# TFAWS Active Thermal Paper Session

## Study of Thermal Transport in Highly Anisotropic Materials for Space Recuperator Applications

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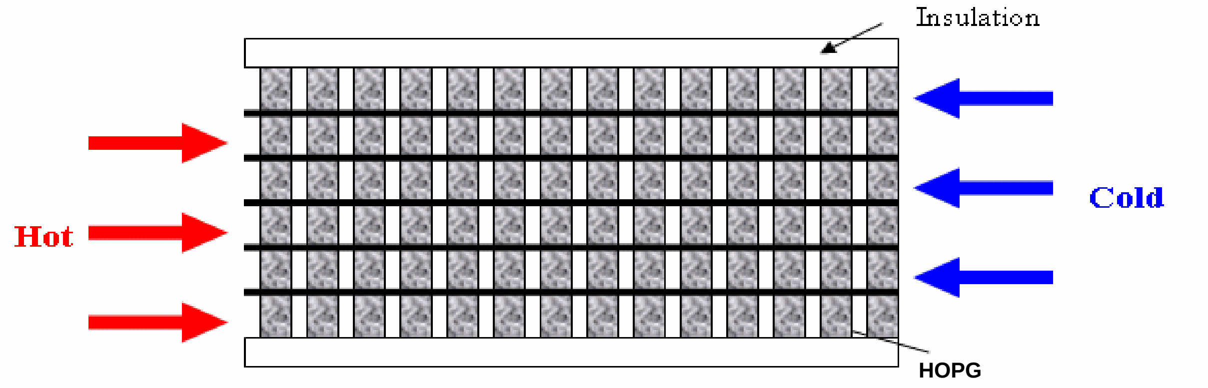
# Outline

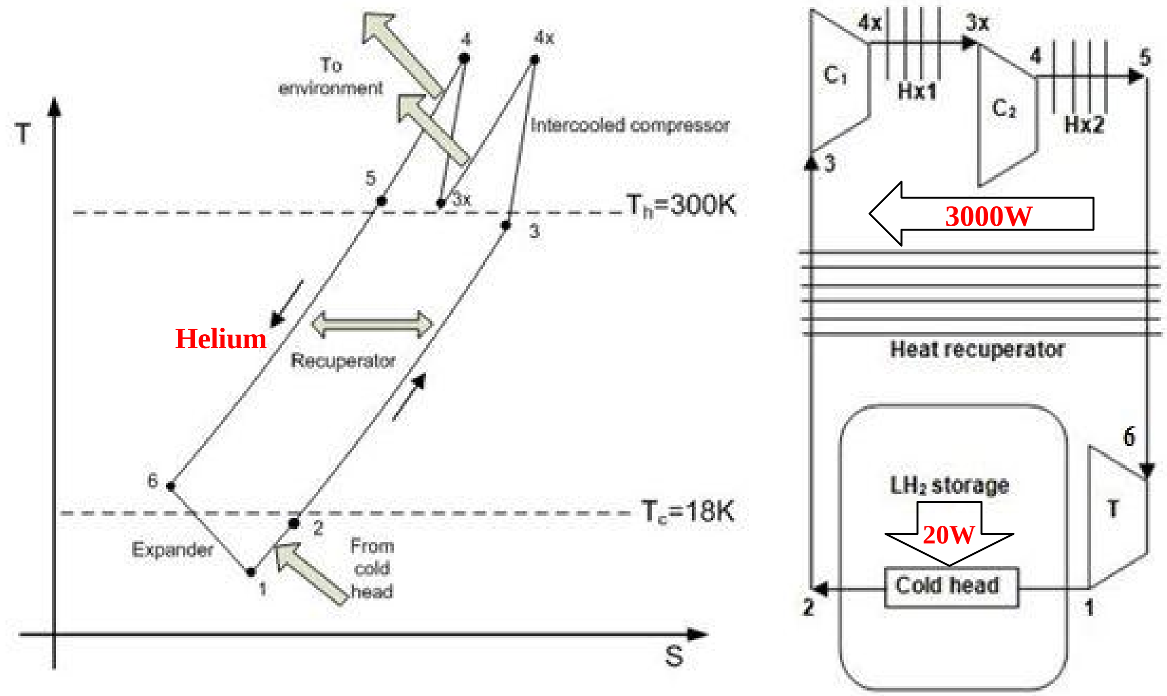
- State-of-the-art recuperator
- Problem statement and objectives
- Highly Oriented Pyrolytic Graphite (HOPG)
- Recuperator design
- Numerical model
- Numerical results
- Conclusion




**Schematic of the proposed heat exchanger**

# State-of-the-art recuperator

- Single-step, two-stage intercooled RTBC cryocooler (current study)

