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A Second Law Study of the Regenerators in Cryocoolers based on Pore-level Analysis of Entropy Generation

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Abstract. Regenerators are key components of regenerative cryocoolers and losses in regenerators have a significant effect on the performance of cryocoolers. In previous studies, the efficiency of regenerators has been characterized mostly based on the first law of thermodynamics, and second-law analyses have been based on exergy considerations or irreversibility associated with macroscopic flow models. In this work, we investigate the entropy generation in regenerators based on detailed pore-level simulations. Computational Fluid Dynamics (CFD) simulations are used to model two-dimensional regenerator geometries, and examine the microscopic flow and heat transfer phenomena that cause irreversibility. A CFD approach and a volume averaging semi-analytical approach are developed to analyze the entropy generation in pore level. A modified Bejan number (Re_{conv}) and a Performance Evaluation Factor (PEF) are proposed as indicators for the level of entropy generation in regenerators. The predicted entropy generation rates at various Reynolds numbers and geometric dimensions are analyzed. The results indicate that the proposed semi-analytical approach can be a convenient alternative to CFD simulations when empirical data of convective heat transfer and friction factor are available. The analysis of entropy generation using Re_{conv} and PEF can be used to minimize the irreversibility of regenerators.

1. Introduction

The regenerator is arguably the most important component in a regenerative cryocooler. Complicated mechanisms that result in performance losses, such as viscous loss, axial conduction and net enthalpy flow due to non-equilibrium temperature, all occur in regenerators. Minimization of these losses is desired. However, the losses are usually correlated and cannot be optimized independently. Thus, designing of regenerators takes a considerable amount of iterations and is usually accomplished by modeling. Volume averaging method [1-5] is the most common approach taken by researchers. Microscopic governing equations are converted to macroscopic equations in volume averaging methods. Codes that utilize averaging method to model regenerators include REGEN [6] and SAGE [7]. In order to accurately model regenerators, parameters such as Darcy permeability, Forchheimer inertial coefficient, heat transfer coefficient are needed.

In previous studies, the efficiency of regenerators has been characterized mostly based on the first law of thermodynamics, and second-law analyses have been based on exergy considerations or irreversibility associated with macroscopic flow models. Finding the optimum design was usually not straightforward. The second law analysis addressing entropy generation has recently been used by researchers to minimize exergy destruction and optimize various thermal-fluid systems. It can be a



convenient method to analyze the losses in regenerators. Bejan [8, 9] has comprehensive discussions regarding the application of entropy generation minimization in optimizing thermal-fluid systems.

In this research, the second law analysis in terms of entropy generation is used for the optimization of regenerators. A pore-level Computational Fluid Dynamic (CFD) method and a semi-analytical volume averaging method are developed. The predicted volumetric entropy generation rates are accordingly analyzed. A modified Bejan number and a Performance Evaluation Factor (PEF) are proposed to evaluate the relative performance of regenerators.

2. Entropy generation in regenerators

The instantaneous volumetric entropy generation rate in a fluid has two parts: 1) due to heat transfer, $\dot{S}_{gen,heat}'''$; and 2) due to viscous dissipation, $\dot{S}_{gen,vis}'''$.

$$\dot{S}_{gen}''' = \dot{S}_{gen,heat}''' + \dot{S}_{gen,vis}''' \quad (1)$$

The terms $\dot{S}_{gen,heat}'''$ and $\dot{S}_{gen,vis}'''$ in 2D Cartesian system can be expressed as:

$$\dot{S}_{gen,heat}''' = \frac{k}{T^2} \left[\left(\frac{\partial T}{\partial x} \right)^2 + \left(\frac{\partial T}{\partial y} \right)^2 \right] \quad (2)$$

$$\dot{S}_{gen,vis}''' = \frac{\mu}{T} \left\{ 2 \left[\left(\frac{\partial v_x}{\partial x} \right)^2 + \left(\frac{\partial v_y}{\partial y} \right)^2 \right] + \left(\frac{\partial v_x}{\partial y} + \frac{\partial v_y}{\partial x} \right)^2 \right\} \quad (3)$$

where k is the thermal conductivity, T is the local temperature, μ is the dynamic viscosity, and v is the velocity.

