A Survey on Application of Noble Gases and its Binary Mixtures in High Temperature Gas Cooled Reactors

Ankit Gandhi[a*], Paritosh Chaudhuri[b], Nimesh Gajjar[c], Nirav Joshi[d]

[a] PG Research Scholar, Mechanical (Thermal), Gandhinagar Institute of Technology, Gandhinagar, Gujarat, India.
[b]Institute for Plasma Research, Gandhinagar, Gujarat, India.
[c,d]Assistant professor, Gandhinagar Institute of Technology, Gandhinagar, Gujarat, India.

Abstract

This paper presents a comprehensive survey on the use of noble gases and its binary gas mixtures as primary coolant for heat extraction in high temperature gas cooled reactors. It also discusses and compares the advantages & disadvantages of using various binary gas mixtures with respect to conventional noble gases in high temperature applications. Helium (He) gas is widely used as a coolant for high temperature reactors due to its good transport and thermal properties. But on the other hand, due to extremely low density of helium, very high input circulation power is required when compared to other noble gases and their binary mixtures. As an alternative, it has been found out that mixing pure helium gas with a relatively dense gas like Carbon dioxide (CO_2), Xenon (Xe), Krypton (Kr), Nitrogen (N_2), Argon (Ar) may overcome the deficiency of high circulation power. Recent research works on application of various binary mixtures (He-CO_2, He-Xe, He-N_2 etc ;) in high temperature reactors have indicated that they have the advantage in terms of reduction of circulation power and compact size of equipments over pure He gas. Also, it is important to mention that out of various mixtures studied, it is found that He-CO_2 binary mixture at an optimum mole fraction offers the best solution in terms of reducing the input circulation power while also maintaining the cooling performance of the reactor.

Keywords: Helium, Binary Gas Mixtures, High Temperature Reactor

---

Nomenclature

Ar	*Argon*
CFD	*Computational Fluid Dynamics*
CO_2	*Carbon Dioxide*
DEMO	*Demonstration Power Plant*
Kr	*Krypton*
N_2	*Nitrogen*
SFR	*Sodium cooled Fast Reactor*
VHTR	*Very High Temperature Reactor*
Xe	*Xenon*

1. Introduction

High temperature gas cooled reactors have gained attention in recent times owing to requirement of higher efficiency (> 45%) as compared to water cooled reactors. Earlier most of high temperature reactors were cooled by water but they have their own limitations in terms of maximum critical temperature (374 °C) at critical pressure of 7.73 MPa. In order to increase the reactor exit temperature, it is essential to increase the operating pressure of water (close to 20 MPa) in order to have comparable efficiency of gas cooled reactors. There are also inherent safety and handling issues of activated water in irradiated conditions. In contrast gas cooled reactors like breeding blankets of experimental fusion reactors [1],[2], proposed DEMO reactor [3], Very High Temperature gas-cooled Reactor (VHTR) [4] [5], Sodium cooled Fast Reactor (SFR) [6], can attain higher exit temperature and hence, higher efficiency of the reactor. These reactors can be broadly classified in two categories – nuclear fission and fusion. Under nuclear fission type of reactors, VHTR and SFR operates at maximum temperature of 950 °C and 550 °C. In nuclear fusion category, breeding blankets operates at maximum temperature of 550 °C. It is reported that noble gases have an advantage of chemical inertness and thermodynamic stability at high temperatures which is quite essential for operation of high temperature gas cooled reactors. It includes noble gases like He, Xe, Kr, Ar etc.

---

* Ankit Gandhi
E-mail address: 200120721001@git.org.in

Helium gas is considered as the most promising coolant of all the noble gases due to its high thermal conductivity, low dynamic viscosity, good heat capacity, thermally stability at high pressure and temperature, low neutron cross-section and compatibility to structural materials. On the other hand, helium gas has the lowest density of all the above mentioned noble gases which in turn makes it undesirable from input circulation power point of view. Also, the bigger size of the turbomachines with more number of stages and more inventory space requirement is also expected due to its low density. Therefore, as an alternative and as per the recent research works in high temperature reactors applications have highlighted that it is possible to reduce the input circulation power by mixing the pure helium gas with a relatively dense gas (CO_2, N_2, Xe etc). These mixtures will result in compact size of the equipment of the reactor and in turn, may also increase the overall efficiency of the reactor.

