UNIST NThRS

(Nuclear Thermal-hydraulics and Reactor Safety)

A Study on Thermoelectric Hybrid Heat Exchanger Concept for Heat Pipe Cooled Micro Reactors

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I. Introduction

[1] K.C. Wagner et al., “MELCOR Integrated Severe Accident Code Application to Safety Assessment of Heat Pipe Reactors”, SAND2021, 2021.
[2] M. M. Swartz et al., “Westinghouse eVinci Heat Pipe Micro Reactor Technology Development”, ICONE28, August 4-6, 2021.

➢ Heat pipe cooled micro reactors;

- The heat pipe cooled micro reactors have been developed for space applications, military bases and transportable solutions (by Westinghouse, LANL, INL, MIT, Oklo power etc.).
- Typically cooled by liquid metal heat pipes (K, Na, Li etc.).
- The system has high reliability, passive heat transfer, and a high operating temperature.

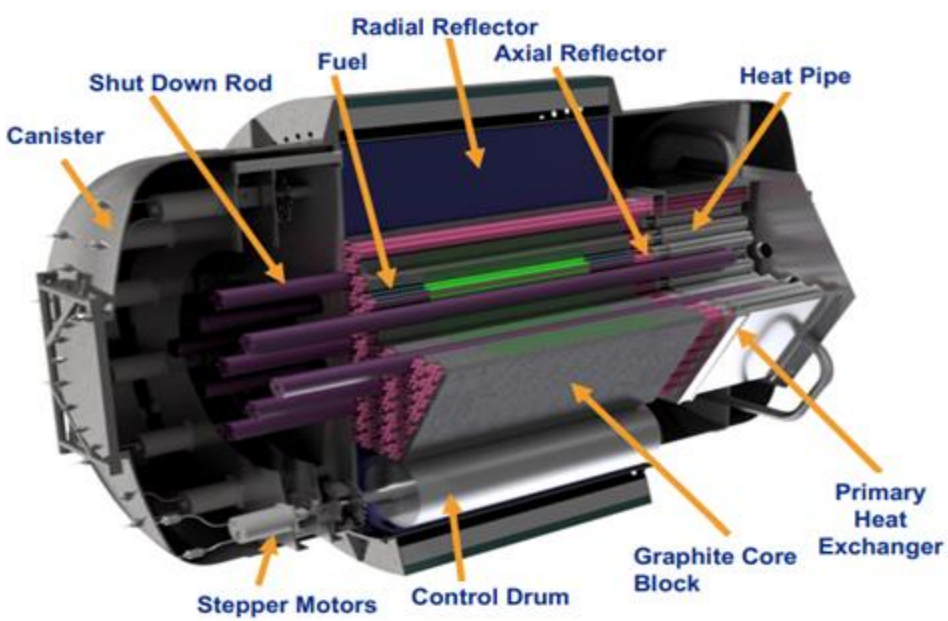


Fig. eVinci micro reactor overview [2].

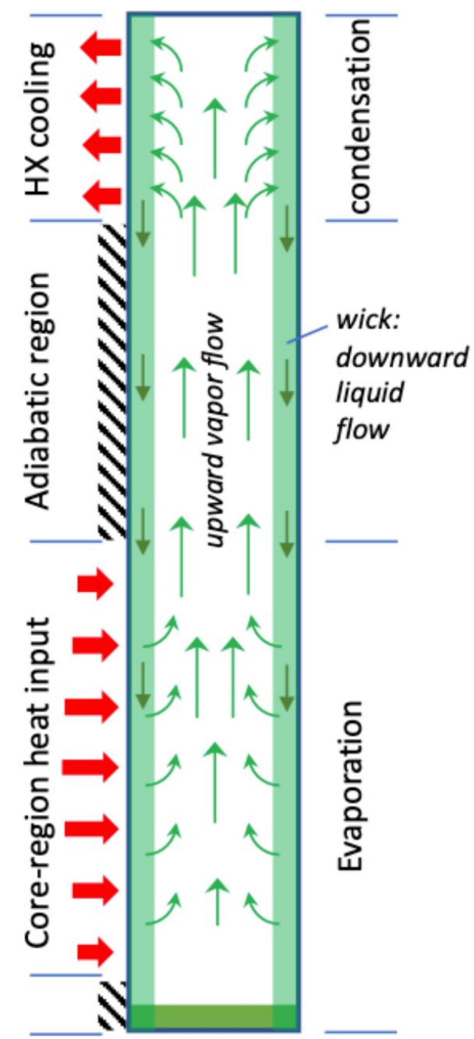


Fig. Illustration of a vertically oriented heat pipe [1].

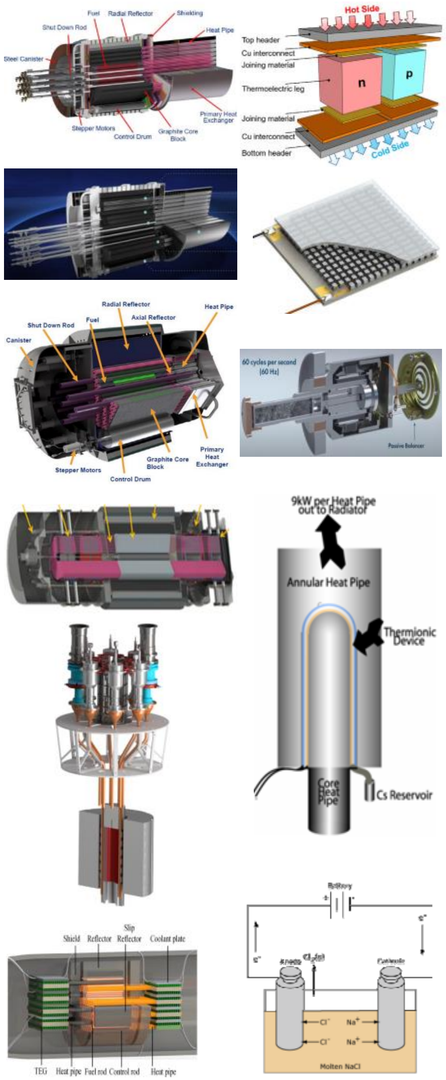
I. Introduction

➢ Dynamic Power Conversion Systems

- It is also known as Kinetic Energy Conversion Systems.
- These systems involve moving parts, and can often achieve higher power densities and efficiencies.
  - Brayton and Rankine Cycle,
    - Annular Flow Heat Exchanger (AFHX),
    - Printed Circuit Heat Exchanger (PCHE),
    - Finned Heat Exchanger (FHX).
  - Stirling Engine.

