

# Noble gas, binary mixtures for commercial gas-cooled reactor power plants

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## Abstract

This paper investigates the attributes and limitations of noble gasses and binary mixture as potential working fluids for gas-cooled nuclear power plants with Closed Brayton Cycles (CBC). Compared are the heat transfer coefficient and pressure losses of helium and other noble gases and binary mixtures, at typical operating conditions in commercial power plants (7.0 MPa and 400 – 1200 K), for the same molecular flow rate and geometry. Also investigated is the impact of the working fluid choice on the performance of nuclear power plants with direct CBCs and single-shaft and multiple-shafts turbo-machines. These plants typically operate at a system pressure of ~ 7 MPa and reactor and compressor exit temperatures of  $\leq 1200$  K and  $\leq 450$  K. The effects of the working fluid choice on the number of stages of the turbo-machines and the nuclear power plant's thermal efficiency and electrical power output are calculated and compared. Although He has high heat transfer coefficient and significantly lower pumping requirement, the heat transfer coefficient of the He-Xe binary gas mixture is ~7% higher and the turbo-machines have 75% fewer stages than for helium. The pumping requirement for this binary mixture, however, is 3.5 times that of helium, decreasing the plant peak efficiency by ~ 2 percentage points. Thus, using He-Xe, over He, as working fluid for gas-cooled reactor power plants would have to be based on considerations of reducing the size, mass, and cost of the turbo-machines.

*Keywords:* Gas-cooled nuclear reactors; noble gasses and binary mixtures; turbo-machines; plant efficiency, Brayton cycle.

## Nomenclature

$A$	Cross-section flow area ( $\text{m}^2$ )
$C_p$	Specific heat capacity at constant pressure (J/kg.K)
$\hat{C}_p$	Molar heat capacity at constant pressure (J / mole.K), $\hat{C}_p = R_g \times \gamma / (\gamma - 1)$
$C_v$	Specific heat capacity at constant volume (J/kg.K)
$D$	Diameter or equivalent hydraulic diameter (m)
$h$	Convective heat transfer coefficient ( $\text{W} / \text{m}^2.\text{K}$ )
$k$	Thermal conductivity ( $\text{W} / \text{m.K}$ )
$L$	Length of flow channel (m)
$M$	Molecular weight (g / mole)
$\dot{N}$	Molar flow rate (moles / s)
$n$	Number of stages in axial-flow turbo-machinery
$P$	Pressure (Pa)
$Q_{RX}$	Reactor thermal power ( $\text{MW}_{th}$ )
$r$	Cycle compression pressure ratio
$R_b$	Blades average radius (m)
$R_g$	Universal gas constant (8.3144 J / mol.K)
$S$	Heat transfer area ( $\text{m}^2$ )
$T$	Temperature (K)
$U$	Average, blade tangential velocity (m / s)
$Z$	Gas compressibility factor

## Greek

$\gamma$	Gas specific heat ratio, $C_p / C_v$
$\Delta H_C$	Enthalpy rise in compressor (J / kg)

$\Delta H_{unit}$	Enthalpy rise in turbo-machine unit (J / kg)
$\Delta P$	Total pressure losses (Pa)
$\Delta T_b$	Coolant temperature drop through flow channel (K)
$\Delta T_w$	Temperature drop between coolant bulk and heat exchanger wall surface (K)
$\varepsilon$	Recuperator effectiveness
$\varepsilon_{UT}$	Fraction of electrical power used for housekeeping
$\eta$	Plant net efficiency
$\eta_C$	Compressor polytropic efficiency
$\eta_G$	Generator efficiency (windage and EM losses)
$\eta_M$	CBC shaft mechanical efficiency (rotor disks windage and bearing losses)
$\eta_{switch}$	Efficiency of the switch to the Grid
$\eta_{th}$	Reactor thermal efficiency
$\eta_T$	Turbine polytropic efficiency
$\lambda$	Stage aerodynamic loading (or work coefficient)
$\mu$	Dynamic viscosity (kg / m.s)
$\pi$	Loop pressure loss factor
$\rho$	Density (kg / m <sup>3</sup> )
$\omega$	Shaft angular speed (radians / s)
$\omega$	

#### Subscript / Superscript

b	Coolant bulk
C	Compressor
FC	Forced convection
HP	High pressure spool
LP	Low pressure spool
o	Stagnation or total
T	Turbine
w	Wall
Xe	Xenon
1	Inlet of LP compressor
2	Exit of HP compressor
3	Inlet of nuclear reactor
4	Inlet of power turbine
5	Inlet of recuperator hot leg
6	Exit of recuperator hot leg
7	Exit of nuclear reactor
8	Exit of bleed line to mixing chamber
9	Inlet of HP turbine
10	Inlet of LP turbine
11	Exit of LP compressor
12	Inlet of HP compressor

## 1. Introduction

Helium-cooled nuclear reactors are being developed for modular, medium and small size, power plants in developing countries for electricity generation, and perhaps co-production of hydrogen. Examples are the Pellet Bed Modular Reactor (PBMR) [1-3], the Gas Turbine-Modular Helium Reactor (GT-MHR) [1,4], and the Gas Turbine High Temperature Reactors (GTHTR300 and GTHTR300C) [5-8]. These graphite-moderated, helium cooled reactors are directly coupled to Closed Brayton Cycles (CBCs), with a single-shaft, or multiple-shafts, multistage, axial flow turbo-machines.