2. Motivation

Helium gas is widely accepted as primary coolant for heat extraction in high temperature gas cooled reactors due to its superior thermal and transfer properties. It is considered in both nuclear fusion and fission type gas cooled reactors where the maximum operating temperature can be in excess of 500 °C. The detailed comparison of thermo-physical properties of helium versus other noble gases & CO_2 at reference operating conditions of 8 MPa, 700 K is presented in table-1.

Table 1. Thermo-physical properties of various noble gases and CO_2 [7]

Parameters	He	Xe	Kr	Ar	CO_2
Molecular weight (g/mole)	4.003	131.29	83.80	40	44
Density (kg/m^3)	5.43	181.70	113.50	53.75	60.45
Thermal conductivity (W/m-k)	0.285	0.0126	0.0196	0.0354	0.051
Dynamic viscosity (Pa-s)	$3.6x10^{-5}$	$5.06x10^{-5}$	$5.12\ x10^{-5}$	$4.41x10^{-5}$	$3.24x10^{-5}$
Heat capacity (kJ/kg-k)	5.19	0.173	0.259	0.532	1.167

From above table, it is evident that helium gas has the best thermodynamic properties like high thermal conductivity, low dynamic viscosity and high heat capacity compared to other noble gases and CO_2, except its low density at high pressure and high temperature conditions. To highlight this particular deficiency of low density of pure helium gas, a basic circulation power was performed for a high speed helium turbomachine with following process parameters highlighted in table-2.

Table 2. Process parameters of a typical helium circulator [8]

Technical parameters	Value
Type	Centrifugal (2-stage)
Pressure (In/Out), MPa	7.8/8.3
Temperature (In/Out), °C	60/80
Nominal mass flow rate, g/s	225
Nominal rotational speed, RPM	72000

Using Standard equation for power calculation and other losses, where:

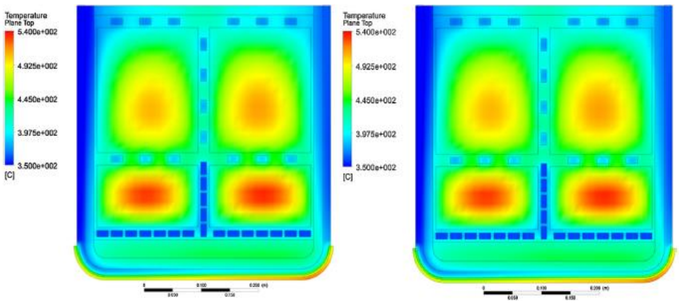
$$P = Z_{avg} \times R \times m \times \gamma \times \frac{(T_2 - T_1)}{(\gamma - 1)}$$

- P = Power, kW
- Z_{avg} = Average compressibility factor
- R = Real Gas constant
- m = Mass flow rate (kg/s)
- Υ = Specific heat ratio (1.67)
- T_2 = Discharge temperature, °C
- T_1 = Inlet temperature, °C

From above calculation, it is found that even for a very low compression ratio of ~1.07, around 30 kW of input circulation power is required. This input power is quite significant considering such low pressure rise and highlights high specific heat ratio and low density of helium. Hence, based on the above preliminary findings, it is desirable to optimize the circulation power of helium gas which may be possible to achieve by mixing it with relatively dense gases.

3. Detailed Literature Survey

Yeon-Gun Lee et al; [1] had proposed a helium-based binary gas mixture as an alternate to helium gas as primary coolant for heat extraction of First Wall of Korea Helium Cooled Molten Lithium Test Blanket Module. In this study, CO_2 was selected and evaluated as an additive gas due to its high density and relatively good thermal characteristics. CO_2 is a naturally abundant gas and has been widely used as a coolant in the early fission gas-cooled reactors and industries. CO_2 also has low neutron cross-section with no activating issues and good chemical stability with metals. They performed CFD analyses with He-CO_2 mixture as a coolant. Using pure helium as a reference coolant, the fluid velocity and the associated circulation power to assess the thermal performance were found from the CFD simulations for various molar compositions (Refer Fig 1). The results shows that the optimal CO_2 mole fraction is estimated to be 0.4 (refer Fig 2) and the circulation power can be reduced compared to 13% of that of pure helium. It also implies that the thermal efficiency of a He-cooled blanket system can be fairly enhanced by means of the proposed binary mixing since the input circulation power is reduced.