➢ Static Power Conversion Systems

- It is also known as Thermodynamic Power Conversion Systems.
- They can be more reliable and require less maintenance.
  - Thermoelectric,
  - Thermionic,
  - Thermophotovoltaic Cells,
  - Magnetohydrodynamic,
  - Electrolytic Cells.



I. Introduction

[3] Y. Ma et al., "Heat Pipe Temperature Oscillation Effects on Solid-State Reactor Operation", 23rd Pacific Basin Nuclear Conference, Beijing, China, 1-4 Nov, 2022.

➢ Heat pipe temperature oscillation;

- The Geyser boiling causes a positive reactivity and thus increases the core power.
- The Doppler effect causes the core to return to the critical gradually, but the heat pipe temperature oscillation still affects the core by significant fluctuations.
- Additionally, the temperature oscillation has effect on the peak stress of the core.
- The oscillation may aggravate the material thermal fatigue and cause structural failure during the long life of heat pipe reactors, which threatens the core safety.

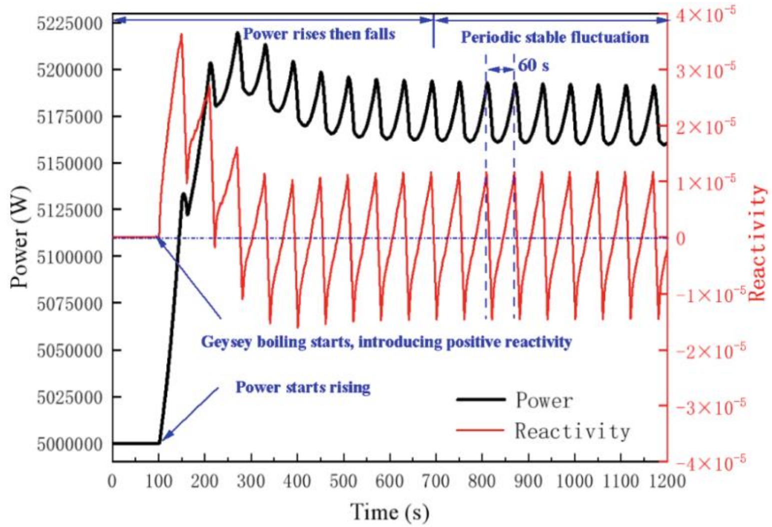


Fig. The effect of temperature oscillation on the core [3].

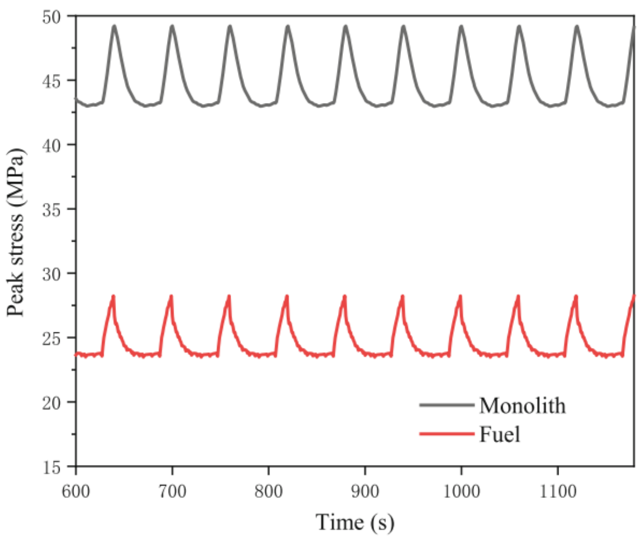


Fig. The stress oscillation for geyser boiling condition [3].

I. Introduction

[4] Y. Ma et al., "Heat pipe failure accident analysis in megawatt heat pipe cooled reactor", Annals of Nuclear Energy, Vol. 149, pp. 107755, 2020.
[5] P. McClure et al.," Design of megawatt power level heat pipe reactors", Technical Report of Los Alamos National Lab. (LANL), Los Alamos, NM, 2015

Heat pipe cascading failure;

- The local heat pipe failure probability is certainly high over the reactor lifetime.
- The cascading failure causes larger temperature rises and stress concentrations on neighboring heat pipes and core.
- Temperature increase affects the failure probability of neighboring heat pipes.
- In LANL design, more than three adjacent heat pipe failures is considered a beyond design basis accident [5].

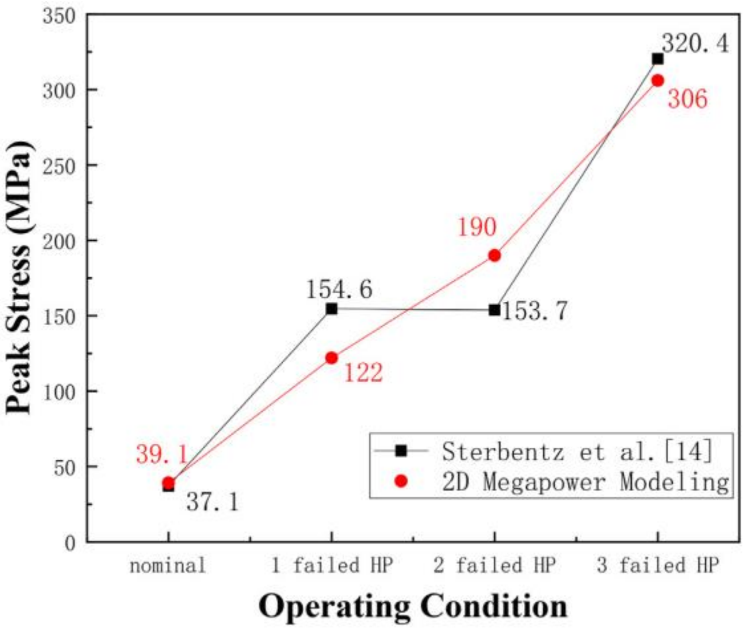


Fig. Peak stresses predicted by the 2-D and 3-D models [4].