The PBMR and GT-MHR heat the helium coolant to 850 °C (1123 K), while the Very High Temperature Reactor (VHTR), currently in the conceptual design stage and cooled with He, would operate at a reactor exit temperature of 950 – 1000 °C (1223 – 1273 K) [9]. Due to the inherent difficulty in manufacturing larger size single-shaft turbo-machines, multiple-shafts turbo-machines are currently being considered for use in gas-cooled reactor power plants generating > 150 MWe. The current experience with helium turbo-machines is limited, and

almost non-existing for noble gas binary mixtures. The largest capacity, helium turbine built to date is a 50 MWe unit in Oberhausen, Germany. It operated for over 30,000 hrs at an inlet temperature of 750 °C [10], but the actual physical dimensions could have supported an output of > 200 MWe at 850 °C [11].

The chemical inertness and the relatively good transport properties of helium have been a key to its selection as the working fluid for gas-cooled reactor power plants [1,3,10,12]. Helium (He) has the highest thermal conductivity,  $k$ , and the lowest dynamic viscosity,  $\mu$  of all noble gases, but when mixed with a heavier noble gas, such as Xenon (Xe) and Krypton (Kr), the transport properties of the resulting binary mixtures could be superior to those of helium and other noble gases of equal molecular weights as the binary mixtures [13]. On the other hand, increasing the molecular weight of the gas working fluid decreases the aerodynamic loading of the turbo-machines, but increases the pumping requirement.

The attributes and limitations of noble gasses and binary mixture as potential working fluids for gas-cooled nuclear power plants with CBCs are investigated in this paper. The heat transfer coefficient and pumping requirement for He and other noble gases and binary mixtures, for the same molecular flow rate, and operating temperatures and geometry, are compared. This comparison used recently developed semi-empirical correlations for the physical and transport properties of noble gases and binary mixtures that accurately account for the effects of pressure and temperature. These correlations are based on the Chapman-Enskog kinetic theory for dilute gases, and use the powerful law of corresponding states to account for the dependence of the gas properties on the pressure [13]. Also investigated is the impact of the working fluid choice on the performance of nuclear power plants with direct CBCs and single-shaft and multiple-shaft turbo-machines. These plants typically operate at a system pressure of ~ 7 MPa and reactor and compressor exit temperatures of  $\leq 1200$  K and  $\leq 450$  K. The effects of the working fluid choice on the number of stages of the turbo-machines and the nuclear power plant's thermal efficiency and electrical power output are calculated and compared.

## 2. Performance parameters of noble gases and binary mixtures

The forced convection, turbulent heat transfer coefficient can be expressed [14] as:

$$h_{FC} = \underbrace{0.023(T_w/T_b)^c N^{0.8}}_{\text{Operation}} \times \underbrace{\left[ D^{-0.2} A^{-0.8} \right]}_{\text{Geometry}} \underbrace{\left[ (M^{0.8} k^{0.35} C_p^{0.65}) / \mu^{0.15} \right]}_{\text{Gas Properties}} \quad (1)$$

The third term on the right hand side of this equation represents the physical properties of the gas working fluid. Thus, for the same operation conditions (temperatures, pressure, and molar flow rate) and geometry (diameter and cross sectional area of flow channels), the heat transfer coefficient is proportional to the thermal and transport properties of the gas working fluid as:

$$h_{FC} \propto (M^{0.8} k^{0.35} C_p^{0.65}) / \mu^{0.15} . \quad (2)$$

The pressure losses for a convective gas flow are given by the Fanning relation [15], as:

$$\Delta P = 0.5 a \left( L / (D^{1+b} A^{2-b}) \right) \left( \mu^b M^{2-b} / \rho \right) \dot{N}^{2-b} . \quad (3)$$

When the gas density,  $\rho = (MP/R_g TZ)$  is substituted into Eq. (2), the following expression for the pressure losses, normalized to the gas pressure at the inlet of a given component in the CBC loop,  $P$ , is obtained, as:

$$\left( \Delta P / P \right) = 0.5 R_g \underbrace{a \left( T / P^2 \right)}_{\text{Operation}} \underbrace{\dot{N}^{2-b} \left( L / (D^{1+b} A^{2-b}) \right)}_{\text{Geometry}} \underbrace{\left( \mu^b M^{1-b} Z \right)}_{\text{Gas Properties}} \quad (4)$$

For turbulent flow, the coefficients  $b \sim 0.2$  and  $a \sim 0.184$  [15], thus, for the same operation conditions and geometry, the normalized pressure losses solely depend on the gas properties, as:

$$\left[ \left( \Delta P / P \right) \propto \left( \mu^{0.2} M^{0.8} Z \right) \right] . \quad (5)$$