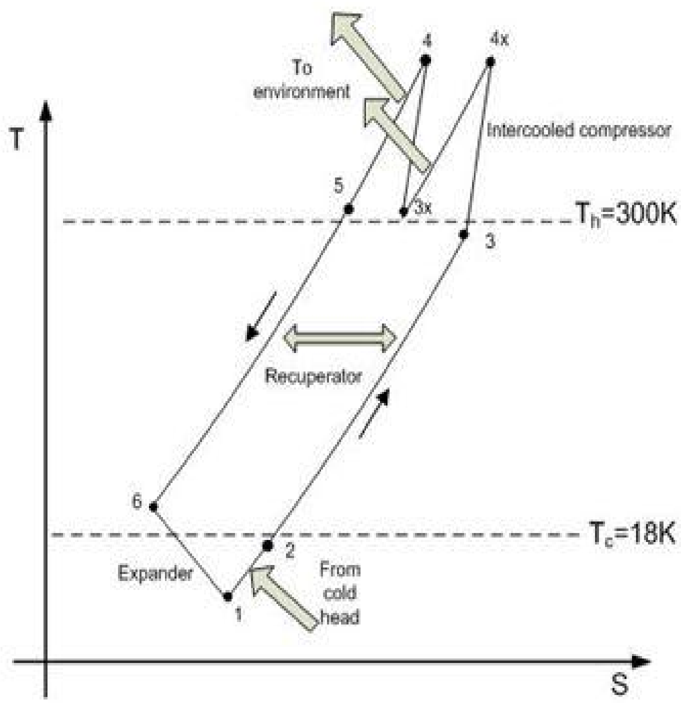



| Status points | T (K) | P (bar) |
|---|---|---|
| *1* | 14 | 4 |
| *2* | 16 | 3.98 |
| *3* | 298 | 3.9 |
| *3x* | 302 | 6.79 |
| *4* | 390 | 11.5 |
| *4x* | 388 | 6.8 |
| *5* | 302 | 11.48 |
| *6* | 20 | 11.4 |

# Effectiveness of recuperator

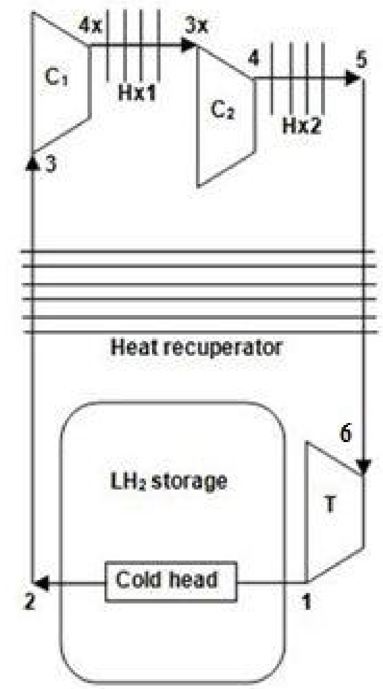
- Cycle parameters (COP, effectiveness and pressure drop)
  - The coefficient of performance (COP) of the reverse Brayton refrigeration cycle depends on the efficiencies of the compressor and the turbine, as well as the effectiveness of the recuperator.

$$COP = \frac{Q_{coldhead}}{\dot{W}_{net}} = \frac{(T_2 - T_1)}{\left(\frac{T_{4x} - T_3}{\eta_{C1}}\right) + \left(\frac{T_4 - T_{3x}}{\eta_{C2}}\right) - ((T_6 - T_1) \times \eta_T)}$$



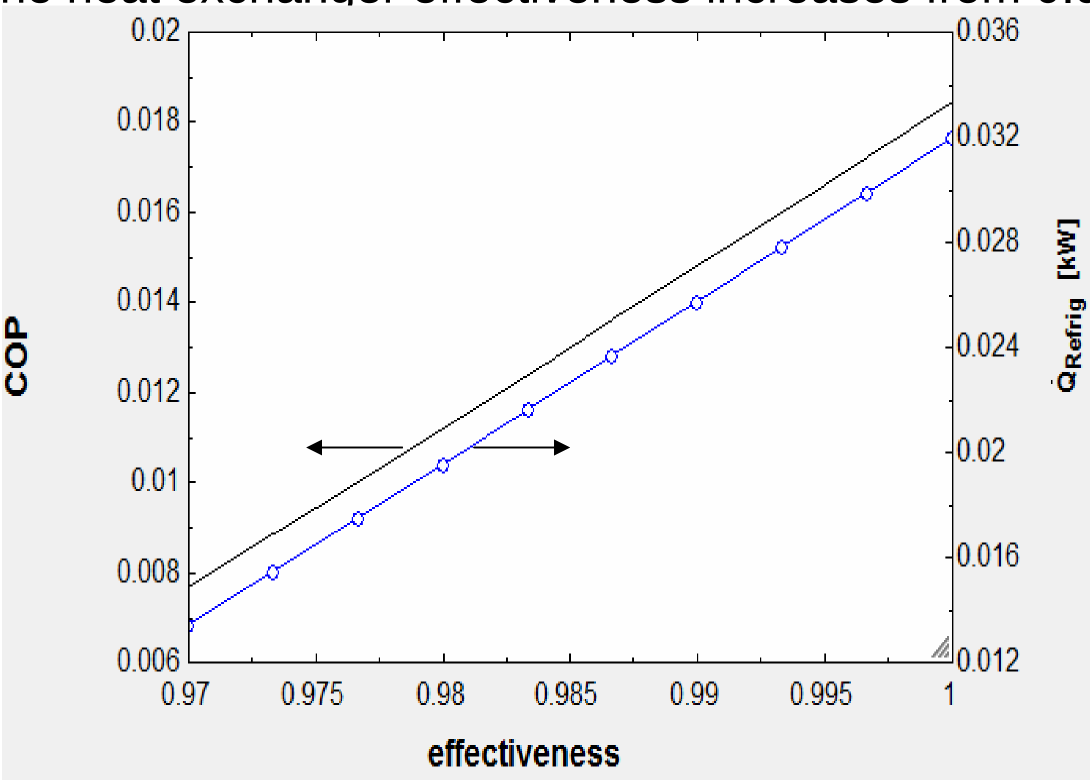

The efficiencies of the two compressors ($\eta_{C1}$, $\eta_{C2}$) and turbine ($\eta_T$) are assumed to be 65% and 75%, respectively, and a pressure ratio of 1.7 is used in this calculation. The effectiveness of the recuperator is defined as the ratio of the actual temperature decrease of the warm gas in the recuperator to the maximum theoretical temperature decrease.