Equation (1) can be implemented in Computational Fluid Dynamic (CFD) models but cannot be directly used in volume-averaging methods. Therefore, an approximate analytical form that can be used in volume-averaging methods is derived.

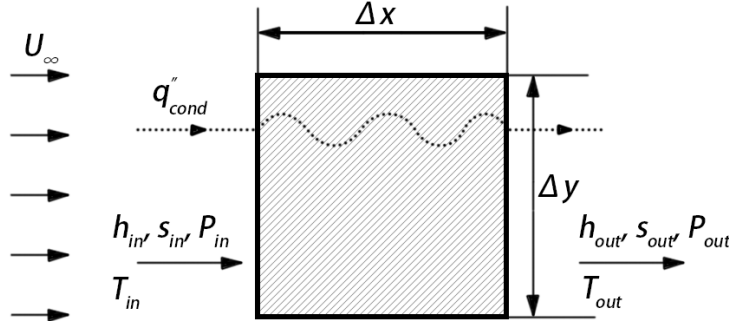


Figure 1. The control volume in a regenerator.

Figure 1 presents a 2D control volume in a regenerator which is filled with a porous material. The porosity is ϕ , and Δx and Δy are the length and height of the control volume, respectively. The main flow is in x direction with free stream velocity U_∞ . The intrinsic velocity of fluid inside the porous medium is $U_f = U_\infty/\phi$. The conductive heat flux due to the x -directional temperature gradient dT/dx in the regenerator is q''_{cond} , and h_{in} , s_{in} , P_{in} , and T_{in} are the specific enthalpy, specific entropy, pressure, and temperature of the upstream fluid, respectively. Parameters h_{out} , s_{out} , P_{out} , and T_{out} are the specific enthalpy, specific entropy, pressure, and temperature of the downstream fluid, respectively.

We proceed by making the following approximations and assumptions: 1) real gas effect is negligible; 2) the porous material in the control volume is represented with a uniform temperature T_w ; 3) the temperature and properties of the fluid inside the control volume are uniform; 4) the difference of temperature between solid and fluid is small compared with the absolute temperature of the fluid; 5) convective heat exchange rate is uniformly distributed on the solid-fluid interface.

The heat transfer contribution of entropy generation is separated into two parts:

$$\dot{S}_{gen,heat}''' = \dot{S}_{gen,cond}''' + \dot{S}_{gen,conv}''' \quad (4)$$

where $\dot{S}_{gen,cond}'''$ is the entropy generation due to axial conduction, and $\dot{S}_{gen,conv}'''$ is the entropy generation due to convection. $\dot{S}_{gen,cond}'''$ can be calculated as:

$$\dot{S}_{gen,cond} = q''_{cond}\Delta y \left| \frac{1}{T_{out}} - \frac{1}{T_{in}} \right| = k_{eff} \frac{dT}{dx} \Delta y \left| \frac{T_{in} - T_{out}}{T_{out}T_{in}} \right| \quad (5)$$

where k_{eff} is the effective thermal conductivity of the regenerator. Noticing that $T_{out} - T_{in} = \Delta x \frac{dT}{dx}$ and $T_{out} \approx T_{in} \approx \bar{T}_f$, where \bar{T}_f is the average temperature of the fluid, Equation (5) can be recast as:

$$\dot{S}_{gen,cond} \approx k_{eff} \left(\frac{dT}{dx} \right)^2 \Delta x \Delta y / \bar{T}_f^2 \quad (6)$$

Therefore, the volumetric entropy generation rate due to conduction is:

$$\dot{S}'_{gen,cond} \approx k_{eff} \left(\frac{dT}{dx} \right)^2 / \bar{T}_f^2 \quad (7)$$