(a) Pure helium (b) He/CO_2 mixture ($X_{CO_2} = 0.4$)

Fig. 1. SEQ Figure * ARABIC 2. Temperature profile of First Wall

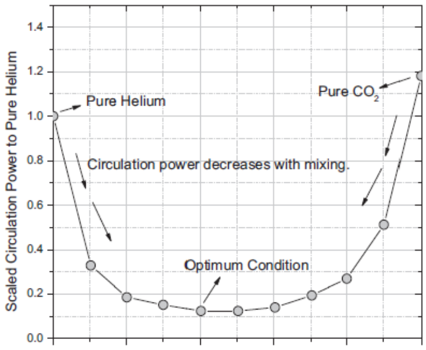


Fig. 2. SEQ Figure * ARABIC 1. Circulation power of He-CO_2 mixture compared with helium

Haifei Deng et al [2] also proposed a similar He-CO_2 binary mixture as primary coolant for heat extraction on their Helium gas cooled Ceramic Breeder Test Blanket Module as an alternate to helium gas. They performed CFD analysis on a single-group flow channel by circulating the binary mixture 4 times and 5 times to estimate the effect on circulation power. The results of thermal-hydraulics parameters can been referred in Fig 3. They found that the optimal CO_2 mole fraction is estimated to be in range of 0.4-0.6 (refer Fig 4) and the circulation power can be reduced by 9% compared to pure helium. They also found out that the circulation power is less influenced by the number of circulation times in a single-group flow channel.

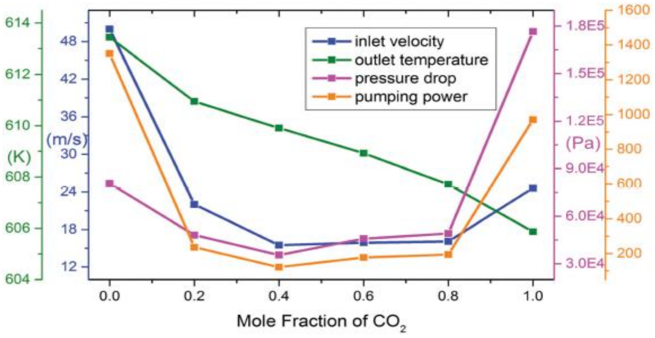


Fig. Thermal-hydraulic parameters variation of coolant with mole fraction of additive CO_2 gas

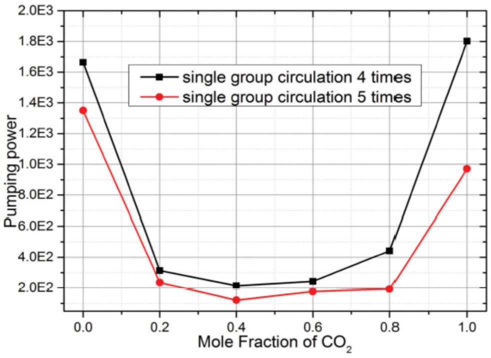


Fig. Variation of circulation power with mole fraction of additive CO_2 gas

Jan Stepanek et al; [3] proposed a comprehensive view of the benefits of using various working media and thermal cycle layouts for efficient conversion of thermal energy from the helium-cooled DEMO reactor for electricity production. The selected working media are water-steam, supercritical CO_2, and helium. Study results compare suitability of using the water-steam, S-CO_2, and helium cycles for different outlet temperatures of the source as well as a view of their complexity in terms of size and number of components. The results shows that the Rankine cycle is the most effective solution from thermodynamics point of view (refer schematic from Fig 6), but S-CO_2 cycles can compete with it in compact size, complexity, cost, and operational flexibility and higher efficiency (refer Fig 5).

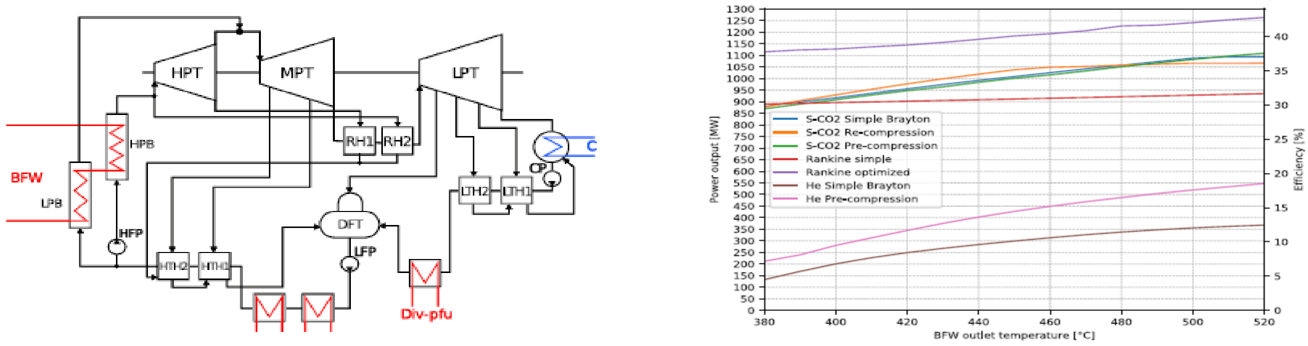


Fig. 5. Power output and cycle efficiency on blanket and first wall PHTS (BFW) outlet temperature