$$\varepsilon = \left(\frac{T_5 - T_6}{T_5 - T_2}\right)$$



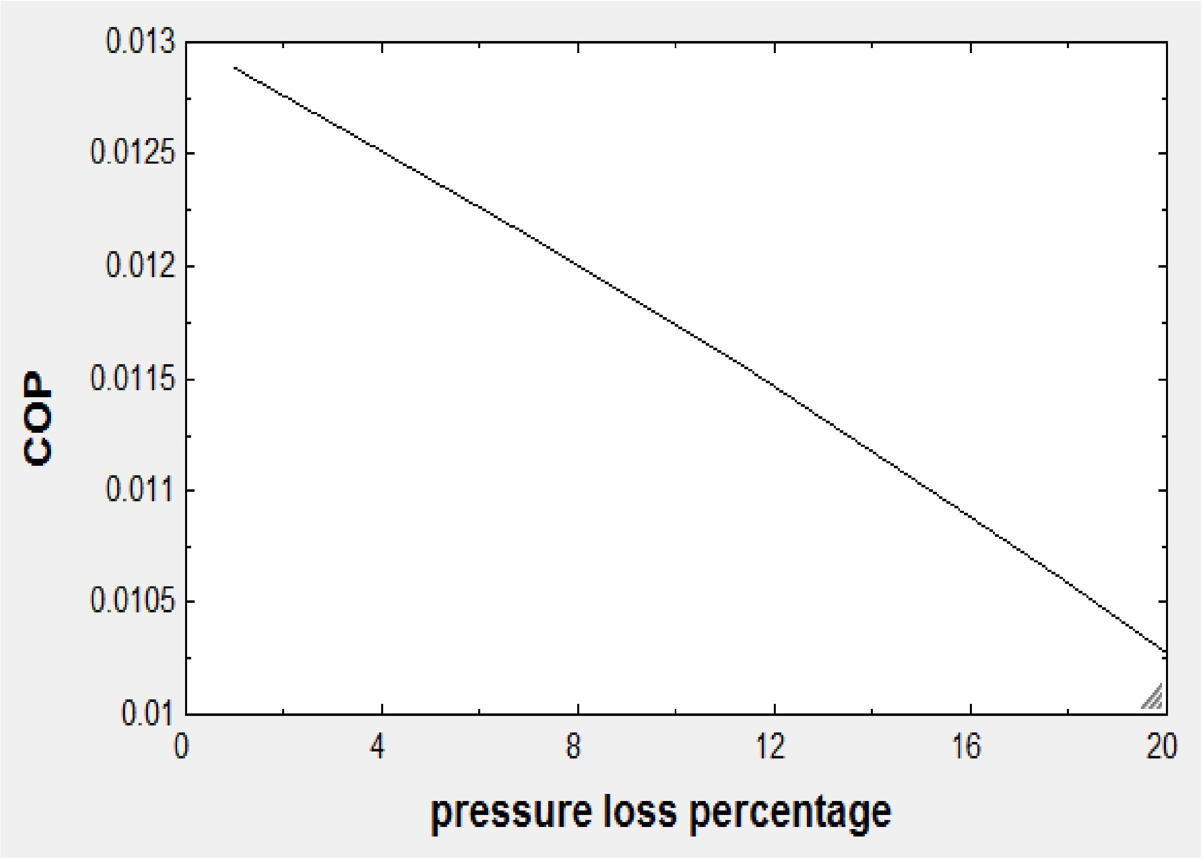
# Effectiveness of recuperator

- Effectiveness
  - Axial conduction can “hurt” heat exchange between the two fluid streams --- complete heat exchange can only be realized with “no axial conduction”.
  - The result indicates that the cycle COP increases from 0.008 to 0.015 when the heat exchanger effectiveness increases from 0.97 to 0.99.



# Pressure drop of recuperator

- Effectiveness
  - To increase the effectiveness, it is required to have more heat transfer area for recuperator flow channels, which could result in a significant frictional pressure drop.
  - Though the pressure drop affects COP, the effect is negligible.



# Problem statement and objectives

- Design considerations

In summary, a recuperator with effectiveness of 0.97 or higher is essential to efficient operation of the RBTC cryocooler. With a 20 W heat removal rate at the cold head, the flow rate of helium is 2 g/s, the heat transfer across the warm and cold streams is 3000 W, and the temperature difference between them is 4K.

