International Journal of Modern Science and Technology
http://www.ijmst.co/
Vol. 2, No. 1, 2017. Page 27-30.
ISSN: 2456-0235.

Research Article

Thermodynamic analysis of stirling cooler applied to emission capture process

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Abstract

Environment pollution by thermal power plants severely affects the global warming. It is necessary to avoid harmful gases getting into the atmospheric air. In order to achieve this several techniques are followed by the industries. All the technical solutions like post combustion gas capturing technique, capturing prior to combustion, absorption of gas, Membrane separation using chemicals and adsorption resulted with some difficulties and needs to be developed. This evolved the aspect of cryogenic distillation a recent trend of research towards the capturing of the harmful gases. Technically speaking the process of cryogenic distillation needs a cryocooler. Thus a Stirling cryocooler is to be analyzed by considering that it is in the application of cryogenic distillation [1]. Thermodynamic parameters for the all four processes namely Compressing process Iso-thermally, Constant volume Heat-addition, Expansion process Iso-thermally, Constant volume Heat removal, Total heat input, Total heat rejection and Network are calculated by considering nominal values of volume ratio and Specific heat. The methodology is applied for cooling of CO_2 and N_2 by the various working fluids like Helium and LNG. The present work is related to thermodynamic analysis of Stirling engine by considering that the cryocooler runs based on Stirling cycle and is working for solidification of emissions from Thermal power plants.

Keywords: Green House gases; CO_2 capturing process; Stirling cooler; Thermodynamic analysis.

Introduction

Need of the work

Presently existing power plants that generates power by burning fossil fuels are liberating excess amounts of harmful gases like carbon dioxide into atmospheric air. These harmful gases are said to be the main cause for change in climatic conditions by influencing the global warming. In future the power plants may increase in number and affect the environment severely. There are only two possible ways either to stop the usage of fossil fuels [2] or to develop a technical solution that can control the harmful gas emission into environment. The way that avoids usage of fossil fuel is not possible practically because the needs and requirement of power is so high. This shows the clear way to opt for controlling of harmful gases entering into the environment.

In India coal is being the primary fuel for generation of electricity and the use of coal is increasing rapidly in recent days to satisfy the electricity demand of country [3]. The power plants will use various coal quality and different combustion technologies. These variations in coal quality and applied techniques in combustion, the plant efficiencies get varied. This intern affects the emission of harmful gases that pollutes the environment. Capturing and storage of these gases is the recent technology [4] that reduces the emissions from coal fired power plants.

The flue gas capturing technology uses cryogenic distillation of gases, offers a new technical approach to control the CO2 emission from power plant. This introduces the application of Stirling cooler [5] on CO2 separation. The technology includes the lowering of temperature conditions below the frosting temperature of CO_2 with the help of Stirling cooler and non-harmful gases exhausts from chimney.

Stirling cycle

It is a thermodynamic cycle which is reversible; it works based on second law of thermodynamics and works as a heat pump with supply of mechanical power. The cycle is closed-cycle and operates with gaseous working

Received: 20.01.2017; Received after Revision: 27.01.2017; Accepted: 28.01.2017; Published: 29.01.2017

fluid. Since it is closed cycle the working fluid circulates within the thermodynamic system continuously. There are several classifications in Stirling engines that works based on Stirling cycle.

The Stirling cycle consists of four main processes namely,

1. Isothermal Compression Process
2. Constant-Volume heat-addition Process
3. Isothermal Expansion Process
4. Constant-Volume heat-removal Process

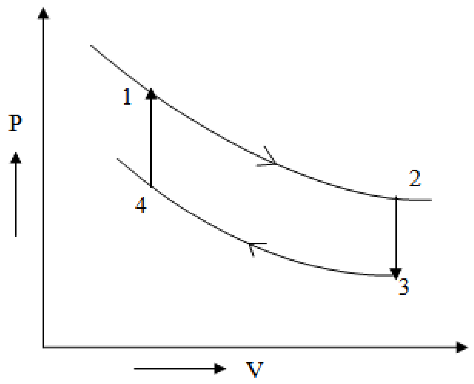

Fig. 1. P – V Diagram

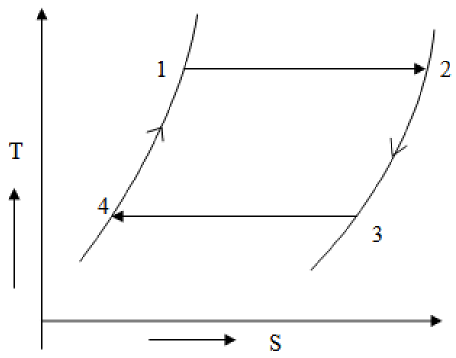

Fig. 2. T – S Diagram

Materials and methods

Stirling cycle analysis

Basic Thermodynamic Analysis [6]

