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Study of reverse Brayton cryocooler with Helium-Neon mixture for HTS cable

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Abstract. As observed in the earlier studies, helium is more efficient than neon as a refrigerant in a reverse Brayton cryocooler (RBC) from the thermodynamic point of view. However, the lower molecular weight of helium leads to higher refrigerant inventory as compared to neon. Thus, helium is suitable to realize the high thermodynamic efficiency of RBC whereas neon is appropriate for the compactness of the RBC. A binary mixture of helium and neon can be used to achieve high thermodynamic efficiency in the compact reverse Brayton cycle (RBC) based cryocooler. In this paper, an attempt has been made to analyze the thermodynamic performance of the RBC with a binary mixture of helium and neon as the working fluid to provide 1 kW cooling load for high temperature superconductor (HTS) power cables working with a temperature range of 50 K to 70 K. The basic RBC is simulated using Aspen HYSYS V8.6®, a commercial process simulator. Sizing of each component based on the optimized process parameters for each refrigerant is performed based on a computer code developed using Engineering Equation Solver (EES-V9.1). The recommendation is provided for the optimum mixture composition of the refrigerant based on the trade-off factors like thermodynamic efficiency such as the exergy efficiency and equipment considerations. The outcome of this study may be useful for recommending a suitable refrigerant for the RBC operating at a temperature level of 50 K to 70 K.

Nomenclature

D_{hub}	Turbine wheel diameter	mm	N	Compressor speed	rpm
D_{tip}	Turbine wheel diameter	mm	P	Pressure	kPa
D_r	Compressor rotor diameter	mm	Q	Heat leak or loss	kW
D_{wheel}	Turbine wheel diameter	mm	R	Gas constant	J/mol.K
h	Enthalpy	kJ/kg	s	Entropy	kJ/kg.K
ΔE_d	Exergy destruction	kW	T	Temperature	K
ex	Exergy	kJ/kg	V_c	Calculated volume flow	m^3/hr
m	Mass flow rate	kg/s	V_L	Volume flow limit	m^3/hr
η_{ex}	Exergy efficiency		V_1	Required volume flow	m^3/hr
η_v	Volumetric efficiency		W	Work	kW
y	Mole fraction		Z	Compressibility Factor	
$\dot{Q}$	Heat transfer rate	kW	U	Overall heat transfer coefficient	W/m^2K
A	Heat transfer area	m^2	k	Characteristic constant	

Subscripts

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in	Inlet	out	Outlet
o	Reference (ambient)	comp	Compressor
c	Critical point	m	Mixture
hin	Hot inlet	hout	Hot outlet
cin	Cold inlet	cout	Cold outlet

1. Introduction

There is a need for large capacity cryocoolers for High Temperature superconductor (HTS) power cables. Reverse Brayton based cryocoolers (RBC) are adequate for such large capacity cooling systems [1]. Prototype and large scale RBCs are under development for the HTS power cables with a cooling capacity of 2 kW to 50 kW [2]–[4]. Major applications of RBC are HTS cooling system, Liquefied Natural Gas (LNG) liquefaction and reliquefaction, space applications, and hydrogen liquefaction systems. The working fluid for the reverse Brayton cryocoolers is dependent on the type of application. For HTS power applications, where cooling is required at 60-80 K, neon or helium is used as working fluid.

The RBC can achieve a significant increase in thermodynamic efficiency using pure helium as working fluid as compared to pure neon [5]. It is reported in the literature that helium-neon mixture can be compressed more easily in the turbo-compressor than the pure fluids for the large scale hydrogen liquefier [6]. For the cryocoolers, using helium as the working fluid, there are more stringent constraints for fabrication of components like turbines, turbo-compressors etc. A mixture of helium and neon have the ability to achieve better efficiency than pure neon. Also, the design of components of an RBC for mixtures will be simple compared to pure helium. Therefore, a study of RBC with a mixture of helium-neon is carried out in the present work.