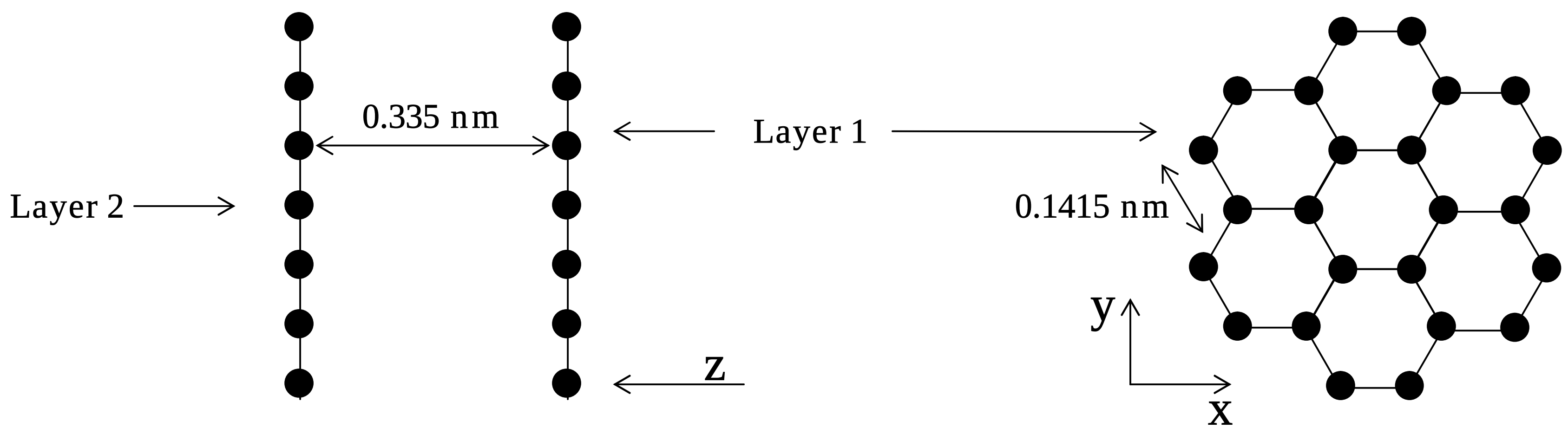
The technical requirements for the recuperator can be summarized as follow:

- 3000 W capacity for heat transfer from the hot to the cold gas stream.
- 98% effectiveness (based on the temperature values mentioned above).
- The pressure loss should be less than 2% of pressure difference across the compressor, i.e., less than 2 psi.

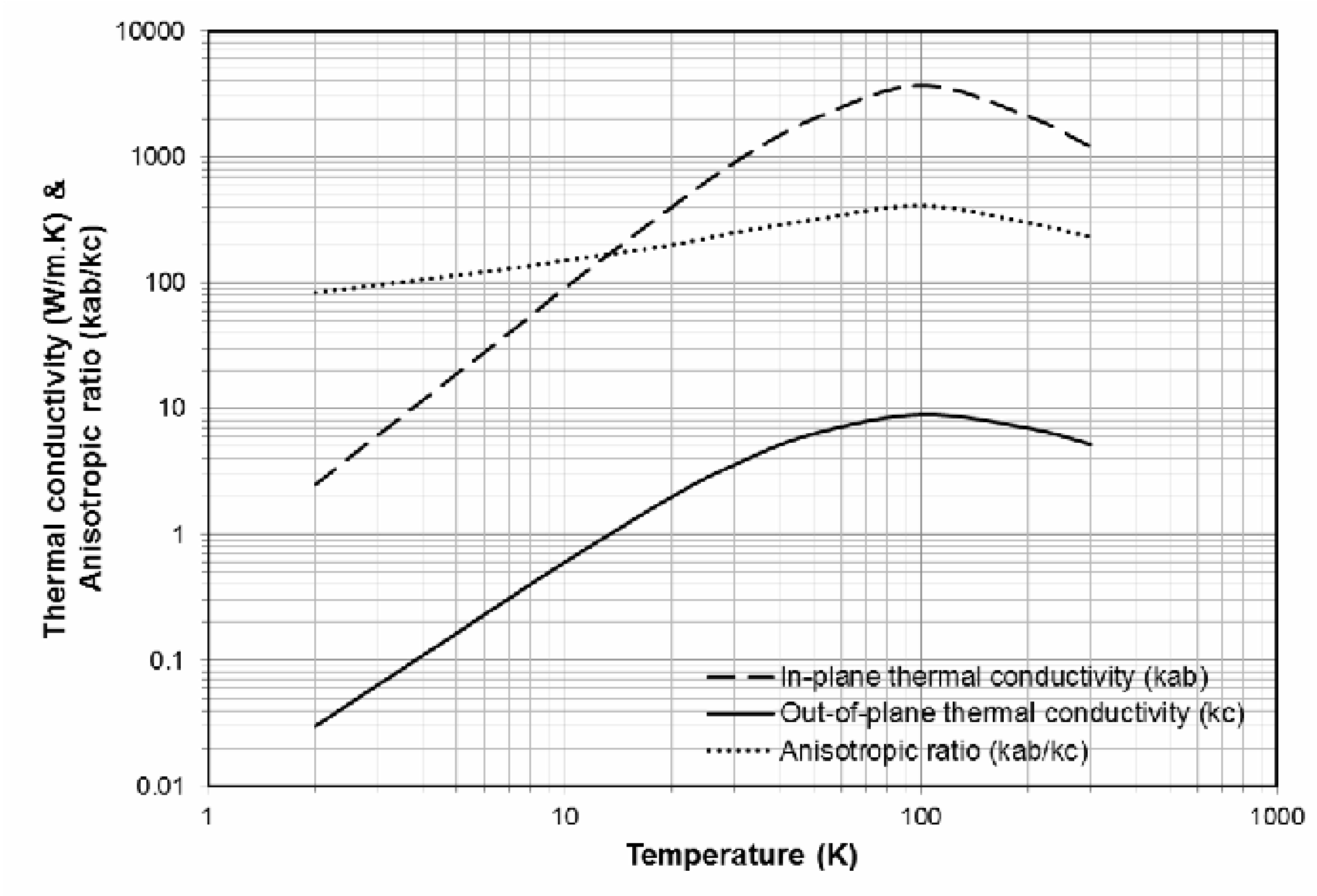
The desired refrigeration load is a small fraction of the heat transferred within the heat exchanger (20 W : 3000 W ~ 0.67% in current study). In this case, the axial heat conduction can degrade the performance of the cryocooler to an unacceptable level.