The aerodynamic loading in a single-stage, of a multi-stage turbo-machine unit,  $\lambda$ , is directly proportional to the total change in the enthalpy of the working fluid in the unit,  $\Delta H_{unit}$ , but inversely proportional to the number of stages,  $n$ , and the square of the average speed of the blades,  $U$ , and can be expressed as [16]:

$$\lambda = \Delta H_{unit} / (n U^2) = \Delta H_{unit} / (n \omega^2 R_b^2). \quad (6)$$

Therefore, for the same rotational speed and aerodynamic loading of blades, the average radius of the blades and/or the number of stages, along with the size and cost of the turbo-machines, increase as the enthalpy change in the unit,  $\Delta H_{unit}$ , increases. The enthalpy rise in a compressor unit is given, in terms of the inlet temperature, polytropic efficiency, compression ratio, and the gas properties, as:

$$|\Delta H_C| = (\hat{C}_p / M) T_{1,o} \left[ r_C^{(\gamma-1)/(\gamma \eta_c)} - 1 \right] \propto (\hat{C}_p / M). \quad (7)$$

Combining equations (6) and (7) gives:

$$n \propto \hat{C}_p / (M \lambda_C \omega^2 R_b^2). \quad (8)$$

The molar heat capacity of noble gases and binary mixtures at the inlet temperature of the compressor ( $T_{1,o} = 300$  K - 450 K) is nearly constant. Thus, for the same compressor inlet temperature,  $T_{1,o}$ , polytropic efficiency,  $\eta_c$ , and compression ratio,  $r_C$ , and the same stage aerodynamic loading,  $\lambda_C$ , rotation speed,  $\omega$ , and blades tip radius,  $R_b$ , the number of stages of the compressor unit is inversely proportional to the molecular weight of the gas working fluid. Thus, increasing the molecular weight of the noble gas or binary mixture working fluid would significantly decrease the number of stages of the turbo-machines.

The choice of the working fluid also affects the heat transfer area and volume of the heat exchange components in the CBC loop such as the recuperator, intercooler, and pre-cooler. For a characteristic heat exchanger channel, the heat transfer surface area,  $S$ , can be written as:

$$S \propto \underbrace{\left[ (T_w / T_b)^c (\Delta T_b / \Delta T_w) \dot{N}^{0.2} \right]}_{\text{Operation}} \underbrace{\left[ D^{0.2} A^{0.8} \right]}_{\text{Geometry}} \underbrace{\left[ M^{0.2} \mu^{0.15} (C_p / k)^{0.35} \right]}_{\text{Properties}} \quad (9)$$

Thus, for the same operation conditions and geometry, the heat transfer surface area, and hence the volume, solely depends on the thermal and physical properties of the gas working fluid. This is expressed by the third term on the right hand side of Eq. (9).

### 3. Relative performance comparisons

When the heat transfer coefficient of the gas working fluid (Eq. 1) is normalized to that of helium, the obtained values are indicative of the relative changes to that of helium (Fig. 1). As delineated in Figure 1, the heat transfer coefficients for noble gases decrease as the molecular weight increases, however, the binary mixtures of He with the higher molecular weight gases of Ar, Kr, and Xe have higher heat transfer coefficients than pure He, when the molecular weight of the mixture is  $\leq 8$ , 25, and 45 g/mole, respectively. At higher molecular weights, the heat transfer coefficients of these noble gas binary mixtures are lower than that of He, but remain higher than those of the high molecular weight gases in the mixtures. The binary mixtures of He-Xe with molecular weights  $< 45$  g/mole have higher heat transfer coefficients than He, thus, are potentially good choices for reducing the heat transfer area and size of the recuperator, gas cooler and the intercooler in CBC loops, and for enhancing the reactor cooling. The maximum heat transfer coefficient is that of He-Xe with a molecular weight of 15 g/mole; it is 7% higher than those of helium and He-Xe with a molecular weight of 45 g/mole (Fig. 1). The relative heat transfer coefficients of noble gases and binary mixtures decrease with increasing temperature. The difference, however, is negligible for molecular weights  $\leq 20$  g/mole, but increases significantly at higher molecular weights (Fig. 1).

The pumping requirement of the compressor equals the sum of the pressure losses in the piping segments, recuperator, inter-cooler and the pre-cooler of the CBC loop and in the nuclear reactor. The normalized pressure losses to those of helium indicate that the values for the noble gases and binary mixtures with molecular weights  $< 60$  g/mole are almost independent of temperature, but increase with increasing molecular weight (Fig. 2). For Ar and the binary mixtures of the same molecular weight (40 g/mole), the normalized pressure losses are nearly the same and more than 6.5 times those with helium. Figure 2 shows that the number of stages of the turbo-machines is

practically independent of the gas temperature, but decreases rapidly with increasing molecular weight of the gas working fluid (Eq. 8).

For the He-Xe binary mixture with a molecular weight of 15 g/mole, the normalized pressure losses, corresponding to the maximum heat transfer coefficient (Fig. 1), are 3 times those of He (Fig. 2). For application to terrestrial nuclear power plants, this He-Xe binary mixture is potentially an attractive working fluid, based on considerations of similar or slightly higher, heat transfer coefficient than for He, along with a significantly fewer stages in the turbo-machines. Conversely, based solely on low-pressure losses considerations, helium is by far a better choice for a working fluid, because of the low pumping requirement, which increases the plant efficiency.