2. Objectives

The reverse Brayton based cryocooler as shown in figure 1 is studied. Pure helium, neon and a helium-neon mixture is used as the working fluid in the present study. Exergy analysis of the cycle is carried out by analyzing the exergy destruction to understand the effects of different working fluids on the performance of the RBC's components. Preliminary design and selection of all components of the RBC are done to understand the effect of working fluid on the size of components.

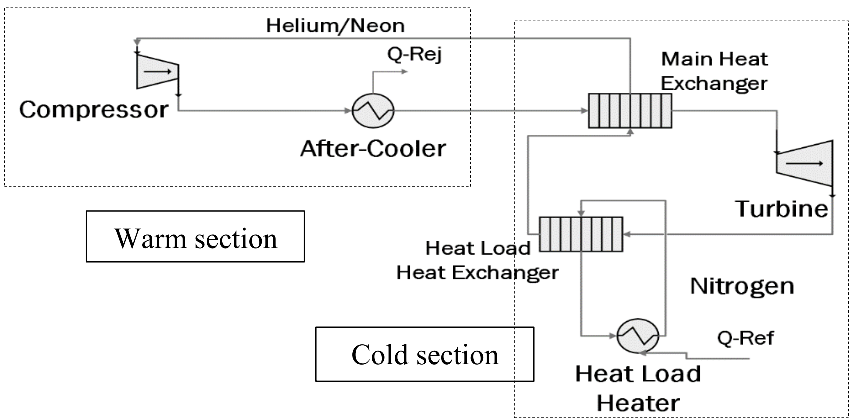

Figure 1. Reverse Brayton Cryocooler for HTS power cables.

3. Methodology

The basic RBC with 1 kW cooling capacity at 65 K has been simulated and investigated using Aspen HYSYS V8.6®. The RBC cycle was optimized for pure helium and neon in the previous work. The inlet pressure and pressure ratio are chosen for which exergy efficiency of the RBC is optimum both pure helium and neon as working fluids[5].

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3.1. Assumptions and the parameters
The assumptions and optimum parameters for the simulation are as follows:

- The polytropic efficiency of the compressor is 60 %.
- The optimized inlet pressure is 1000 kPa.
- The optimized pressure ratio for both helium and neon is 1.9.
- The adiabatic efficiency of the turbine is 70 %.
- Maximum pressure drop in after-cooler is 20 kPa.
- Maximum allowable pressure drop in the both heat exchangers is 5 kPa.
- The minimum approach in the main heat exchanger is 3 K. Where minimum approach is defined as the smaller of ($T_{hin} - T_{cout}$) and ($T_{hout} - T_{cin}$) for counterflow heat exchanger.
- The minimum approach in the heat load heat exchanger is 1.5 K.
- The temperature at the aftercooler outlet is 300 K.
- Subcooled liquid nitrogen is used for cooling the HTS cable.

3.2. Performance analysis
The exergy destruction (ΔE_d) in components are calculated using equation (1) and analyzed.

$$\Delta E_d = \sum m_{in} ex_{in} - \sum m_{out} ex_{out} + \sum_i Q_i \left(1 - \frac{T_o}{T_i}\right) - \sum_j W_j \tag{1}$$

In the above expression, ex refers to the exergy of the fluid [ex = (h-h$_o$)-T$_o$(s-s$_o$)], T_o is ambient temperature and m is mass flow rate of the stream enter and exit in component. The third and fourth terms in the above expression are the net power obtain from the heat transfer from ambient and net power supplied to the component, respectively [13].

The exergetic efficiency of the system is calculated using only compressor input work (w_{comp}) as shown in equation (2).