# Highly Oriented Pyrolytic Graphite (HOPG)

- HOPG is a graphite material with a high degree of preferred crystals orientation in the plane perpendicular to the surface of the substrate (c-plane or out-of-plane). The microstructure of HOPG is uniquely characterized by the arrangement of carbon atoms which are stacked in parallel layers. In each layer, atoms form a grid of exact hexagons.
- HOPG is obtained by graphitization heat treatment of carbon or by Chemical Vapor Deposition (CVD) at temperatures above 2500K then annealed under pressure at approximately 3300K.
- **In-plane thermal conductivity $k_{ab} \approx 1700$ W/m.K at room temperature.**
- **Out-of-plane thermal conductivity $k_c \approx 8$ W/m.K at room temperature.**

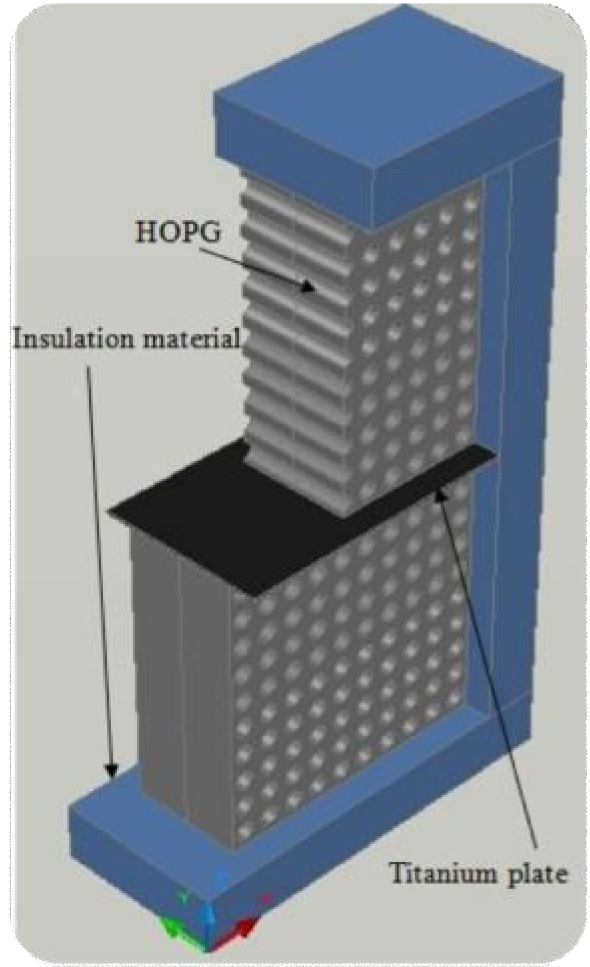


# Highly Oriented Pyrolytic Graphite (HOPG)



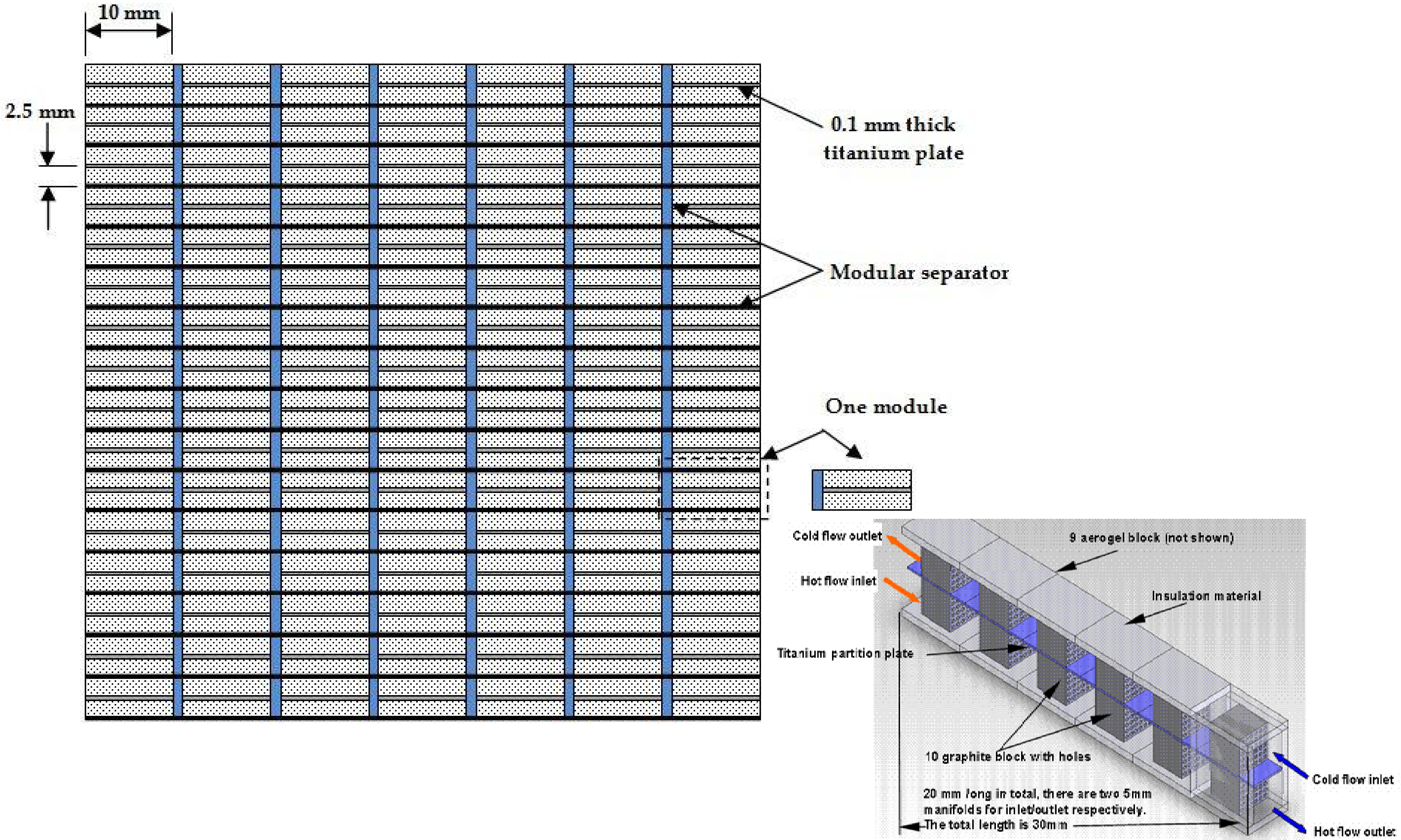
# Recuperator design

- The two HOPG inserts are 1 mm in length and have cross-sectional area of 2.5 mm height x 10 mm width. One HOPG insert consists of ***900*** holes of 0.1 mm in diameter. These holes are distributed as 60 holes along the 10 mm width and 15 holes along the 2.5 mm height.
- To achieve heat removal rate of 3000 W with flow of helium of 2 g/s, 112 modules as described have to be stacked together as shown in the next slide. Helium enters these holes at the hot side with velocity of 1.37 m/s while as the velocity is 0.21 m/s at the cold side.