Tab. Temperature result summary [4].

	Normal	One Failure	Two Failures	Three Failures
Peak fuel temperature/K	1060	1139	1250	1413
Change from normal/K	——	79	190	353
Peak monolith temperature/K	1003	1115	1225	1335
Change from normal/K	——	112	222	332
Maximum heat pipe operating temperature/K	983	1000	1026	1037
Minimum heat pipe operating temperature/K	886	886	886	886
Average heat pipe operating temperature/K	950	951	951	951
Maximum operating temperature difference/K	97	114	140	151

I. Introduction

[6] C. Wang et al., “Numerical evaluation of non-condensable gas influence on the heat transfer characteristics of high-temperature lithium heat pipe during reactor operation”, Annals of Nuclear Energy, Vol. 173, pp. 109077, 2022.
[7] L. Soffer et al., “Activation of Sodium, Lithium, and Potassium in Compact Fast Reactor and Its Effect on Shielding”, NASA Lewis Research Center, 1968.

➢ Neutron activation of working fluid;

- The neutron irradiation generates non-condensable gases which deteriorate thermal performance.
- The NCG distribution increases over the lifetime.
- Additionally, the neutron flux activates the working fluid isotopes.

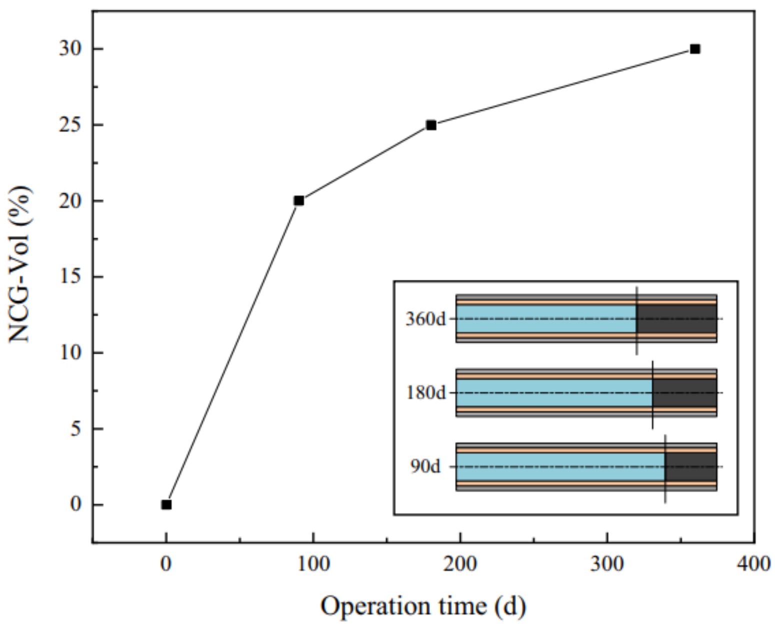


Fig. Change in NCG-vol during one year of operation [6].

Target nuclide	Product nuclide	Half-life
Na^{23}	Na^{24} Ne^{23} Na^{22} F^{20}	15.0 hr 38 sec 2.58 yr 11 sec
Li^{6}	He^{6}	0.8 sec
Li^{7}	He^{6} Li^{8}	0.8 sec 0.8 sec
K^{39}	Ar^{39} K^{38} Cl^{36}	260 yr 7.7 min 3×10^{5} yr
K^{40}	Ar^{39}	260 yr
K^{41}	K^{42} Ar^{41} Cl^{38}	12.4 hr 1.83 hr 37.3 min

Fig. Saturated specific activities of alkali metal isotopes [7].

I. Introduction

[8] K.C. Wagneret al., “MELCOR Integrated Severe Accident Code Application to Safety Assessment of Heat Pipe Reactors”, SAND2021, 2021.

➢ Radioactive product release;

- At the high power conditions, as the temperature increases, the pressure increases in HP.
- If the creep rupture exceeded, the HP wall will strain and fail.
- Fuel cladding and HP wall fail simultaneously near the melting temperature of stainless steel (~1400 °C).
- The fuel cladding failure begins the fission product release from the fuel.

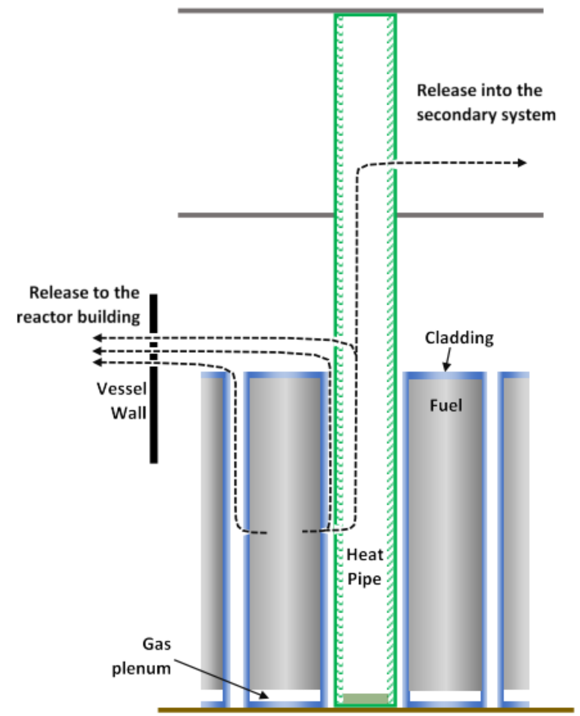


Fig. HP failure pathways [8].