Jean-Michel Tournier, Mohamed S. El-Genk [4] [5] investigates the performance of Very High Temperature Reactor (VHTR) power plants with helium as working fluid in direct and indirect Closed Brayton Cycles (refer schematic in Fig 7), and compared with binary mixture working fluids of He–Xe and He–N_2 at molecular weight of 15 g/mole. They have found that above mixtures results in higher forced convection heat transfer coefficients (7% and 4.6% respectively) compared to pure helium gas. Also, it results in less number of stages and hence, more compact size of turbomachines in case of He-Xe and He-N_2 mixtures (refer Fig 8). It is also to be noted that for the same piping and heat exchange components design, the loop pressure losses with He–Xe are three times those with He gas.

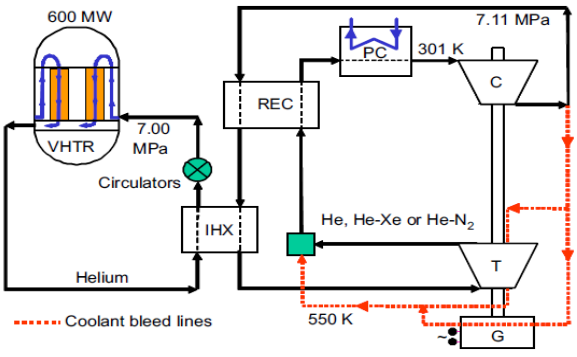


Fig. 7. Schematic of VHTR plant with indirect CBC

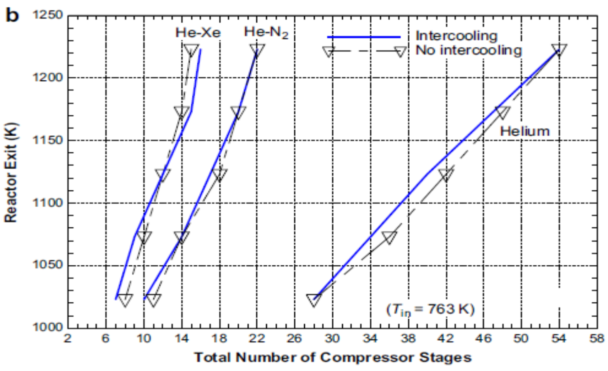
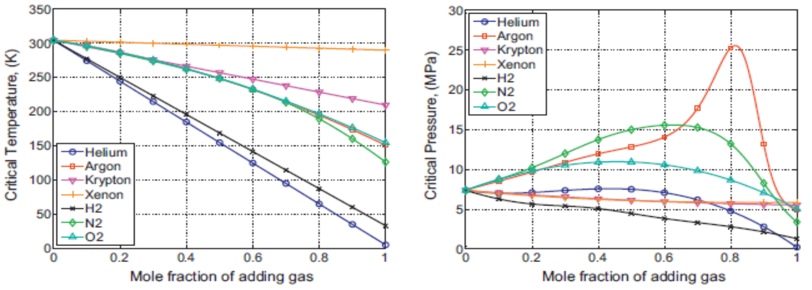


Fig. 8. Number of stages of the He, He–Xe and He–N_2 turbo-machines in indirect CBCs

Woo Seok Jeong, Jeong Ik Lee, Yong Hoon Jeong [6] presents an alternative of power conversion cycle (Brayton cycle) instead of an indirect Rankine cycle for a supercritical CO_2 fluid in Sodium cooled Fast Reactor (SFR). To prevent any hazards from sodium–water reaction, a SFR with the Brayton cycle using Supercritical Carbon dioxide (S-CO_2) as the working fluid can be an alternative approach to improve the current SFR design.