The rate of entropy generation due to convection and viscous dissipation is given by the second law:

$$\dot{S}_{gen,flow} = \dot{S}_{gen,conv} + \dot{S}_{gen,vis} = \dot{m}s_{out} - \dot{m}s_{in} - \iint_A \frac{q''_A}{T_w} dA \quad (8)$$

where $\dot{S}_{gen,conv}$ and $\dot{S}_{gen,vis}$ are the entropy generations due to convection and viscous dissipation, respectively, \dot{m} is the mass flow rate of the fluid through the control volume, A is the wetted surface of the solid porous material in the control volume, and q''_A is the heat flux on the wetted surface of the solid. The first law also applies to the same system as:

$$\dot{m}h_{in} + \iint_A q''_A dA - \dot{m}h_{out} = 0 \quad (9)$$

The thermodynamic second Tds relation leads to:

$$h_{out} - h_{in} \approx \bar{T}_f(s_{out} - s_{in}) + \frac{1}{\bar{\rho}_f}(P_{out} - P_{in}) \quad (10)$$

where $\bar{\rho}_f$ is the average density of the fluid. Combining Equation (8), (9) and (10), we get:

$$\dot{S}_{gen,flow} = \iint_A q'' \left(\frac{1}{\bar{T}_f} - \frac{1}{T_w} \right) dA - \frac{\dot{m}}{\bar{T}_f \bar{\rho}_f} (P_{out} - P_{in}) \quad (11)$$

Assuming the fluid temperature and solid temperature are uniform in the control volume, Equation (11) can be recast as:

$$\dot{S}_{gen,flow} = \left(\frac{1}{\bar{T}_f} - \frac{1}{T_w} \right) \iint_A q'' dA - \frac{\dot{m}}{\bar{T}_f \bar{\rho}_f} (P_{out} - P_{in}) \quad (12)$$

Noticing that $\rho_{in} \approx \rho_{out} \approx \bar{\rho}_f$. Then the mass flow rate can be expressed as:

$$\dot{m} = \Delta y \bar{\rho}_f U_\infty \quad (13)$$

The heat transfer rate due to convection can be calculated from:

$$\iint_A q'' dA = \overline{h_{conv}} A (T_w - \bar{T}_f) \quad (14)$$

where $\overline{h_{conv}}$ is the average convective heat transfer coefficient. Conservation of energy also applies to the control volume:

$$\iint_A q'' dA = \dot{m} C_p (T_{out} - T_{in}) = \dot{m} C_p \Delta x \frac{dT}{dx} \quad (15)$$

where C_p is the heat capacity of the fluid. Combining Equation (12) through (15) and noticing that $T_w \approx \bar{T}_f$, the instantaneous volumetric entropy generation rate due to convection will be:

$$\dot{S}_{gen,flow}'''' = \frac{(U_{\infty}\bar{\rho}_f C_p \frac{dT}{dx})^2}{\bar{h}_{conv}\bar{T}_f^2 \Omega} + \frac{U_{\infty}\bar{\rho}_f}{\bar{T}_f} \frac{dP}{dx} \quad (16)$$

where Ω is the wetted solid surface area per unit volume $A/\Delta x\Delta y$. The first term on the right side of this equation represents the rate of entropy generation caused by convective heat transfer, $\dot{S}_{gen,conv}''''$, while the second term represents the rate of entropy generation caused by viscous dissipation, $\dot{S}_{gen,vis}''''$. To solve Equation (16), the properties of the fluid, \bar{h}_{conv} , and dP/dx are required. \bar{h}_{conv} and dP/dx can be obtained from empirical correlations.

Equation (16) is the instantaneous form which can be solved using time-advancing finite difference tool, such as REGEN. But for quick design calculation, the cycle-average form is needed. It can be calculated by integrating Equation (16):

$$\langle \dot{S}_{gen,flow}'''' \rangle = f \int_0^{1/f} \left[\frac{(U_{\infty}\bar{\rho}_f C_p \frac{dT}{dx})^2}{\bar{h}_{conv}\bar{T}_f^2 \Omega} + \frac{U_{\infty}\bar{\rho}_f}{\bar{T}_f} \frac{dP}{dx} \right] dt \quad (17)$$

where f is the frequency of the oscillation flow. Assuming U_{∞} and dP/dx are sinusoidal, and \bar{h}_{conv} and other variables are constants, Equation (17) can be expressed as:

$$\langle \dot{S}_{gen,flow}'''' \rangle = \frac{(U_{\infty,max}\bar{\rho}_f C_p \frac{dT}{dx})^2}{2\bar{h}_{conv}\bar{T}_f^2 \Omega} + \frac{U_{\infty,max}\bar{\rho}_f}{2\bar{T}_f} \left(\frac{dP}{dx} \right)_{max} \quad (18)$$

where $U_{\infty,max}$ is the amplitude of free stream velocity, and $(dP/dx)_{max}$ is the amplitude of pressure drop per unit length. Equation (18) is evidently approximate and may require empirical adjustment:

$$\langle \dot{S}_{gen,flow}'''' \rangle = \alpha \frac{(U_{\infty,max}\bar{\rho}_f C_p \frac{dT}{dx})^2}{2\bar{h}_{conv}\bar{T}_f^2 \Omega} + \beta \frac{U_{\infty,max}\bar{\rho}_f}{2\bar{T}_f} \frac{dP}{dx_{max}} \quad (19)$$

where α and β are correction factors. The result from the CFD simulation in this research indicated $\alpha = 1$ and $\beta = 2$. The total cycle-averaged entropy generation rate thus has three parts:

$$\langle \dot{S}_{gen}'''' \rangle = \langle \dot{S}_{gen,cond}'''' \rangle + \langle \dot{S}_{gen,conv}'''' \rangle + \langle \dot{S}_{gen,vis}'''' \rangle \quad (20)$$

$$\langle \dot{S}_{gen,cond}'''' \rangle = k_{eff} \left(\frac{dT}{dx} \right)^2 \Delta x \Delta y / \bar{T}_f^2 \quad (21)$$

$$\langle \dot{S}_{gen,conv}'''' \rangle = \alpha \frac{(U_{\infty,max}\bar{\rho}_f C_p \frac{dT}{dx})^2}{2\bar{h}_{conv}\bar{T}_f^2 \Omega} \quad (22)$$

$$\langle \dot{S}_{gen,vis}'''' \rangle = \beta \frac{U_{\infty,max}\bar{\rho}_f}{2\bar{T}_f} \frac{dP}{dx_{max}} \quad (23)$$

3. CFD setup

Pore-level CFD simulation is another approach for the analysis of entropy generation. Comparing with the analytical approximation in Section 2, CFD simulations are more accurate but also more time-consuming. In this research, ANSYS FLUENT [10] is used for the development of the pore-level CFD model. Equation (2) and (3) were implemented using User Defined Functions. As shown in Figure 2, the computational domain is a 2D straight channel with staggered parallel cylinders. A specific temperature gradient from the warm end to the cold end was defined for the cylinders in the simulations. Symmetric boundary conditions were used for the top and bottom boundaries. Oscillation mass flow

boundary was defined at the warm end and pressure boundary was defined at the cold end. The regions near the inlet and the outlet are the buffer zones which were created to improve the convergence performance. Energy source terms were defined in the buffer zones so that the fluid leaving the buffer zones has desired warm end or cold end temperature.

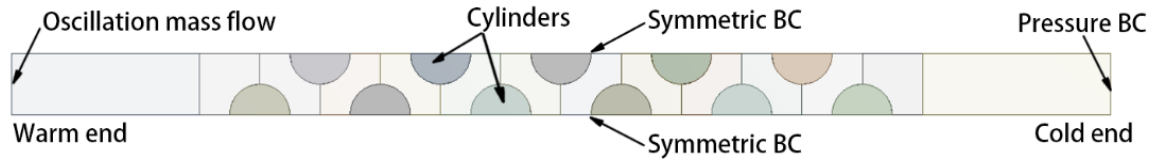


Figure 2. The computational domain and boundary conditions for CFD.

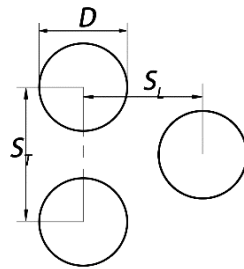


Figure 3. Geometric parameters.