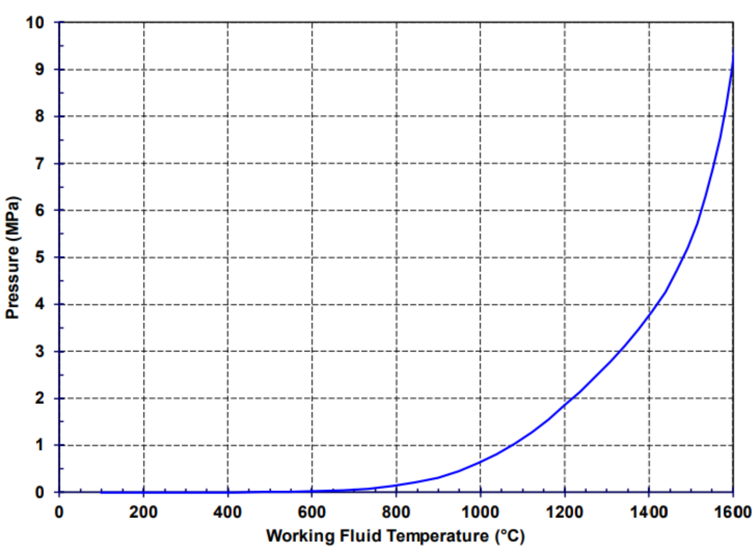


Fig. Potassium Equilibrium Pressure Temperature Curve [8].

- If the HP wall fails, the high pressure fluid exits from the HP and it ceases to operate.
- The fission product release to the atmosphere by secondary system.

I. Introduction

➢ Motivation

- Heat pipes are key components in cooling systems for micro nuclear reactors.
- The challenges and heat pipe failure scenarios generally related with overheating.
- Unplanned downtime due to heat pipe failure can lead to economic losses.
- A new design can incorporate better safety features, mitigating risks of overheating or failure.

➢ Objectives

- The new heat exchanger design is investigated to examine overheating.
- Examine the new design's safety features to see how they lower risks and boost overall safety.

II. Conceptual Hybrid Heat Exchanger: Thermoelectric Generator + Brayton Cycle

➢ Design concept of heat exchanger;

- The integration of a thermoelectric generator and Brayton cycle was aimed to overcome these overheating challenges
- To mitigate the effect of thermal expansion difference and localized wall heating, the heat pipes are enveloped within a coolant integral to the Brayton cycle system.
- TEGs is integrated into the walls enclosing the Brayton cycle coolant.
- The air coolant counter-flow directions create temperature difference between TEGs′ sides.

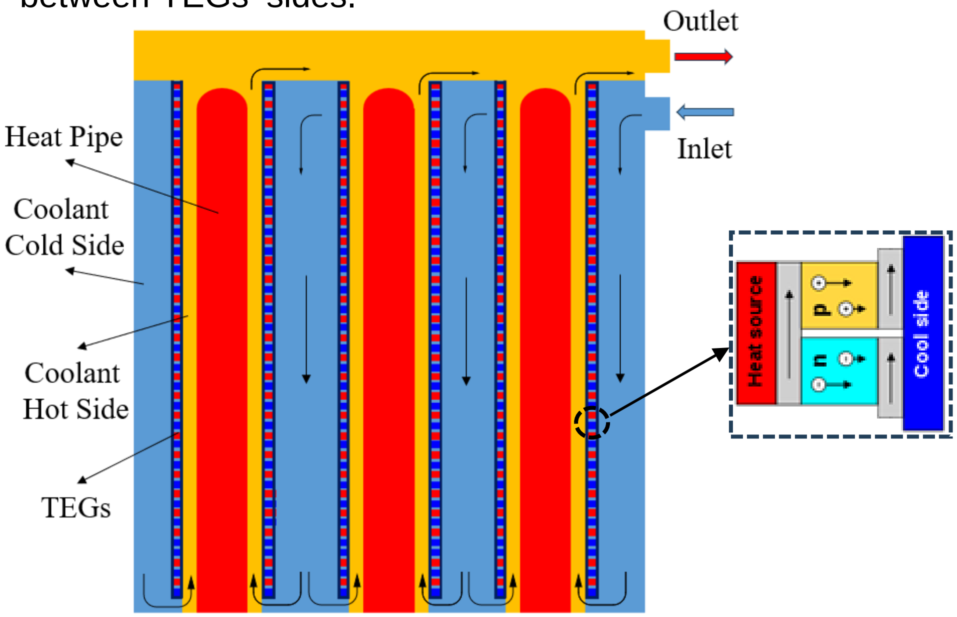


Fig. Simplified cross-sectional model of hybrid heat exchanger.

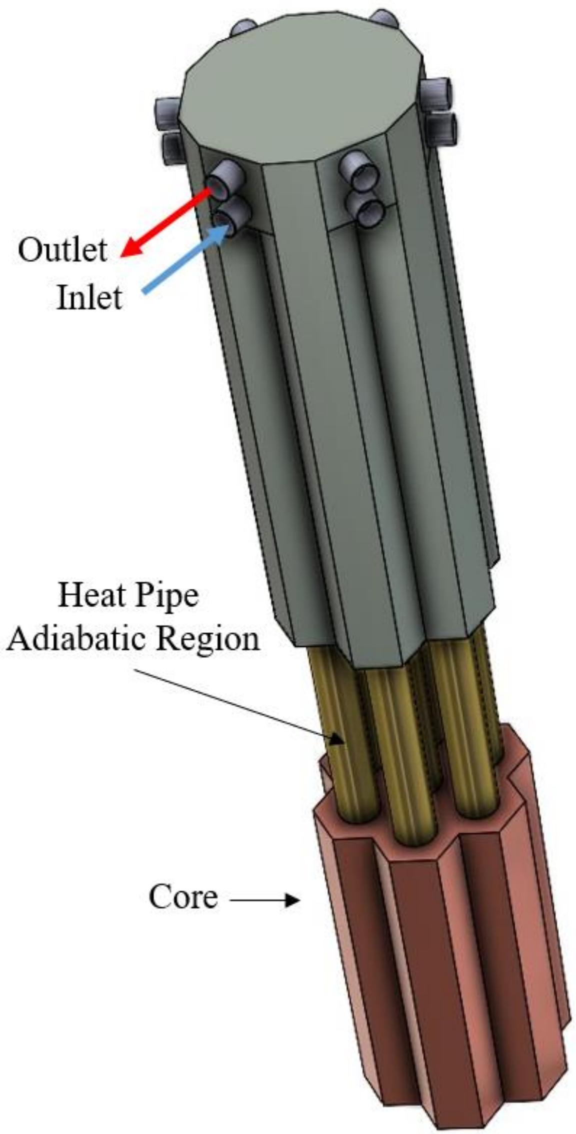


Fig. 3D representation of the design featuring seven heat pipes.