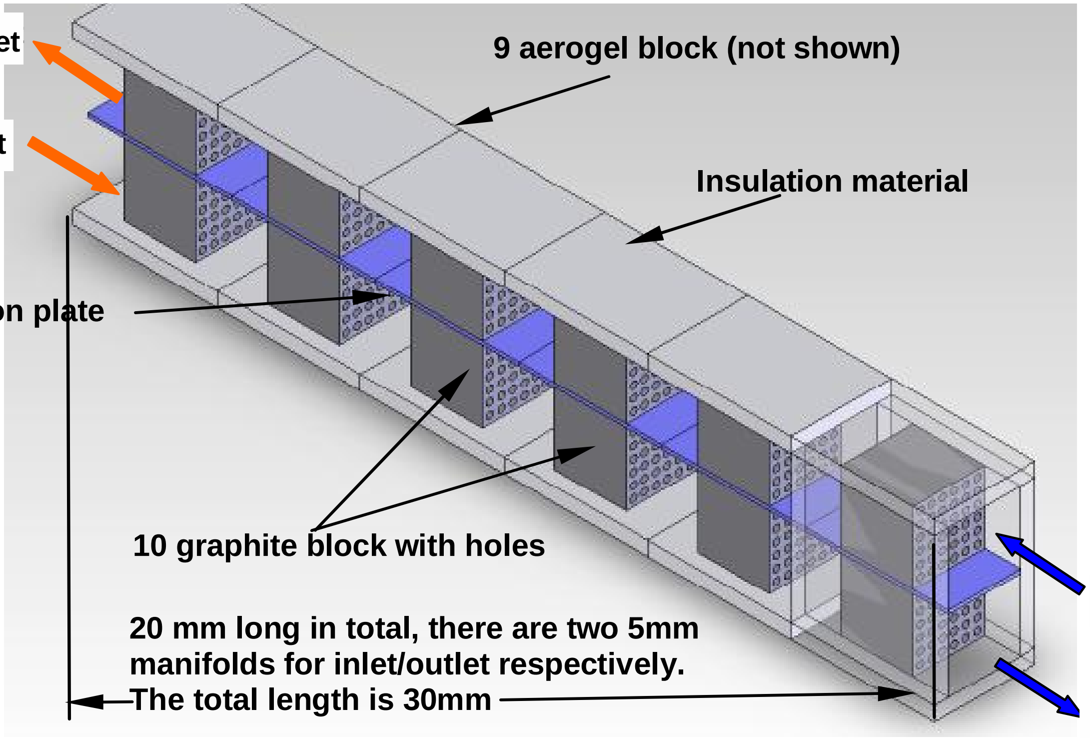

**Schematic of single-stage recuperator**

# Recuperator design




**Cross-sectional area of the recuperator with 112 modules**

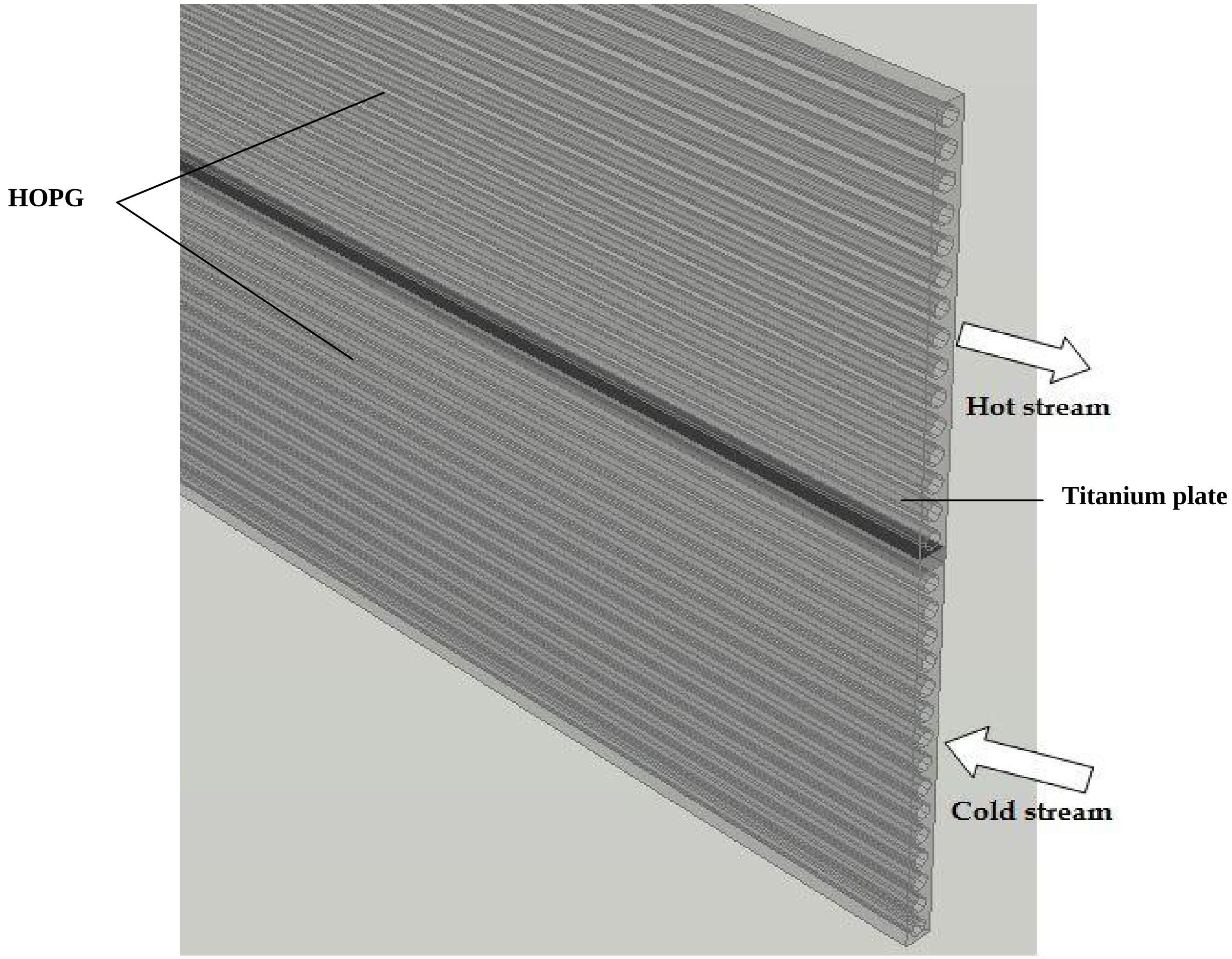
# Recuperator design




| HEX (Cooling Load) | Length, mm | Size | Weight, kg |
|---|---|---|---|
| Proposed HOPG HEX (20 W) | 30 | 100 mmx100 mm | 1 |
| Creare, Inc., SPHX (200 mW) [1] | 660 | 90 mm dia. | 10.5 |
| Creare, Inc., RFHX (200 mW) [1] | 120 | 210 mm dia. | 5.1 |


[1] J. McCormick, G. Nellis, H. Sixsmith, M. Zagarola, J. Gibbon, M. Izenson, and W. Swift, "Advanced developments for low temperature Turbo-Brayton cryocoolers," Cryocoolers 11, pp. 481-488, 2002.