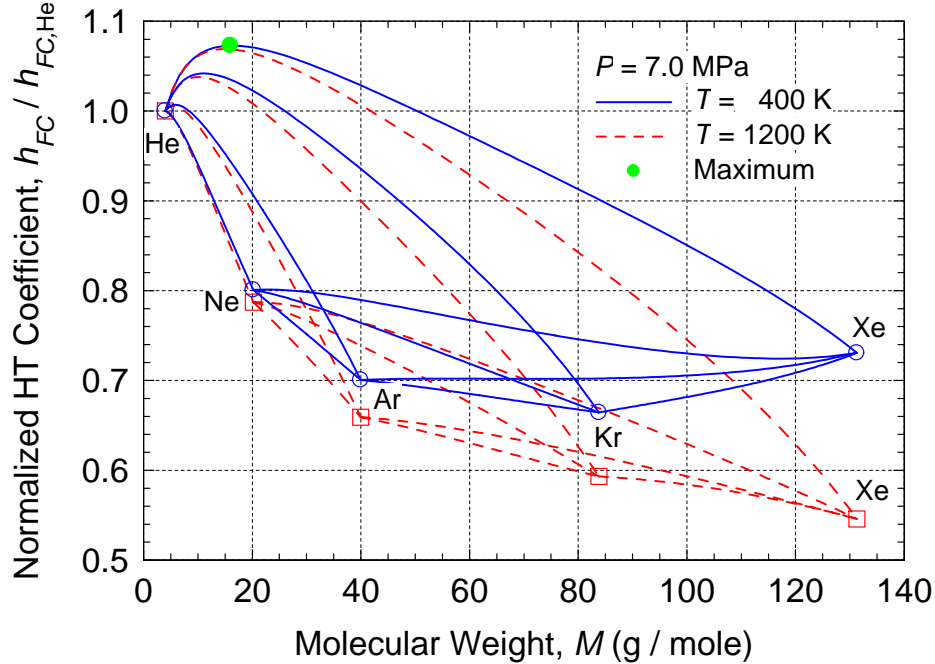


Fig. 1. Normalized, turbulent heat transfer coefficients for noble gases and binary mixtures.

For a He-Xe binary mixture with higher molecular weight than 15 g/mole, the decrease in the number of stages in the turbo-machines comes at the expense of even higher pressure losses and a lower heat transfer coefficient. The latter decreases the heat transfer area and the size and cost of the gas cooler(s), inter-cooler(s), and the recuperator in the CBC loop (Figs. 3 - 6). The binary mixture of He-Xe with a molecular weight of 25 g/mole, is also a potentially attractive working fluid, since the number of stages of the axial-flow turbo-machines is only 16% ( $\sim 1/6$ ) of that with a helium working fluid, while the heat transfer coefficient is 6% higher than that of He (Fig. 1). However, the pressure losses with this working fluid are 4.7 times those with He, which decrease the power plant thermal efficiency, as detailed next.

#### 4. Comparisons of nuclear power plants performance

The performance analysis presented in this section examines the effect of using working fluids of He, and He-Xe with a molecular weight of 15 g/mole, on the thermal efficiency and load electrical power of terrestrial nuclear power plants with CBCs (Figs. 3 and 4 for He, and Figs. 5 and 6 for He-Xe). This plant analysis with helium and He-Xe working fluids assumes a shaft mechanical efficiency,  $\eta_M = 99\%$ , electrical generator efficiency,  $\eta_G = 0.95$ , an electrical switching efficiency,  $\eta_{switch} = 99.4\%$  and a house-keeping electrical power utilization,  $\epsilon_{UT} = 2.5\%$  of that produced by the electrical generator. The plant performance results in Figs. 4 - 9 are for a compressor inlet temperature of 301 K, same reactor design, and equal relative pressure losses in the piping segments and heat transfer components of the CBC loop. As a result, the piping diameter in the plants with He-Xe binary mixture working fluid is increased by 23%, and the effective hydraulic diameter in the heat exchange components of the CBC loop is decreased by  $\sim 27\%$ , compared to those with He. However, the calculated pressure losses in the reactor with the He-Xe working fluid are 2.7 times those with He; they correspond to a relative pressure losses in the reactor of  $\sim 5.4\%$  of the inlet pressure, compared to only 2% with helium.

The higher pressure losses with the He-Xe working fluid (15g/mole) decrease the pressure loss factors,  $\pi$ , to 0.9024 and 0.8906, for the nuclear power plants with single-shaft turbo-machines (Figs. 3 and 5) and multiple-shaft turbo-machines (Figs. 4 and 6). With He as working fluid and single-shaft turbo-machines, the total relative pressure losses is  $\sim 6.7\%$ , which correspond to a loop pressure loss factor,  $\pi = 0.9346$ . With the same working fluid and multiple-shafts turbo-machines, the relative pressure losses in the plant are higher,  $\sim 8\%$  and correspond to a lower pressure loss factor,  $\pi = 0.9224$ .