II. Conceptual Hybrid Heat Exchanger: Thermoelectric Generator + Brayton Cycle

[9] J.W. Sterbentz et al., "Special Purpose Nuclear Reactor (5 MW) for Reliable Power at Remote Sites Assessment Report", Idaho National Laboratory, April 2017.

➢ CFD analysis;

- The thermal analysis were only performed on one heat pipe channel.
- SPR design was chosen as a reference design.
- Inlet temperature into the turbine is 675 ℃.
- Heat exchanger of this reactor operates between 486.1 ℃ and 675 ℃.
- SolidWorks Flow Simulation was used to simulate all conditions.

Parameter	Unit	Value
HP Inner Diameter	cm	1.575
HP Outer Diameter	cm	1.757
HP Operating Pressure	MPa	0.1
HP Working Fluid		Potassium
HE Inlet Temperature	°C	486.1
HE Inlet Pressure	kPa	246.3
HE Inlet Flow Rate	kg/s	0.020
Condenser Length	cm	210
Material		SS 316
Coolant		Air
HP-to-HP Pitch	cm	2.771

Tab. Design and flow analysis parameters [9].

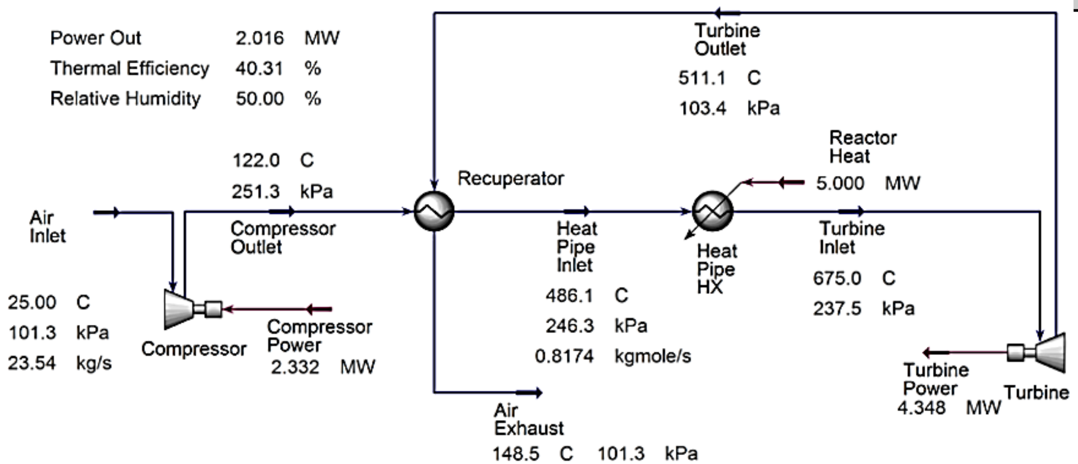


Fig. Aspen HYSYS model of heat recuperated air Brayton cycle [9].

- Heat pipe operating temperatures are;
  - Case 1 – 727 °C [9],
  - Case 2 – 765 °C [4].

II. Conceptual Hybrid Heat Exchanger: Thermoelectric Generator + Brayton Cycle

➢ Mathematical modeling of thermoelectric generator;

- TEGs contain p and n semiconductor legs which operate between hot and cold sides.
- The number of p-n couples ranges from 1 to n_r radially, and superscript i is used for axial numbering which ranges from 1 to n_x.
- The external load R_L (Ω) is connected to the modules in series to form a closed loop.
- The power output and efficiency are strong function of external load and temperature difference.

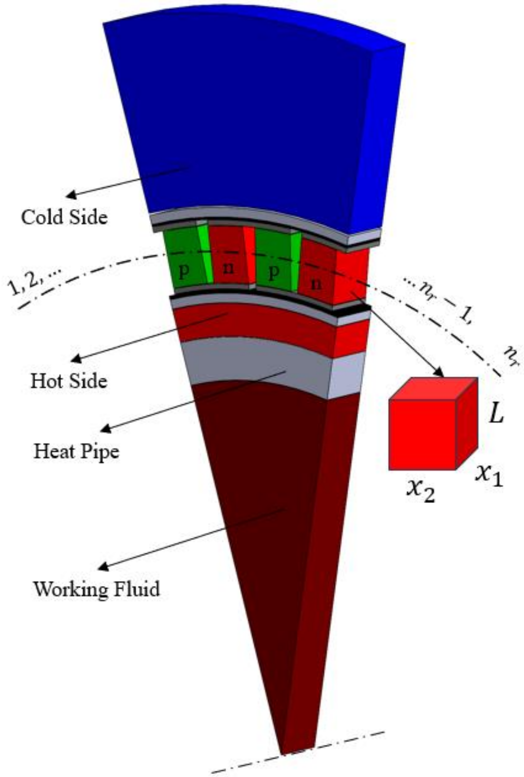


Fig. Cross-sectional 3D view of thermoelectric p-n units.

$$P^i = {I^i}^2 R_L = \left[\frac{n_r \alpha_{pn}^i \left(T_h^i - T_c^i\right)}{R_L + n_r R_{pn}^i}\right]^2 R_L$$

$$\eta^i = \frac{P^i}{Q_h^i}$$

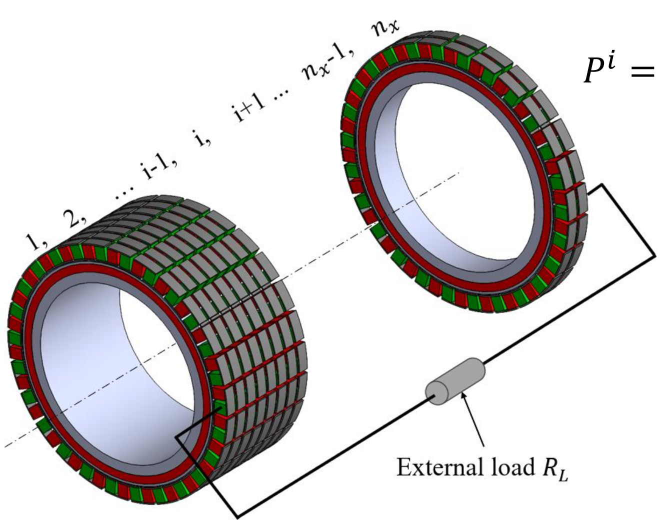


Fig. Axially segmented 3D model of one heat pipe channel.