Considering 1 kg of ideal gas and R is characteristic gas constant in KJ/kg K

Isothermal compression process:

In the compression process, the cold-side working fluid is compressed from V_3 to V_4.Then the heat rejected and work given during the isothermal compression process 3-4 is

$Q_{3-4} = W_{3-4} = - RT_2 \ln V_3/V_4$

Isochoric heating process:

The heat added and work done during the isochoric heating process 4-1 is

$Q_{4-1} = C_V (T_1 – T_4)$ and $W_{4-1} = 0$

Where C_V is the specific heat at constant volume in J/kg K, and is assumed to be constant. Here we can observe that heat input to this process depends on the regenerator effectiveness only.

Isothermal expansion process:

In the expansion process, the hot-side working fluid volume changes from V_1 to V_2. The heat added and work done during the isothermal expansion process 1-2 is

$Q_{1-2} = W_{1-2} = RT_1 \ln V_2/V_1$

It is evidenced that the expansion work is dependent on the dead volumes.

Isochoric cooling process:

The heat rejected and work done during the isochoric cooling process 2-3 is

$Q_{2-3} = — C_V (T_3 — T_2)$ and $W_{2-3}= 0$

Helium [9] *used for Cooling of CO_2 gas:*

Since the flue gas temperature is 393.15K for black coal and freezing point of CO_2 is 194.7K

The Temperature limits [7,8] are 393.15K and 194.7K

The Ratio of Volumes considered is = 11.25

The C_V value of working fluid Helium is = 3.12KJ/kg K

The gas constant R = 8.314 J/mole K

Consider for unit mass and ideal regenerator

During the Isothermal Compression process (3-4)

Work done is = W_c = - $RT_2 \ln V_3/V_4$

= -8.314 × 194.7 × ln (11.25)

= -3917.93 J

In Isochoric Heating process (4-1)

Heat added is = $Q_{in} = C_V (T_1 – T_4)$

= 3.12 × (393.15 – 194.7)

= 619.16 KJ/Kg

In Isothermal Expansion process (1-2)

Work done is = $W_E = RT_1 \ln V_2/V_1$

= 8.314 × 393.15 × ln (11.25)

= 7911.33 J

In Isochoric cooling process (2-3)

Heat rejected is = $Q_{out} = – C_V (T_3 –T_2)$

= - 3.12 × (194.7 – 393.15)

= 619.16 KJ/Kg

Helium used for Cooling of N_2 gas:

Since the flue gas temperature is 393.15K for black coal and freezing point of N_2 is 63K

The Temperature limits are 393.15K and 63K

The Ratio of Volumes considered is = 11.25

The C_V value of working fluid Helium is = 3.12 KJ/kg K

The gas constant R = 8.314 J/mole K

Consider for unit mass and ideal regenerator

During the Isothermal Compression process (3-4)
Work done is = W_c = - $RT_2 \ln V_3/V_4$
= -8.314 × 63 × ln (11.25)
= -1267.74 J
In Isochoric Heating process (4-1)
Heat added is = Q_{in} = $C_V (T_1 – T_4)$
= 3.12 × (393.15 – 63)
= 1030.06 KJ/Kg
In Isothermal Expansion process (1-2)
Work done is = W_E = $RT_1 \ln V_2/V_1$
= 8.314 × 393.15 × ln (11.25)
= 7911.33 J
In Isochoric cooling process (2-3)
Heat rejected is = Q_{out} = – $C_V (T_3 –T_2)$
= - 3.12 × (63 – 393.15)
= 1030.06 KJ/Kg

Natural gas used for Cooling of CO_2 gas [10]:
Since the flue gas temperature is 393.15K for black coal and freezing point of CO_2 is 194.7K
The Temperature limits are 393.15K and 194.7K
The Ratio of Volumes considered is = 11.25
The C_V value of working fluid Natural gas is = 1.85 KJ/kg K
The gas constant R = 8.314 J/mole K
Consider for unit mass and ideal regenerator
During the Isothermal Compression process (3-4)