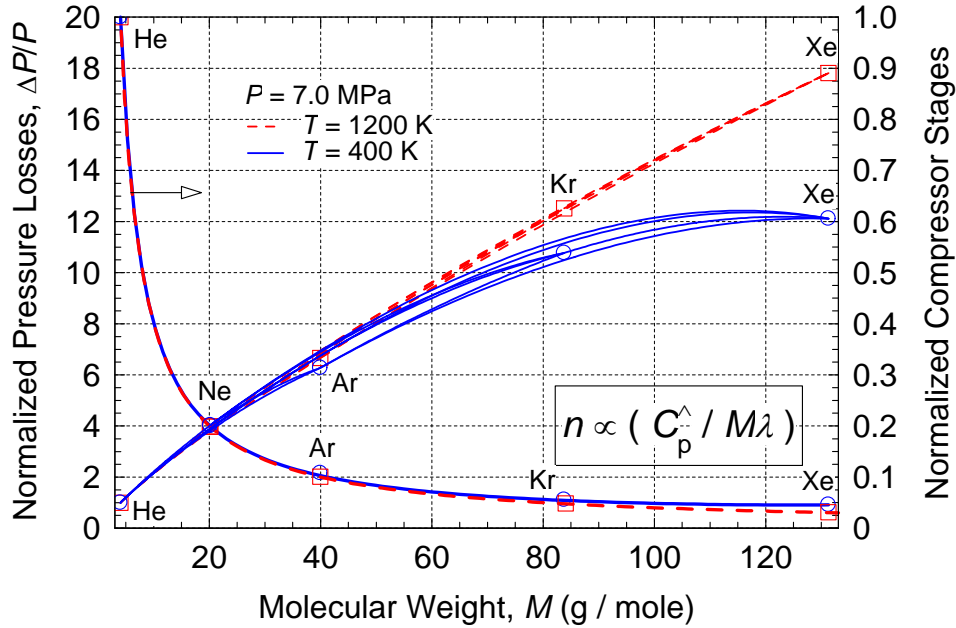


Fig. 2. Pressure losses and compressor stages for noble gases and binary mixtures CBC working fluids.

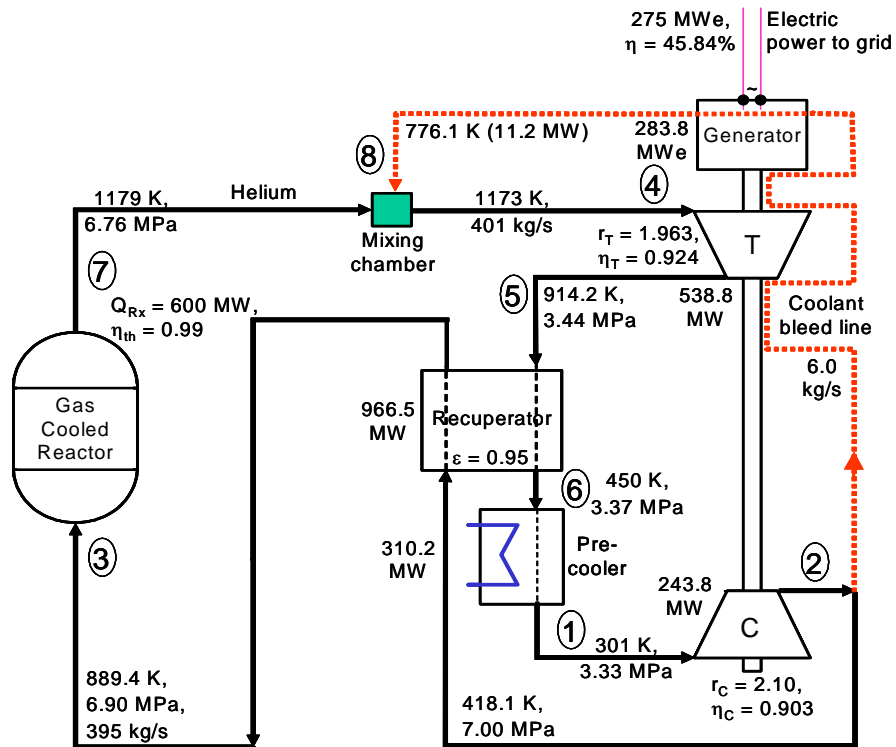


Fig. 3. Nuclear power plant with direct CBC, helium working fluid, and single-shaft turbo-machine.



Due to the absence of similar data for He-Xe, these correlations are also used in the present plant analysis with single- and multi-shafts turbo-machines and He-Xe working fluid (15 g/mole). Such an approach is valid, as long as the He and He-Xe turbo-machines are designed with identical stage reaction, loading, flow coefficient, and identical blades stagger angle and solidity.