Parameter	Value
x1	1 mm
x2	1 mm
Length of legs (L)	1.2 mm
TEG material	Skutterudite
# of p-n couple (n_r)	26
# of axial ring (n_x)	1655

Tab. p-n units design parameters for a channel.

III. CFD and Calculation Results

➢ Coolant temperature variation;

- The temperature difference between hot and cold sides is decreased via the channel length for both cases.
- The maximum temperature gradients were observed at the inlets of the channel.
- Case 1 exhibits a maximum temperature difference of 194.06 °C.
- Case 2 displays a gradient varies between 0 - 224.02 °C.

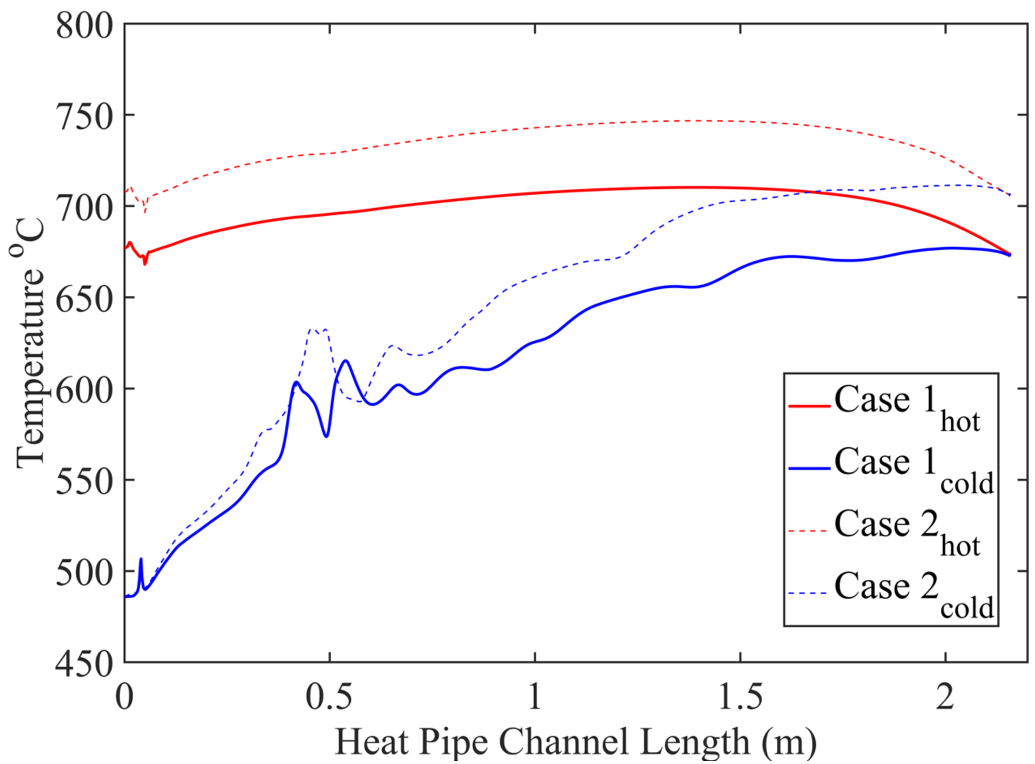


Fig. Temperature distribution of hot and cold sides via the channel length for both scenarios.

III. CFD and Calculation Results

External load effect;

- The external load has a paramount importance in determining its operational efficiency and overall power output.

- The resistance of the external load is equal to the internal resistance of the thermoelectric generator at point 1 which maximize the power output.

- TEG modules extract less power at point 2 and 3

- By adjusting the external load, it is possible to regulate heat extraction rates.

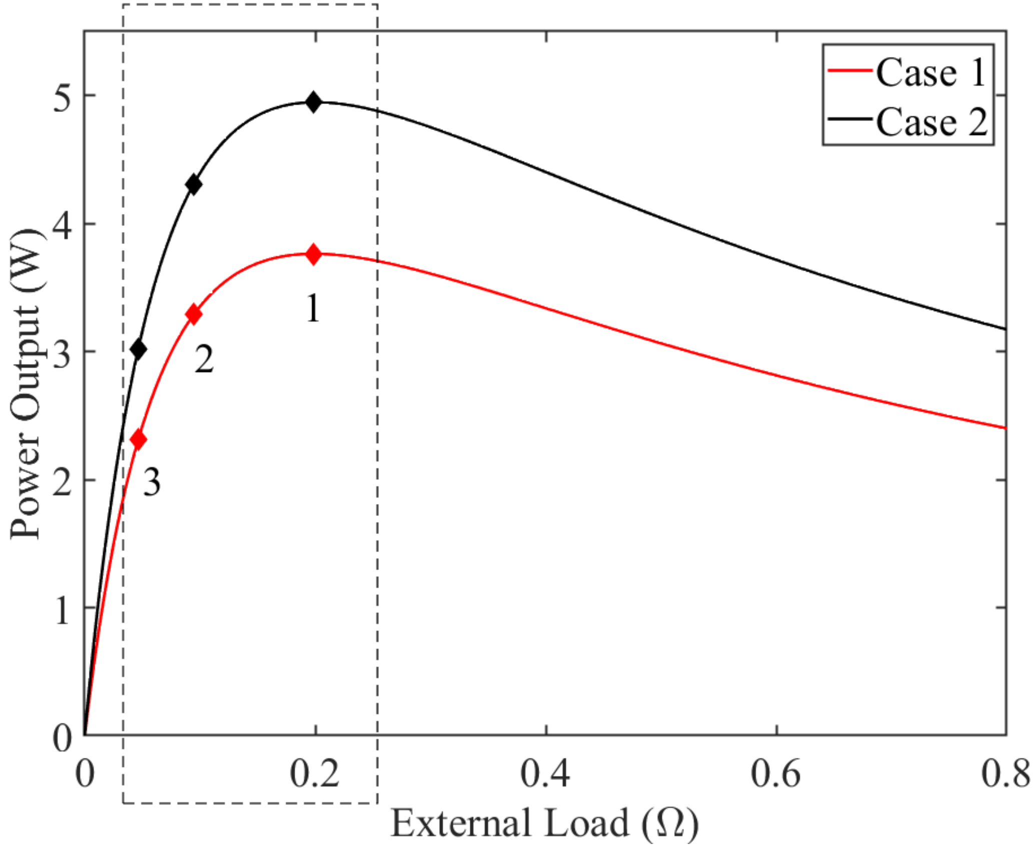


Fig. External load effect on power output of both cases.