$$\eta_{ex} = 1 - \frac{\sum \Delta E_d}{W_{comp}} \tag{2}$$

3.3. Fluid properties
In the present study, pure helium and neon, and their mixtures are studied. The deviation of thermodynamic properties of pure helium and neon is less than 5 % using the Ping-Robinson equation of state (PR EOS) for the temperatures above 55 K. The PR EOS is acceptable for both fluids and also for the mixture. The mixture properties of real gases includes compressibility factor (Z) are calculated as follows [7]:

$$Z^3 - (1-B)Z^2 + (A - 2B - 3B^2)Z - (AB - B^2 - B^3) = 0 \tag{3}$$

Where:
$$A = \frac{aP}{(RT)^2} \qquad a = 0.457232\frac{(RT_c)^2}{P_c}\alpha$$
$$B = \frac{bP}{RT} \qquad b = 0.077796\frac{RT_c}{P_c}$$
$$\alpha^{0.5} = 1 + k(1 - T_r^{0.5}) \qquad T_r = \frac{T}{T_c}$$

$$(P_c)_m = \sum_i y_i P_{ci} \tag{4}$$
$$(T_c)_m = \sum_i y_i T_{ci} \tag{5}$$

Where $(P_c)_m$ and $(T_c)_m$ are critical pressure and temperature of mixture, respectively. y_i, P_{ci}, and T_{ci} are the mole fraction, critical pressure and temperature of ith component of the mixture.

4. Selection of components

4.1. Design assumptions of heat exchanger

For counter-flow applications, the heat transfer rate is defined as the product of overall conductance (UA) and the log-mean temperature difference (LMTD) as given in equation (6) and (7),

$$LMTD = \frac{\Delta T_{out} - \Delta T_{in}}{\log \frac{\Delta T_{out}}{\Delta T_{in}}} \tag{6}$$

Where, ΔT_{out} = Temperature difference between hot and cold fluid outlet temperature
ΔT_{in} = Temperature difference between hot and cold fluid inlet temperature

$$\dot{Q} = UA \times LMTD \tag{7}$$

Where, U = Overall heat transfer coefficient, W/m^{2}K
A = Heat transfer area, m^2

The overall heat transfer coefficient is a function of fluid properties and geometry etc. UA is referred to as the overall conductance or thermal size of heat exchanger [14].

The main heat exchanger is designed in this work to estimate its size using Aspen Exchanger Design and Rating V8.6®. The following assumptions are considered for the design:

- The plate fin heat exchanger is selected for the design.
- Serrated type of fins with fin efficiency of 0.98 (best performance among all types of fins) are selected [8].

4.2. Turbine design assumptions

For the cryogenic applications, the inward flow radial turbo-expanders are recommended to achieve very low temperatures with high speed [9]. Thus, a radial inward-flow turbine is selected for the design. The specific speed and specific diameter of the turbine at maximum efficiency of 90 % are 0.5 and 3.9 respectively, from the Balje's curve for a radial inflow turbine [10].

4.3. Compressor selection criteria

The selection criteria of the compressor are the inlet volumetric flow rate and the pressure ratio. In the present study, the volumetric flow rate (V_1) is between 500-600 m^3/hr, and the pressure ratio is 1.9. For volumetric flow less than 1000 m^3/hr, screw compressors and reciprocating compressors are available. Screw compressors have higher efficiency than reciprocating compressors. Thus, an oil free screw (OFS) compressor is selected for the RBC [11]. The calculated volumetric flow rate (V_c) for selection of compressor size is calculated using volumetric efficiency (η_v) as given in equation (8).

$$V_c = V_1/\eta_v \tag{8}$$

5. Results and discussion

5.1. Exergy analysis

It is observed in the previous study that helium can achieve higher efficiency than neon [5]. A similar trend is also observed in the present study. The specific heat capacity of helium is greater than that of neon. Thus, the required mass flow rate in the RBC decreases with an increase in the helium percentage in the mixture for 1 kW refrigeration, which results in a reduction of power consumption by the compressor. Hence, the exergy efficiency of the cycle is increased when increasing the helium concentration in the helium-neon mixture as shown in figure 2.