The calculated performance parameters of the nuclear power plants with axial flow, multi-stage turbo-machines are summarized and compared in Figs. 7 - 9. With He working fluid, not only the plant peak efficiency is higher, but also the corresponding cycle compression ratio,  $r$ , is lower than with the He-Xe working fluid (15 g/mole). When the recuperator effectiveness,  $\varepsilon = 0.95$ , and the reactor's exit temperature is  $\sim 1173$  K, the peak efficiency of the plant with helium working fluid and single-shaft turbo-machine is 45.8% and the corresponding cycle compression ratio is 1.96. These values for the plant with the He-Xe working fluid with 15 g/mole are 43.6% and 2.36, respectively (Figs. 3, 5 and 7). The plant's peak efficiency and the corresponding cycle compression ratio increase almost linearly as the turbine inlet temperature increases. Increasing the turbine inlet temperature to  $950^\circ\text{C}$  ( $1223$  K) increases the plant's peak efficiency and the corresponding cycle compression ratio with helium working fluid to 47.2% and 2.14, compared to 45% and 2.41 with the He-Xe working fluid (15 g/mole) (Fig. 7).

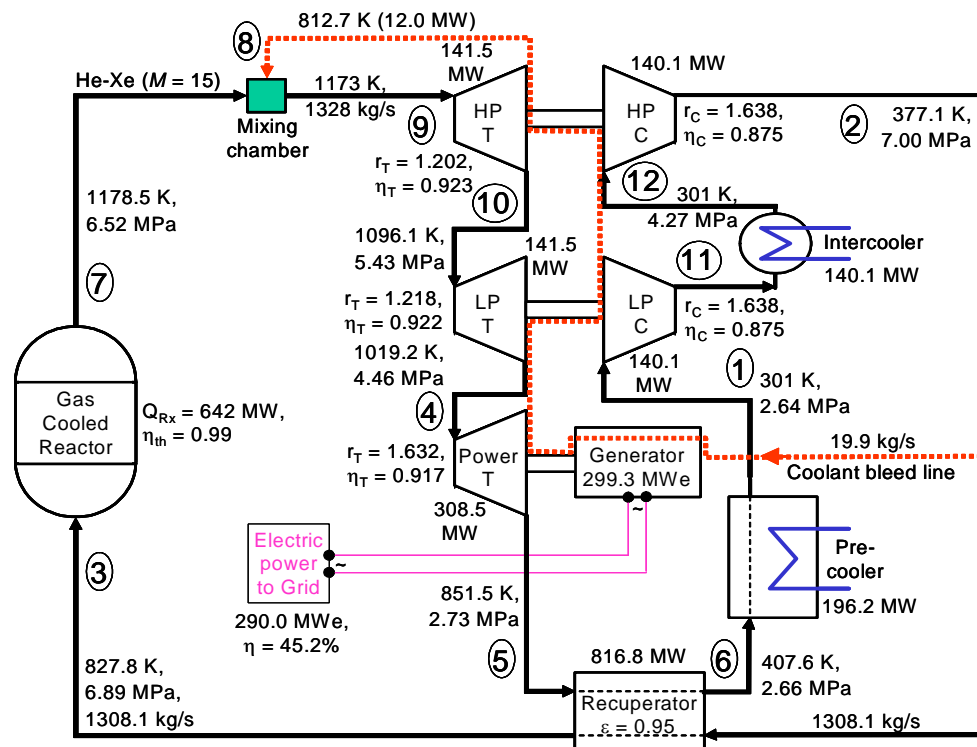


Fig. 6. Nuclear power plant with direct CBC, He-Xe working fluid, and multiple-shaft turbo-machines.

Similar results are obtained for the dependence of the performance parameters of the power plants with multiple-shafts turbo-machines and inter-cooler, on the type of the working fluid. For the same recuperator effectiveness of 0.95 and high pressure (HP) turbine inlet temperature of  $850^\circ\text{C}$  ( $1123$  K), the peak efficiency of the plant with helium working fluid is 45.5% and the corresponding cycle compression ratio is 2.32 (Fig. 8). This efficiency increases to 48.5% and the corresponding cycle compression ratio increases to 2.41 when the turbine inlet temperature increases to  $950^\circ\text{C}$  ( $1223$  K). With the He-Xe working fluid (15 g/mole), the plant's peak efficiency and the corresponding cycle compression ratio are 43.6% and 2.62 and 46.7% and 2.75, when the inlet temperature of the working fluid to the HP turbine is  $850^\circ\text{C}$  ( $1123$  K) and  $950^\circ\text{C}$  ( $1223$  K), respectively.

The calculated performance parameters of the nuclear power plants with either single-shaft or multiple-shafts turbo-machines and with either He or He-Xe working fluid are compared in Figs. 9a and 9b, as functions of the reactor exit temperature. Figure 9a shows that the net peak efficiencies of the plants with helium working fluid are a little more than 2 percentage points higher than those of the same plants with the He-Xe working fluid (15 g/mole).

However, the thermal power of the nuclear reactor could be 7% higher (642 MW) in the plants with the He-Xe working fluid, when operating at the same average fuel temperature in the reactor core. This is because the convective heat transfer coefficient of the binary mixture of He-Xe with a molecular weight of 15 g/mole is 7% higher than that of helium (Fig. 1). As a result, the plants using the He-Xe working fluid could deliver up to 2% more electrical power to the Grid than similar plants using helium working fluid (Fig. 9b).