III. CFD and Calculation Results

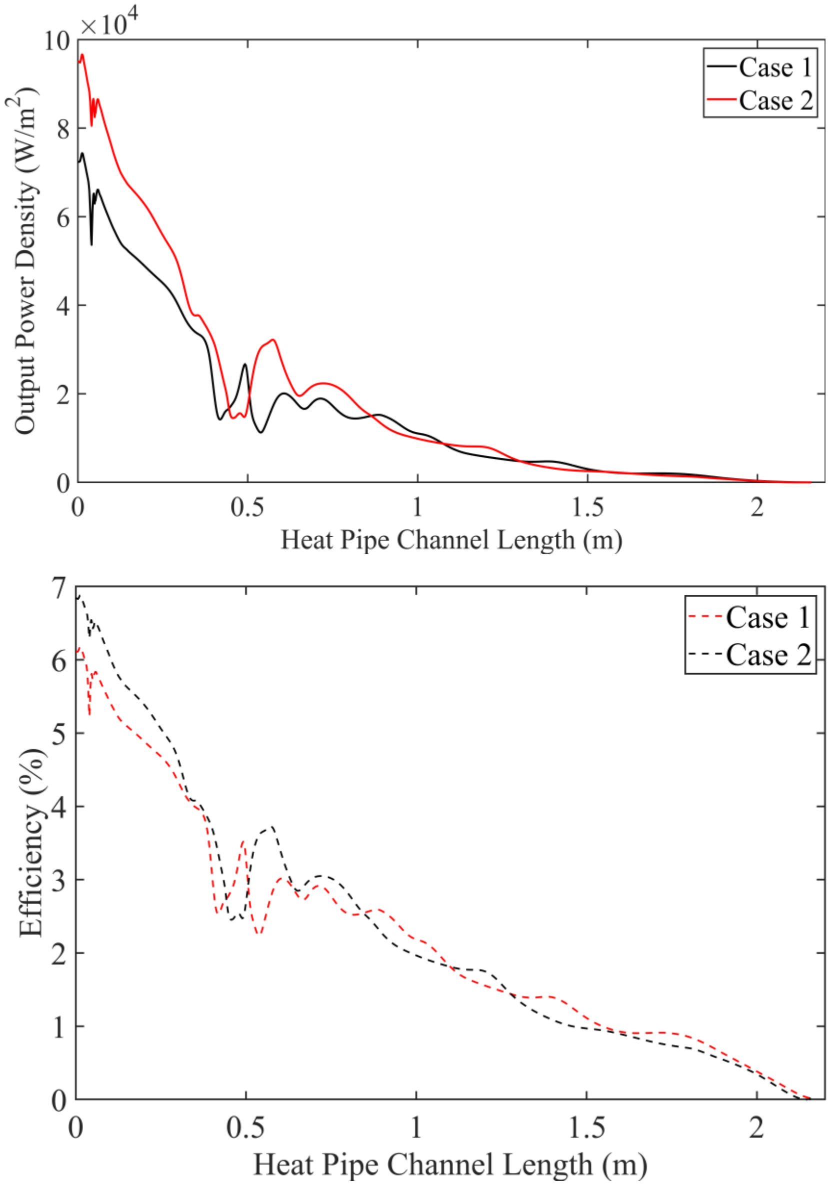


Fig. Power output and efficiency change via the channel.

➢ Power output and efficiency;

- In the inlet rings of TEG system:
  - The highest power density of case 1 and case 2 are 7.43e+04 $\mathrm{W/m^2}$ and 9.59e+04 $\mathrm{W/m^2}$, respectively.
  - The efficiency percentages are 6.17 % and 6.87 %, respectively.
- Both parameters decreases towards the channel end due to less temperature difference.

III. CFD and Calculation Results

➢ Power output comparison;

- The power density outputs from the inlet rings vary as 7.43e+04 W/m^2, 6.49e+04 W/m^2, and 4.56e+04 W/m^2, respectively.
- The thermoelectric system extracts 1.32 kW and 1.61 kW for case 1 and case 2, respectively.
- TEG modules extract an additional 0.29 kW of power from a single heat pipe autonomously, without any external intervention.
- This value can be increased to 0.81 kW by allocating a safety margin of external load which varies between 0.0465 Ω and 0.1988 Ω.