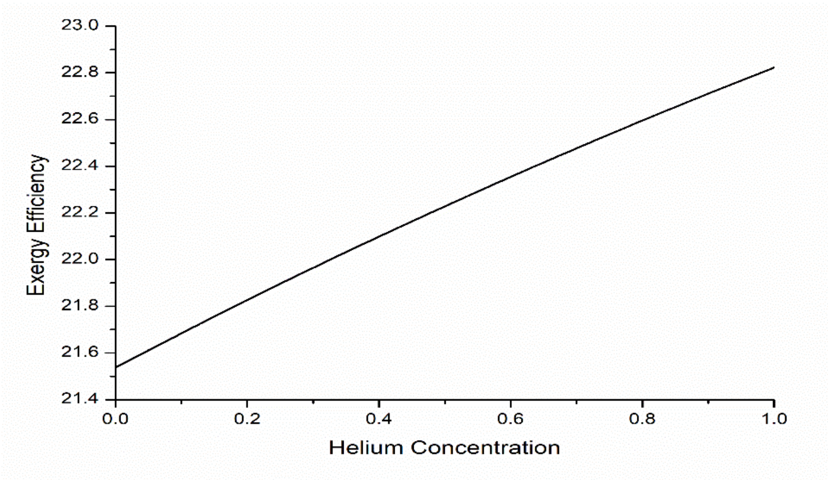

Figure 2. Exergy efficiency of RBC on variation of helium concentration in helium-neon mixture

It is also observed that the rate of increase in the exergy efficiency is decreased with increase in the helium Concentration. Helium-neon mixture with 60 % helium by mole has 3.8 % better exergy efficiency than pure neon and 2.1 % less than pure helium.

The exergy destruction in the components of the warm section and cold section of the RBC are shown in figure 3 and 4, respectively. As the mass flow rate requirement in the cycle is reduced on increasing helium concentration, it is observed that the exergy destruction in the compressor and after-cooler is reduced about 6.7 % in both cases on increasing helium concentration. In the cold section, there is significant 28.5 % decrease in the exergy destruction in main heat exchangers and 11 % increase in exergy destruction in the heat load heat exchanger. In contrast, there is a negligible decrease in the exergy destruction in the turbine. The heat transfer coefficient of helium is higher than that of neon which results in better heat transfer. Hence, there is a decrease in the exergy destruction. It is also observed that the rate of decrease in the exergy destruction in the main heat exchanger is decreased with increase in the helium concentration. However, in the case of the heat load heat exchanger, the enthalpy difference between inlet and outlet of cold stream increases because of the lower temperature produced at the turbine outlet on increasing helium concentration in the mixture. As a result, there is an increase in the exergy destruction in the heat load heat exchanger.