# Numerical model




**Numerical model and computational domain**

# Numerical model

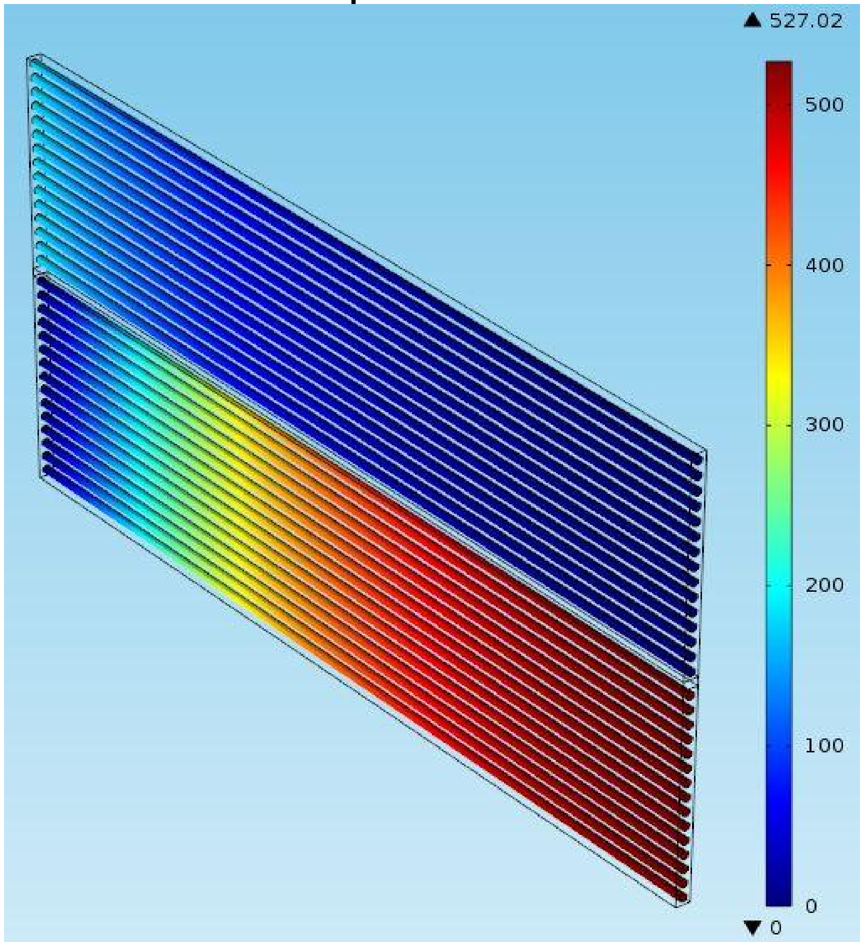
- The variation of HOPG thermal conductivity is considered, where thermal conductivity is temperature dependent.
- Thin sheets (1 mm thick) of highly insulating materials, like aerogels, can be sandwiched between thin sheets (1 mm thick) of HOPG to reduce axial conduction.
- Thermal conductivity of aerogels is about 0.01 W/m.K, so the effective out-of-plane thermal conductivity ($k_{eff}$) would be 0.02 W/m.K.