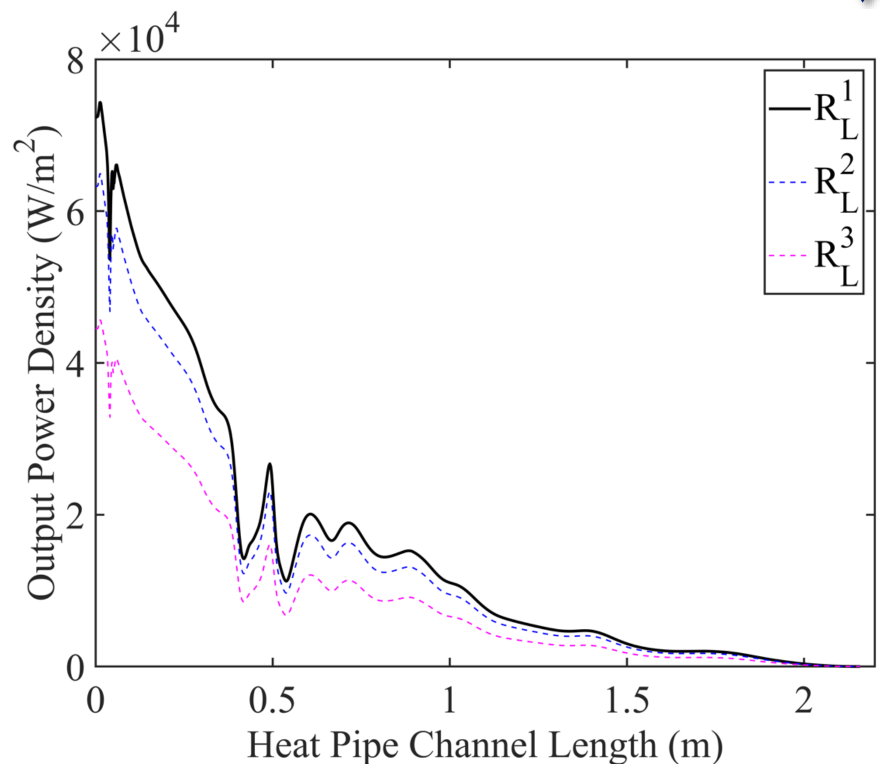


Fig. Power output change of case 1 under the selected external loads..

	Point 1 - 0.1988 Ω	Point 2 – 0.0946 Ω	Point 3 – 0.0465 Ω
Case 1	1.32 kW	1.15 kW	0.80 kW
Case 2	1.61 kW	1.39 kW	0.97 kW

Tab. Cumulative power output of 1655 TEG rings under chosen external loads.

IV. Conclusion and Future Works

➢ Conclusion

- The integrated thermoelectric and Brayton cycle heat exchanger for heat pipe cooled reactor was designed to overcome mentioned challenges.
- The heat pipe normal operating conditions and cascading failure conditions are investigated on the current design.
- The heat extraction of thermoelectric system increased from 1.32 kW to 1.61 kW by converting the additional 0.29 kW heat energy into electricity from a single heat pipe passively.
- If the heat pipe temperature rises, the thermoelectric system's safety margin lets it pull more heat, from 0.80 kW to 1.61 kW.

➢ Future works

- The further CFD and safety analysis will be performed for different operating condition of both heat pipe and Brayton cycle coolant.
- The detailed structural analysis of TEG's module is needed to have more efficient thermoelectric system.

Thanks for your attention.

UNIST Reactor Innovation Loop (URI-LO)

V. Fluctuation on Cold Side

- When the coolant is heated, the density changes of fluid can lead to buoyancy effects which also lead to flow instabilities.
- Moreover, the cross-sectional area of cold side flow has a significant effect on the buoyancy effects, particularly in the context of flow instabilities.

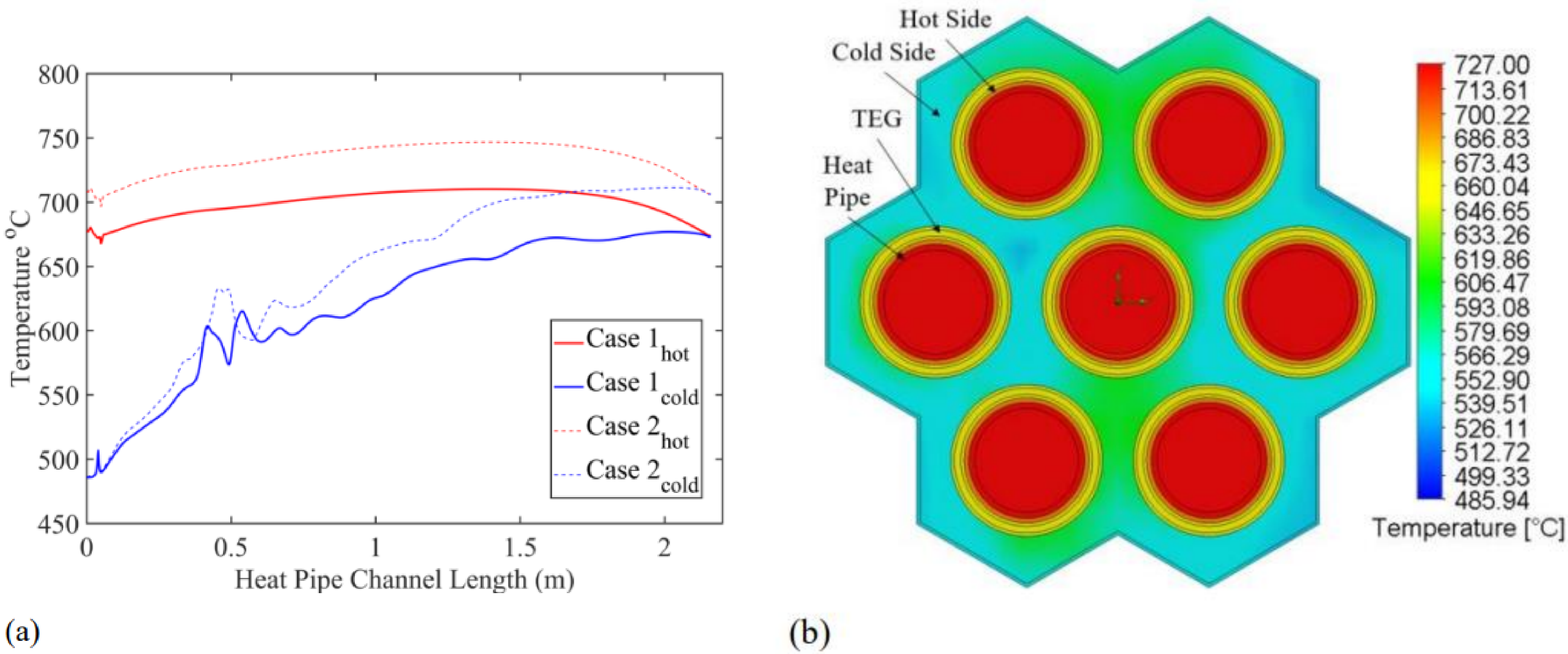


Fig. Temperature distribution of hot and cold sides, (a) via the channel length for both scenarios, and (b) midplane view of case 1 at 0.5 m.