Figure 3 shows the geometric parameters, where D is the diameter of the cylinders, S_L is the horizontal distance between the columns of cylinders, and S_T is the vertical distance between two cylinders in the same column. In this research, the relative distances between the cylinders were kept constant as $S_T = 2S_L = 2D$. The geometry was thus scaled without changing the relative distances between cylinders.

4. Evaluating the performance of a regenerator in terms of entropy generation

Theoretically, if the entropy generation in the generator is minimized, the associated losses will also be minimized. Two criteria are proposed here to evaluate the performance of a regenerator. The first criterion is a slightly modified Bejan number:

$$Be_{conv} = \frac{\langle \dot{S}_{gen,conv}''' \rangle}{\langle \dot{S}_{gen,conv}''' \rangle + \langle \dot{S}_{gen,vis}''' \rangle} \quad (24)$$

The original Bejan number is the ratio of entropy generation rate due to heat transfer, $\langle \dot{S}_{gen,heat}''' \rangle$, divided by the total entropy generation rate, $\langle \dot{S}_{gen}''' \rangle$, where $\langle \dot{S}_{gen,heat}''' \rangle$ is the combination of entropy generation from conduction and convection. In the modified Bejan number, the contribution of conduction is not considered because it is independent from convection and viscous dissipation. Convective heat transfer and viscous dissipation are, however, normally correlated. The improvement of heat transfer in regenerators usually will also result in more viscous loss. In other words, the reduction of $\langle \dot{S}_{gen,conv}''' \rangle$ can simultaneously result in the increasing of $\langle \dot{S}_{gen,vis}''' \rangle$. Therefore, in theory, the total combined entropy generation from convection and viscous dissipation can be minimized when $Be = 0.5$. Be_{conv} can be useful when the axial conduction, total mass flow rate, and warm-to-cold end temperature gradient are kept constant.

The second criterion is the Performance Evaluation Factor (PEF) which represents the entropy generation rate in a regenerator:

$$PEF = \frac{\dot{S}_{gen}''' V}{\dot{m}_{tot,max}(T_h - T_c)} = \frac{\dot{S}_{gen}'''}{\rho_f U_{\infty,max} dT/dx} \quad (25)$$

where V is the volume of the regenerator, $\dot{m}_{tot,max}$ is the total mass flow rate amplitude, and T_h and T_c are the warm and cold end temperatures, respectively. Thus, PEF represents the rate of entropy generation per unit mass flow rate per unit warm-to-cold end temperature difference through the regenerator. PEF can be useful for the optimization of regenerators since the mass flow rate amplitude and warm-to-cold end temperature difference are usually determined by the desired working condition of the cryocooler.

5. Results and discussion

The predictions of entropy generation by the analytical approximation, Equation (20), and the pore-level CFD were analyzed. As mentioned earlier, $\overline{h_{conv}}$ and dP/dx are required for solving Equation (20). Because there was no available empirical correlation for the modelled geometry and flow condition, $\overline{h_{conv}}$ and dP/dx were calculated using the CFD model. The cylinder diameter, D , and the flow velocity amplitude, $U_{\infty,max}$, were the variables that were studied in this research.

5.1. Prediction of volumetric entropy generation rate

Figure 4 and Figure 5 show the prediction of volumetric entropy generation rate due to heat transfer, $\langle \dot{S}_{gen,heat}''' \rangle$, and viscous dissipation, $\langle \dot{S}_{gen,vis}''' \rangle$. The results from both CFD and analytical method are presented in these figures. The cases in Figure 4 were based on $D = 80\mu m$. The cases in Figure 5 have same velocity amplitude, $U_{\infty,max} = 0.952m/s$. As noted, except for very small Re or $D < \dot{S}_{gen,vis}'''$ predicted by the analytical approximation and CFD simulations are in very good agreement. However, $\langle \dot{S}_{gen,heat}''' \rangle$ is slightly underpredicted by the analytical approximation when Re or D are small.