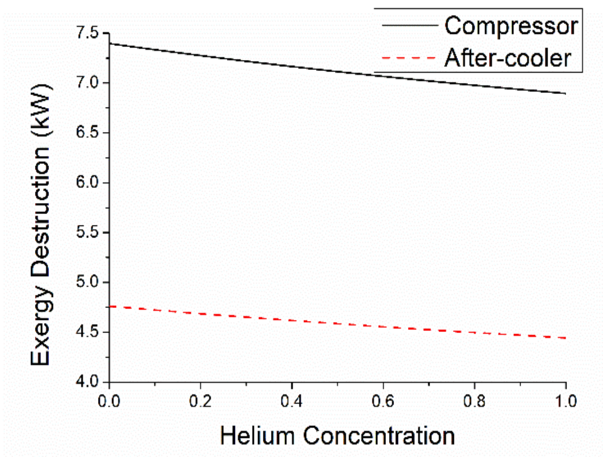

Figure 3. Exergy destruction in the warm section of the RBC

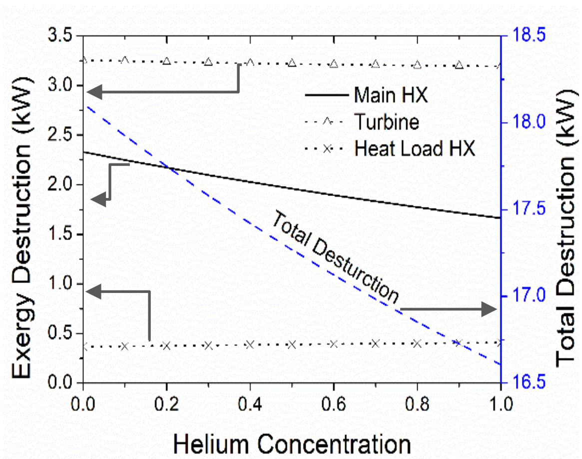

Figure 4. Exergy destruction in the cold section of the RBC

5.2. Heat exchanger design

The UA of the main heat exchanger exponentially increases on increasing the helium concentration in the mixture, and volume and weight of the heat exchanger exponentially decrease as shown in figure 5. As helium has higher specific heat and LMTD is increased on increasing the helium concentration in mixture, the UA is increased. There is 53.7 % decrease in the volume and 40 % decrease in the weight of the heat exchanger on increasing the concentration of helium by 60 % in the mixture. However, on further increase in the concentration to 100% helium, there is a total decrease of 69 % in the volume and 52 % in the weight of the main heat exchanger. Similarly, the UA of the heat exchanger is increased by 2.1 % by increasing the concentration to 60 % helium. However, on the further increase to 1, there is 5.1% decrease in the UA of the main heat exchanger. As we have observed that the exergy destruction using 60 % Helium mixture is reduced by 18.5 %, on further increasing the helium concentration from 60 % to 100 %, decrease in the exergy destruction is 10 %, but the volume and the weight are decreased by 15.5 and 12 % respectively.

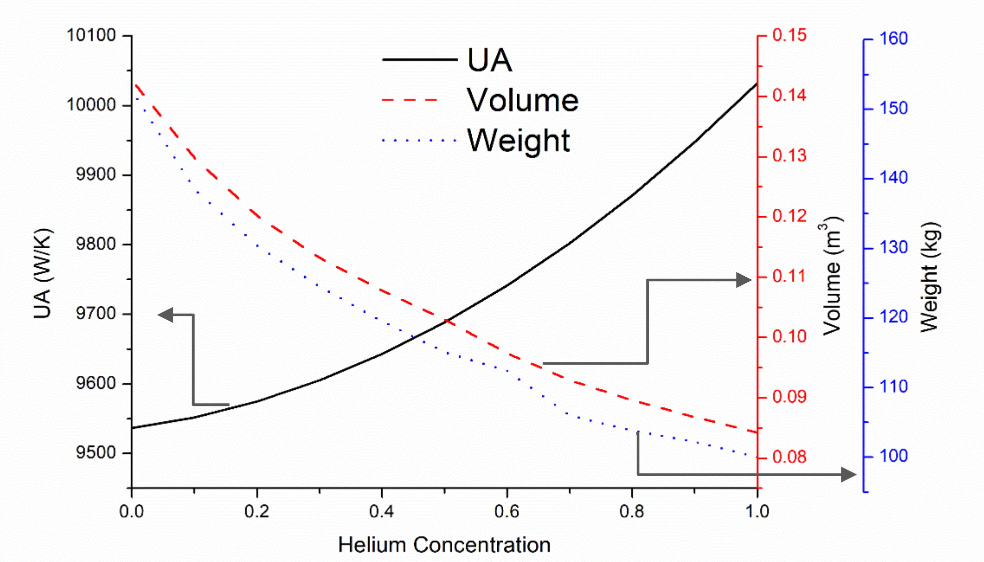

Figure 5. Effect of variation of helium concentration on UA, volume, and weight of the main heat exchanger

5.3. Turbine design

The effect of variation of helium concentration in the mixture on the turbine wheel diameter and rotational speed are shown in figure 6. It is observed that the diameter of the turbine decreases and speed of the turbine increases on increasing the helium concentration in the mixture. A mixture of 60 % helium has 3.4 mm smaller and 3.6 mm larger diameter than neon and helium, respectively. However, the rotation speed is 68 % more and 181 % less than the neon and helium, respectively. There is an exponential increment in the speed of the turbine after 60 % increase in the helium concentration. The rpm.

Table 1. Design parameter of the radial expander for RBC

Parameter	Recommended Range[12]	Calculated value
D_{hub}/D_{tip}	< 0.4	0.35
D_{tip}/D_{wheel}	< 0.7	0.667
Velocity ratio	0.55 – 0.8	0.699
Flow coefficient at exit	0.15 – 0.5	0.303

The calculated design parameters are in the recommended range for the radial inflow turbine as given in table 1. The design results of the turbine for different fluids are given in table 2. It is observed that the power produced by the turbine is 1.7 % higher for the helium-neon mixture with 60 % Helium than it is for pure helium.