Work done is = W_c = - $RT_2 \ln V_3/V_4$
= -8.314 × 194.7 × ln (11.25)
= -3917.93 J
In Isochoric Heating process (4-1)
Heat added is = Q_{in} = $C_V (T_1 – T_4)$
= 1.85 × (393.15 – 194.7)
= 367.13 KJ/Kg
In Isothermal Expansion process (1-2)
Work done is = W_E = $RT_1 \ln V_2/V_1$
= 8.314 × 393.15 × ln (11.25)
= 7911.33 J
In Isochoric cooling process (2-3)
Heat rejected is = Q_{out} = – $C_V (T_3 –T_2)$
= - 1.85 × (194.7 – 393.15)
= 367.13 KJ/Kg

Natural gas used for Cooling of N_2 gas:
Since the flue gas temperature is 393.15K for black coal and freezing point of N_2 is 63K
The Temperature limits are 393.15K and 63K
The Ratio of Volumes considered is = 11.25
The C_V value of working fluid natural gas is = 1.85 KJ/kg K
The gas constant R = 8.314 J/mole K
Consider for unit mass and ideal regenerator
During the Isothermal Compression process (3-4)
Work done is = W_c = - $RT_2 \ln V_3/V_4$
= -8.314 × 63 × ln (11.25)
= -1267.74 J
In Isochoric Heating process (4-1)
Heat added is = Q_{in} = $C_V (T_1 – T_4)$
= 1.85 × (393.15 – 63)
= 610.77 KJ/Kg
In Isothermal Expansion process (1-2)
Work done is = W_E = $RT_1 \ln V_2/V_1$
= 8.314 × 393.15 × ln (11.25)
= 7911.33 J
In Isochoric cooling process (2-3)
Heat rejected is = Q_{out} = – $C_V (T_3 –T_2)$
= - 1.85 × (63 – 393.15)
= 610.77 KJ/Kg

Result and discussions

Results with working fluid as Helium

For cooling of CO_2;
Work required to compress is W_C = 3917.93 J
Heat input Q_{in} = 619.16 KJ/Kg
Work done during Expansion is W_E = 7911.33 J
Ideal Heat rejection Q_{out} = 619.16 KJ/Kg
For cooling of N_2;
Work required to compress is W_C = 1267.74 J
Heat input Q_{in} = 1030.06 KJ/Kg
Work done during Expansion is W_E = 7911.33 J
Ideal Heat rejection Q_{out} = 1030.06 KJ/Kg

Results with working fluid as Natural gas (Methane):

For cooling of CO_2;
Work required to compress is W_C = 3917.93 J
Heat input Q_{in} = 367.13 KJ/Kg
Work done during Expansion is W_E = 7911.33 J
Ideal Heat rejection Q_{out} = 367.13 KJ/Kg
For cooling of N_2;
Work required to compress is W_C = 1267.74 J
Heat input Q_{in} = 610.77 KJ/Kg
Work done during Expansion is W_E = 7911.33 J
Ideal Heat rejection Q_{out} = 610.77 KJ/Kg

Discussions

It has been observed that the compressor work value is independent of Working fluid and is completely dependent on properties of the fluid to be cooled. The expander work is same in all cases as it is only dependent of maximum temperature and ratio of volumes. The change of working fluid does not shown any impact on expander work thermodynamically.

For an Ideal operation of stirling cryocooler the heat supplied will be equal to heat rejected. The observation is clearly showing that the Heat supply required by both working fluids for CO_2 cooling is lesser that that of N_2. Simultaneously the heat supply values with Natural gas as working fluid are lesser compared to working fluid Helium for cooling of both CO_2 and N_2. The comparison of heat supply and heat rejection among working fluids Helium and Natural gas, the observations are better for Natural gas as working fluid for cooling of both CO_2 and N_2.

Conclusions

The thermodynamic analysis of Stirling cryocooler for capturing of emission gases was performed and the theoretical calculations were made. The analysis was done by considering the various working fluids namely Helium and Natural gas. All the necessary values were taken in to consideration and correct values of properties were used. The four processes of Stirling cycle were studied thermodynamically. The values of compressor work required, expander work done, heat supply needed and ideal heat rejection values are calculated and noted. The observations resulted in support of Natural gas preferably for cooling of Carbon dioxide and Nitrogen.

Conflict of interest

Authors declare there are no conflicts of interest.

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