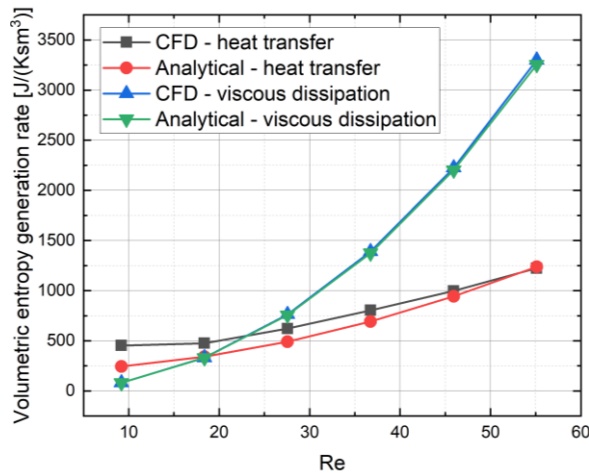


Figure 4. The prediction of volumetric entropy generation rate by CFD and Equation (20) vs. Reynolds number; $D = 80\mu m$.

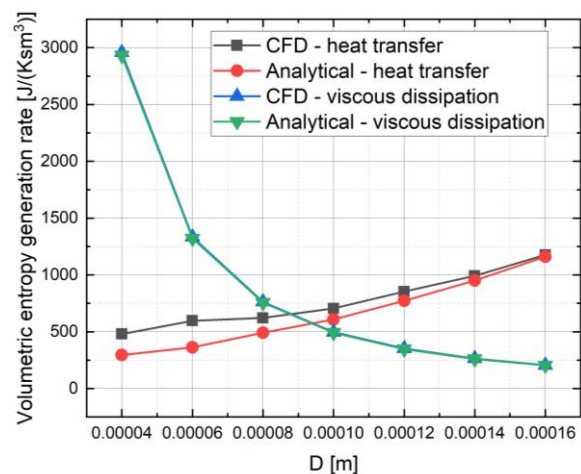


Figure 5. The prediction of volumetric entropy generation rate by CFD and Equation (20) vs. Cylinder diameter D ; $U_{\infty,max} = 0.952m/s$.

5.2. The relationship between total volumetric entropy generation rate and Be_{conv}

The modified Bejan number, Be_{conv} , can be used to minimize the total entropy generation from convection and conduction. It is useful when the axial conduction, total mass flow, and warm-to-cold temperature are constant.

Figure 6 shows the results from an example. The flow velocity amplitude was kept constant at $U_{\infty,max} = 0.952m/s$ while the diameter of the cylinders was varied. The relationship between total cycle-averaged volumetric entropy generation $\langle \dot{S}_{gen}''' \rangle$ and Be_{conv} is shown in Figure 6. Because $\langle \dot{S}_{gen,conv}''' \rangle$ and $\langle \dot{S}_{gen,cond}''' \rangle$ cannot be calculated separately in the CFD model, the analytical method

was used for the calculation of Be_{conv} . Both CFD and analytical method indicate that $\langle \dot{S}_{gen}''' \rangle$ can be minimized when $Be_{conv} \sim 0.5$.

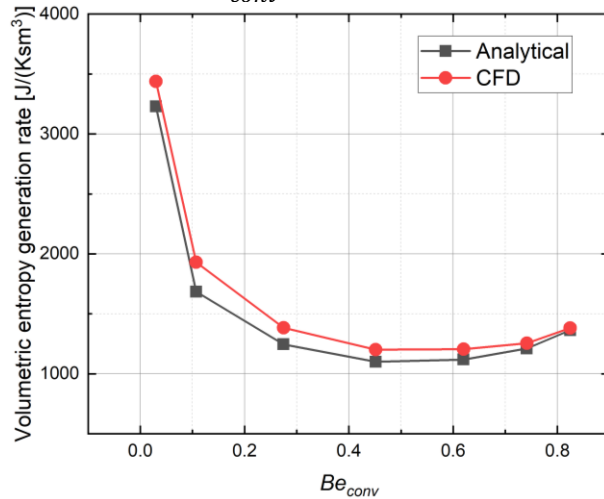


Figure 6. Total cycle-averaged volumetric entropy generation rate $\langle \dot{S}_{gen}''' \rangle$ vs. modified Bejan number for $U_{\infty,max} = 0.952m/s$.