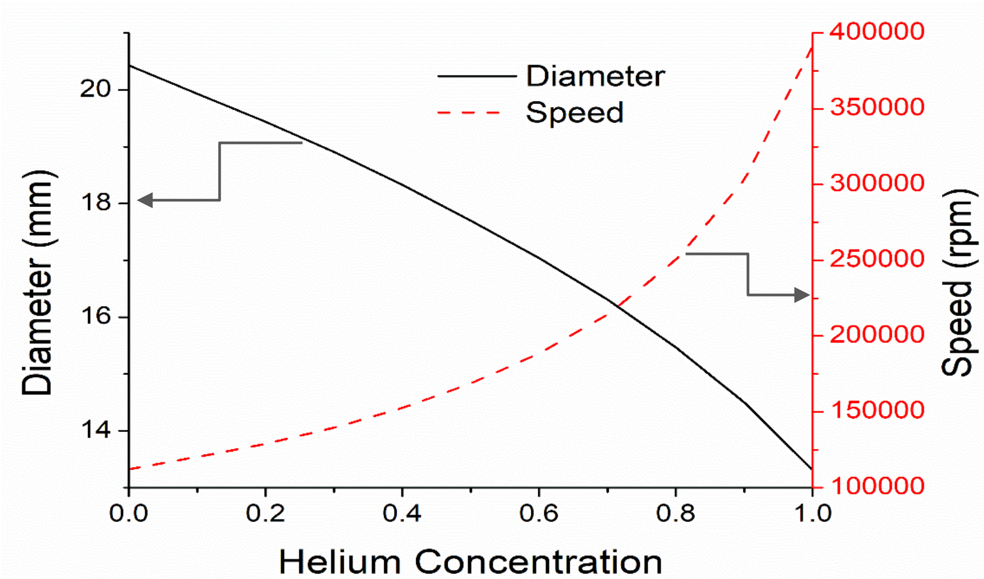

Figure 6. Effect of variation of helium concentration on turbine speed and diameter

Table 2. Design results of RBC expander for different Helium concentration in mixture

Helium Concentration	D_{hub} (mm)	D_{tip} (mm)	Tip velocity (m/s)	Power output (kW)
0.0	4.76	13.62	120	1.448
0.1	4.65	13.28	125.6	1.447
0.2	4.54	12.96	131.6	1.433
0.3	4.41	12.61	138.2	1.425
0.4	4.28	12.22	146.4	1.421
0.5	4.13	11.80	156.5	1.421
0.6	3.98	11.36	168.2	1.414
0.7	3.81	10.88	183	1.406
0.8	3.61	10.32	202.8	1.404
0.9	3.38	9.67	230.2	1.396
1.0	3.10	8.87	272.8	1.390

5.4. Compressor performance

The volumetric flow requirement for the pure neon, helium, and mixture is less than 580 Nm^3/hr. Where, Nm^3/hr stands for volumetric flow rate at normal temperature pressure condition (NTP), which is 273.15 K and 1 atm. The volumetric efficiency is taken as 0.91 for helium and 0.97 for the neon because of their molecular sizes. Thus, an oil free screw compressor with a rotor diameter of 102 mm designed for a tip velocity of 100 m/s and maximum volumetric flow rate (V_L) of 950 Nm^3/hr is available and selected based on the calculated volumetric flow in the cycle for different fluids. However, volumetric flow (V_1) in the RBC cycle for all the fluids does not coincide with the framesize volume limit. Thus, the compressor needs to operate at different rotor speed (N), which is calculated using equation (9) [11].

$$N = \left(\frac{V_1}{V_L}\right) \times \frac{1910}{D_r} \tag{9}$$

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It is observed that the required operating speed of the compressor is 6.4 % more for a pure neon compared to pure helium as shown in figure 7. The tip velocity is reduced to 55.4 % for helium and 59.2% for neon to the maximum designed tip speed. The required operating speed and the input power requirement for the helium-neon mixture with 60 % helium are 4.2 % and 4.5 %, respectively, less than pure neon.

