of all 9 steady-flow cases at q" =750 W/m^2, (a) normalized total volumetric entropy generation, (b) PEC, (c) Bejan number, (d) effect of irregularity on total entropy generation.

➢ **Oscillating flow**

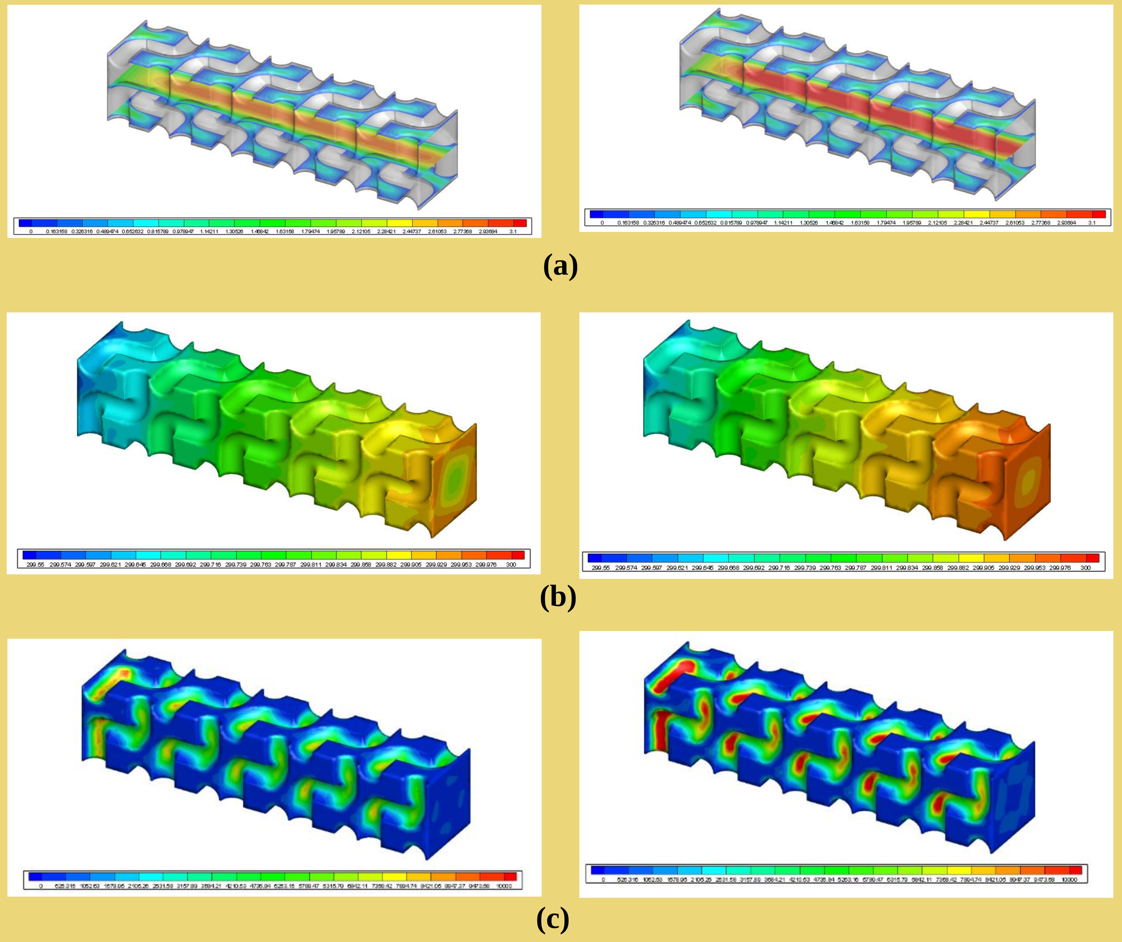

Figure 6. Contours of oscillating flow simulation at 1/8 cycle (left contours) and 1/4 cycle (right contours) for case 1 at Re= 34, (a) velocity magnitude (m/s), (b) temperature (K), (c) total entropy generation (W/m^{3}K).

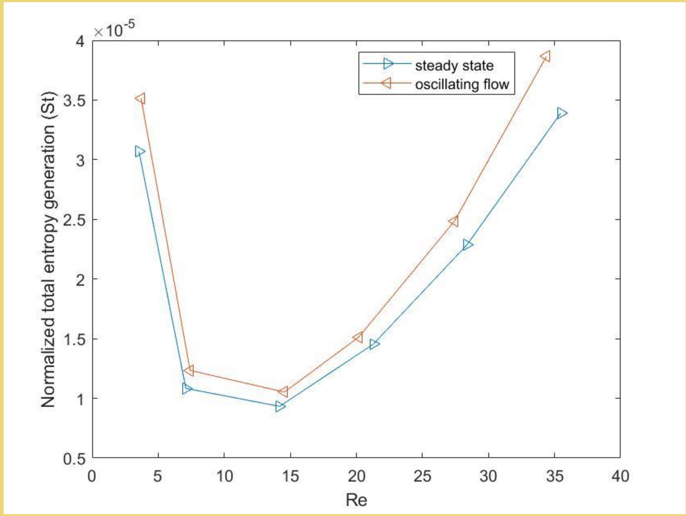

Figure 7. Normalized total entropy generation for steady state with q"=750 W/m^2 and oscillating flow for case 1 at f= 20Hz.

Conclusion

- A pore-level CFD-assisted investigation was performed aimed at the elucidation of entropy generation in woven mesh regenerator fillers.
- Simulations show that the optimum operating conditions are determined by the relative magnitudes of viscous dissipation and entropy generation due to heat transfer.
- For steady flow simulations with constant wall heat flux the contribution of viscos irreversibility increases with Re, while the contribution of heat transfer irreversibility monotonically diminishes. Optimum working conditions occur when the two contribution terms become equal.
- Entropy generation is higher in periodic flow.
- Partial blockage of flow passages caused by particles can significantly increase entropy generation.