5.3. Performance evaluation factor (PEF)

The use of Be_{conv} is limited to conditions when the axial conduction, warm-to-cold end temperature difference, and total mass flow rate amplitude do not change. However, the axial conduction usually changes once the design of a regenerator is modified. The proposed PEF defined in equation (25) is a more universal indicator that can be used to evaluate the performance of a regenerator when these parameters change. When PEF is minimized, the total entropy generation in a regenerator will be minimized.

The comprehensive relationship between PEF , D , and Re is shown in Figure 7 and Figure 8 is from the approximate analytical solution. Both methods indicate that PEF can be minimized at the point where $D = 100\mu m$ and $Re = 18.4$ for the specific cases studied in this research. Similar relationship can be quickly generated using the approximate analytical method for regenerators with given total mass flow and warm-to-cold temperature difference. The optimal design of the regenerator can then be found.

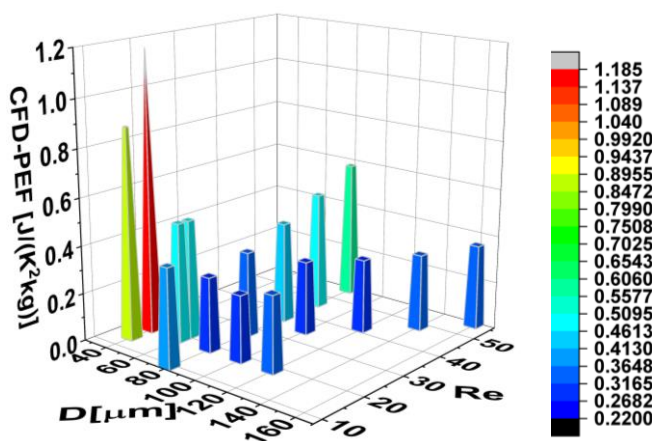


Figure 7. Estimated PEF using CFD

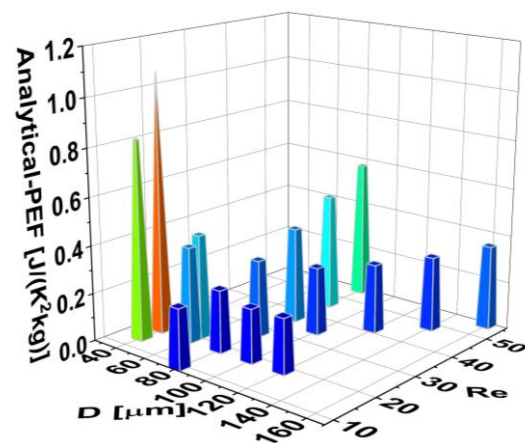


Figure 8. Estimated PEF using analytical approach

6. Conclusion

The second law analysis in terms of entropy generation has been used to analyze the losses in regenerators. A semi-analytical method and a pore-level CFD method were developed in this research

for entropy generation minimization. Additionally, two criteria, Be_{conv} and PEF , were proposed to evaluate the performance of a regenerator in terms of entropy generation. The results yield the following conclusions:

- 1) Be_{conv} can be a convenient indicator to optimize regenerators when the axial conduction, warm-to-cold end temperature, and total mass flow rate are kept constant. It is thus useful when the regenerator in an existing cryocooler is to be modified while the aforementioned parameters need to remain unchanged.
- 2) PEF can be a more universal indicator of the performance of regenerators because the axial conduction is taken into consideration. For any given total mass flow rate and warm-to-cold temperature difference, a comprehensive relationship between PEF , D , and Re can be generated. The optimal design for the given condition can then be determined.
- 3) In general, the analytical approximation showed a good agreement with the pore-level CFD model. $\langle \dot{S}_{gen,conv}''' \rangle$ can be slightly underpredicted by the analytical approximation when Re or D are small.
- 4) When empirical correlations for convective heat transfer coefficient and friction factors are available, the analytical approximation provided by Equation (20) provides a quick way to evaluate a regenerator by estimating Be_{conv} and PEF .
- 5) When empirical correlations for convective heat transfer coefficient and friction factors are unavailable, pore-level CFD model is an alternative method to calculate Be_{conv} and PEF .

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