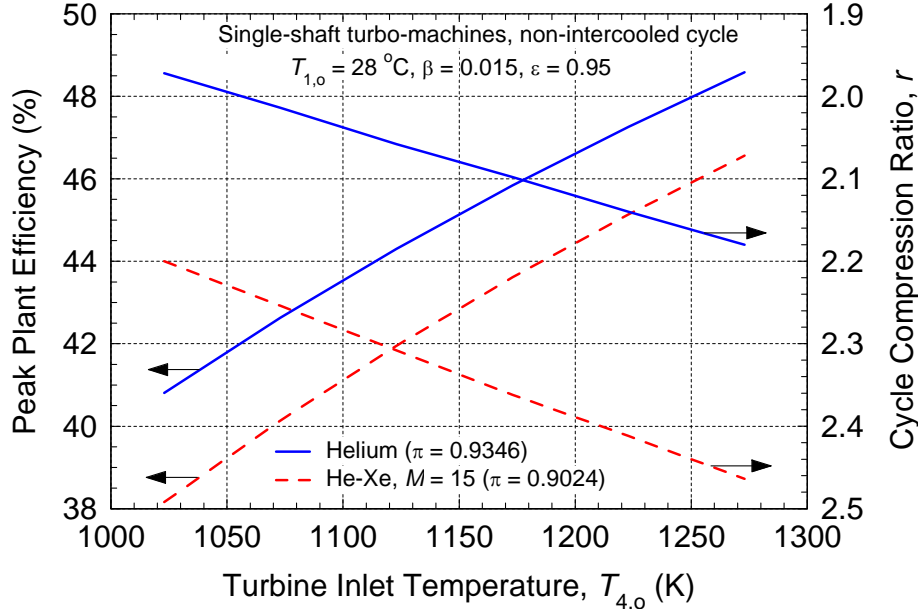


Fig. 7. Peak efficiency of nuclear power plants with CBC and single-shaft turbo-machine.

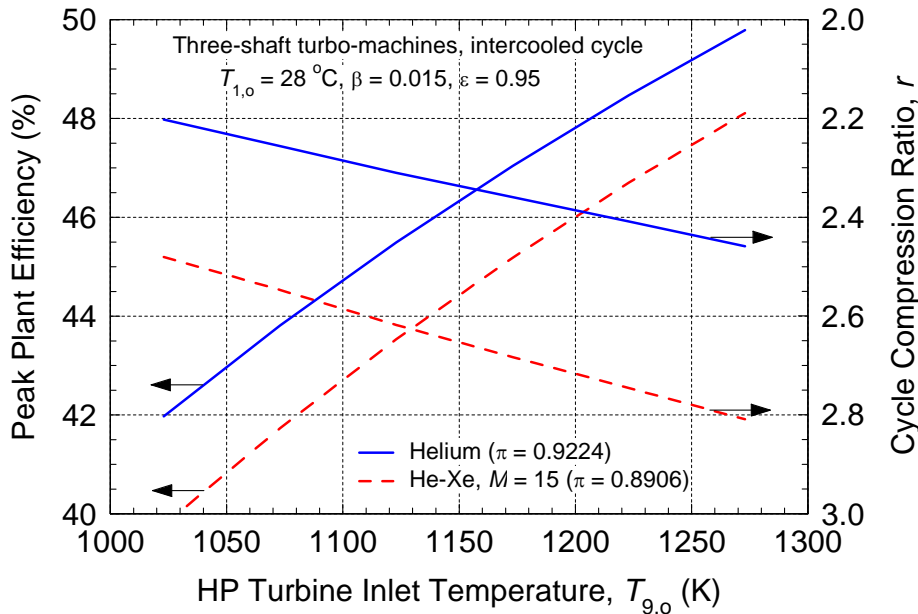


Fig. 8. Peak efficiency of nuclear power plants with CBC and multiple-shaft turbo-machines.

Figure 9a also shows that the peak efficiencies of the power plants with multiple-shafts turbo-machines and inter-cooler are generally 1 - 1.5 percentage points higher than, along with ~ 50 K lower compressor exit temperature, those with single-shaft turbo-machines and no inter-cooler. As a result, the gas temperatures at the exit of the power turbine ( $T_{5,o}$ ) and at the inlet of the nuclear reactor ( $T_{3,o}$ ) in the former are ~ 40 K lower, decreasing the coolant mass flow rate by ~ 10% for the same reactor's thermal power.

With He working fluid, the turbo-machines rotating at the grid frequency (or 3600 rpm) could have between 3 and 4 times the number of stages needed with the He-Xe working fluid (15 g/mole), even though the shaft work with

the latter is higher. For example, with helium, the single-shaft, turbine (538.8 MW) and compressor (243.8 MW) units have 6 and 24 axial stages, compared to only 2 and 8 stages for the turbine (588.3 MW) and compressor (287.6 MW) using the He-Xe working fluid (15 g/mole) (Figs. 3 and 5). In addition, the power turbine (300.1 MW) of the helium, multi-shafts turbo-machines has 4 stages, compared to only one for the He-Xe power turbine (308.5 MW) (Figs. 4 and 6). Since they have nearly the same radii, the volume and mass of the turbo-machine units increase essentially proportionally to the number of stages. Thus, with the He-Xe working fluid (15 g/mole), the turbo-machines and the shafts length will be significantly smaller than those designed to operate with helium.