However, the S-CO_2 Brayton cycle is more sensitive to the critical point of working fluids than other Brayton cycles. This is because compressor work is significantly decreased slightly above the critical point due to high density of CO_2 near the boundary between the supercritical state and the subcritical state. For this reason, the minimum temperature and pressure of cycle are just above the CO_2 critical point. They performed study by mixing S- CO_2 with various gases like He, Ar, N_2 and O_2. It is expected that the cycle efficiency will increase with critical temperature and pressure at slightly above critical point of CO_2 (Fig 9). The highest cycle efficiency (+1.73%) reported is with CO_2-He binary mixture amongst all other mixtures (Fig 10).



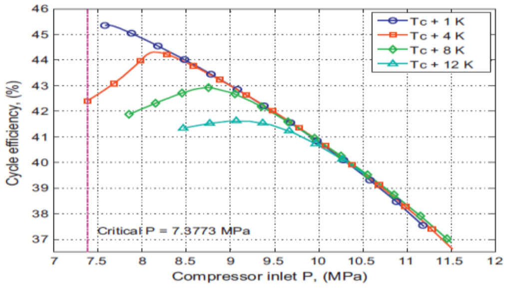


Fig. 10.Cycle efficiency along with various compressor inlet temperature and pressure

4. Discussion

Based on the survey of available literatures on binary gas mixtures, following points can laid out:

- Binary gas mixtures of helium and a relatively dense gas (CO_2 and Xe) is able to reduce the input circulation power in the range of 10% -15% as compared to helium gas.
- The relative size of the turbomachines in terms of shaft length and numbers of stages is reduced.
- The storage space for keeping the inventory is reduced.
- There is an increase in the overall thermal efficiency (~1.75%) of He-Xe mixture compared to pure helium gas.

Also, one more important point is to be noted that He-CO_2 binary gas mixture looks more promising compared to other mixtures (He-Xe, He-Kr etc ;) since CO_2 gas has greater density. It is abundant in nature unlike Xe and Kr and it has also thermodynamically proven as a coolant in various high temperature reactors. It has good compatibility with structural materials and has relatively low neutron cross-section, unlink Xe and Kr which have activation issues under irradiated environment. The only major drawback is CO_2 relatively low thermal conductivity and heat capacity compared to pure helium gas.

5. Conclusion

He-CO_2 is found as the most suitable binary gas mixtures to be used as primary coolant for heat extraction in high temperature gas cooled reactors as a replacement of helium. From the above detailed survey, it has been found that, He-CO_2 gas mixture reduces the circulation power by a magnitude and on the other hand, is able to maintain the thermal-hydraulic performance of the reactor. It is proposed that a Computational Fluid Dynamics (CFD) analysis is required to carry out this optimization works to assess the effect of binary mixture on the reduction of circulation power at an optimum mole fraction of the binary mixture and also to assess the cooling performance of the reactor.

References

1. Yeon-Gun Lee, Il-Woong Park, Dong Won Lee, Goon-Cherl Park, Eung-Soo Kim, 2015, “Reduction of circulation power for helium-cooled fusion reactor blanket using additive CO2 gas” *Fusion Engineering and Design, 100,* 436
2. Haifei Deng, Desheng Cheng, Weihua Wang, Bo Shi, 2017, “The Cooling Performance Improvement of First Wall Using He/CO_2 Binary Mixtures Gas for CN HCCB TBM” *Fusion Science and Technology, 72,* 188
3. Jan Stepanek, Slavomir Entler, Jan Syblik, Ladislav Vesely, Vaclav Dosta, Pavel Zacha, 2021, “Comprehensive comparison of various working media and corresponding power cycle layouts for the helium-cooled DEMO reactor”, *Fusion Engineering and Design, 166,* 112287
4. Mohamed S. El-Genk, Jean-Michel Tournier, 2009,“Performance analyses of VHTR plants with direct and indirect closed Brayton cycles and different working fluids” *Progress in Nuclear Energy, 51,* 556
5. Mohamed S. El-Genk, Jean-Michel Tournier, 2008, “Noble gas binary mixtures for gas-cooled reactor power plants*”, Nuclear Engineering and Design 238,* p. *1353–1372*
6. Woo Seok Jeong, Jeong Ik Lee, Yong Hoon Jeong, 2011, “Potential improvements of supercritical recompression CO_2 Brayton cycle by mixing other gases for power conversion system of a SFR ” *Nuclear Engineering and Design, 241,* 2128
7. NIST Chemistry WebBook , SRD69, https://webbook.nist.gov/chemistry/fluid/
8. M/s ATEKO, Details of Turbo-Circulators, https://www.ateko.cz/media/cache/file/65/turbo-circulators.pdf