## Boundary conditions

1. Hot-side inlet velocity of 1.37 m/s and cold-side inlet velocity of 0.21 m/s.
2. Hot-side inlet temperature of 302 K and cold-side inlet temperature of 16 K.
3. Hot side outlet pressure of 11.5 bar and cold-side outlet pressure of 4 bar.
4. No viscous stress at the outlet of the hot and cold streams.
5. No temperature gradient at the outlet of the hot and cold streams.
6. Thermal symmetry on all of the outer boundaries of computational domain.

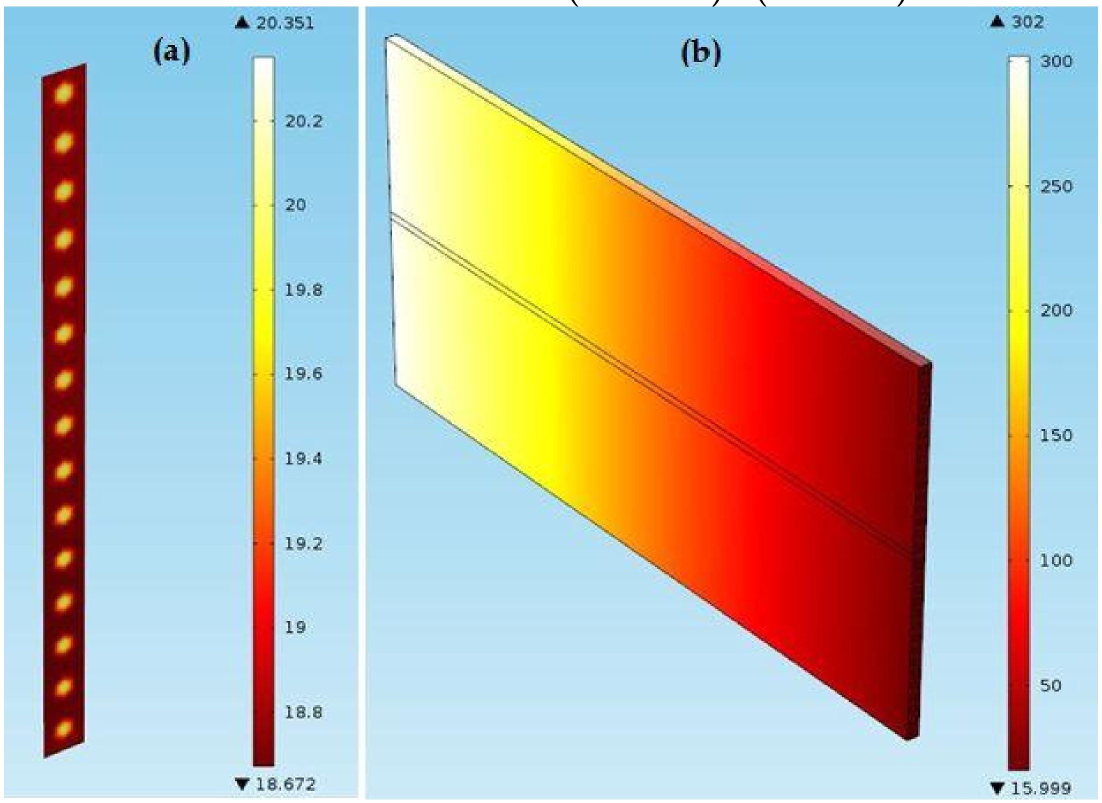
# Numerical Results

- Pressure drop
  - The maximum pressure drop is 527 Pa which is about 0.07% of the pressure rise across the compressor.



# Effectiveness result

- Temperature field
  - The exit bulk temperature of helium from the hot side is 19.6 K and the corresponding effectiveness, $\varepsilon = \left(\frac{T_{hi} - T_{ho}}{T_{hi} - T_{ci}}\right) = \left(\frac{T_{co} - T_{ci}}{T_{hi} - T_{ci}}\right)$, is 98.7 %.




**(a) in-plane temperature variation of HOPG at the exit of the hot stream (K), (b) temperature variation within the computational domain (K).**

# Conclusion

- In this study, a modular recuperator is designed. One module consists of twenty pieces of 1-mm thick HOPG with 900 holes of 0.1 mm in diameter each.
- Heat transfer convection resistance is reduced by having a large number of holes for both fluid streams. The anisotropic thermal conductivity of HOPG allows a very large reduction in thermal resistance in transverse direction while minimizing axial conduction.
- The suggested recuperator design can achieve effectiveness of 98.7% with no excessive pressure drop (less than 0.2%). The suggested concept and design could lead to a disruptive technology and affect how future space heat exchangers are designed and built.

# Thank You