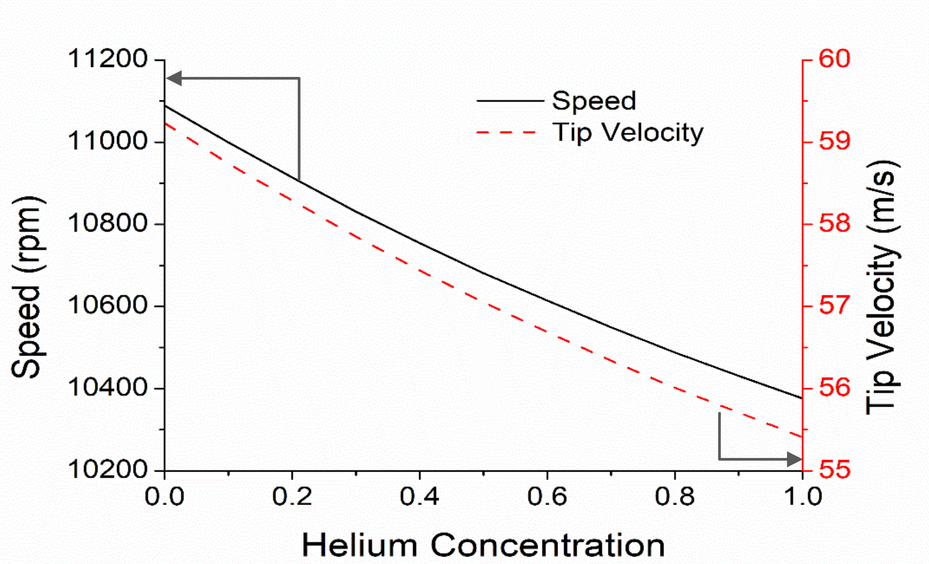

Figure 7. Rotor speed for different helium concentration in mixture

6. Conclusions

The analysis of the RBC for HTS cables with 1 kW cooling load at 65 K is carried out using the Aspen HYSYS V8.6 process simulator. A study on the effect of different working fluids on process and design of components of the RBC cycle is carried out, and the major conclusions are as follows:

- The rate of increase in the exergy efficiency decreases with increasing the helium concentration in the mixture. Thus, helium-neon mixture with 0.6-0.7 mole fraction of helium has exergy efficiency 3.8 – 4.4 % better than pure neon and about 1.5 – 2.1 % less than pure helium.
- A significant change in the exergy destruction is observed in both heat exchangers of the cold section of the RBC. There is a reduction of exergy destruction in the main heat exchanger and increase of exergy destruction in the heat load heat exchanger with an increase in the helium concentration. There is a reduction of 6.7 % exergy destruction in the warm section.
- There is an exponential increase of UA and reduction of volume and weight of the main heat exchanger with increasing the helium concentration in the mixture. There is a small increment in UA and a substantial decrease in volume and weight with increasing mole fraction of helium above 0.6.
- The turbine with pure neon as working fluid has lower speed and larger diameter as compared to the helium turbine. A mixture with 0.6 – 0.7 mole fraction of helium has 27 % larger diameter and 181 % lower speed compared to pure helium. The diameter becomes smaller, the clearance between wheel and the casing becomes proportionality smaller, leading to manufacturing constraints. Also, higher speed involves a precise balancing of the rotor. Thus, manufacturing of turbines for helium is a complex fabrication process and requires highly precise machining tools.
- An oil free screw compressor with 102 mm rotor diameter having a volume flow limit of 950Nm^3/hr is selected for all fluids. There is a need to run the compressor with different speed for different fluids to achieve the required volume flow rates.

Hence, the RBC using helium-neon mixture with 0.6-0.7 mole fraction of helium as working fluid performs thermodynamically better than pure neon. The turbine for this mixture has low speed and large diameter, so its fabrication will be simple.

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