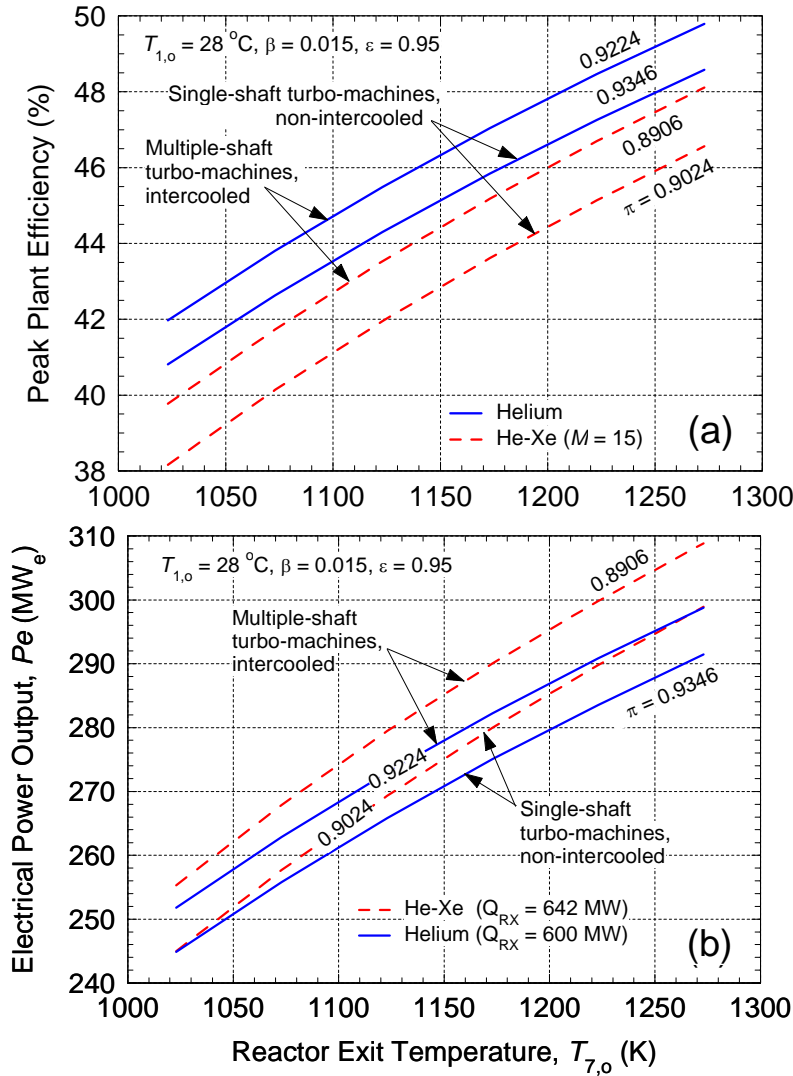


Fig. 9. Performance of nuclear power plants with CBC, and single- or multiple-shaft turbo-machines.

## 5. Summary and conclusions

This study identified the binary mixture of He-Xe with a molecular weight of 15 g/mole as a potentially attractive working fluid for nuclear reactor power plants with a CBC and axial flow, multi-stage turbo-machines. In addition to significantly reducing the number of stages of the turbo-machines, the heat transfer coefficient of this He-Xe binary mixture is  $\sim 7\%$  higher than that of helium. Also, the number of stages of the turbo-machines, (single-shaft turbine and compressor, and multiple-shafts power turbines), is 24% to 30% of those with He working fluid. However, for the same piping segments and heat exchange components design, the pressure losses in the CBC loop with the He-Xe working fluid are  $\sim 3$  times those with He. Consequently, for the same reactor exit temperature and pressure losses in the piping and heat exchange components of the CBC loop, the higher pressure losses in the

nuclear reactor decrease the net peak efficiency of the plant with the He-Xe working fluid (15 g/mole) by a little more than ~ 2 percentage points, and increase the cycle compression ratio, compared to those with He.

Thus, with the He-Xe working fluid (15 g/mole), the turbo-machines and the shafts length will be significantly smaller than those designed to operate with helium, but the plant peak efficiency will be ~ 2 percentage points lower. Results also show that the peak efficiencies of the power plants with multiple-shafts turbo-machines and an inter-cooler are generally 1 - 1.5 percentage points higher than those with single-shaft turbo-machines and no inter-cooler, along with operating at ~ 50 K lower compressor exit temperature.

### Acknowledgments

This work is funded by the University of New Mexico's Institute for Space and Nuclear Power Studies. The authors wish to thank Mr. Bruno Gallo, Ph.D. student, for his assistance in compiling the thermal and physical properties of the noble gases used in this article.

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