6.1 EXERGY ANALYSIS

Exergy or availability is a thermodynamic property that represents the maximum work that can be obtained from a fluid stream in a reversible process until it reaches the thermodynamic equilibrium with the surroundings. Exergy analysis can be used to evaluate the performance of thermodynamic system. Unlike energy, exergy is not conserved but it will be destroyed.

With the experimental data obtained from the tests, the exergy analysis is carried out to find exergy loss of the “three stage ARC system” in order to obtain a quantitative measurement of the system inefficiency. Under the assumption that the change of kinetic and potential energy is negligible and the ambient temperature is $T_0$, the exergy is given by the equation.

$$\psi = h - T_0 s$$

(6.1)

$$\psi = \left( h - h_0 \right) - T_0 \left( s - s_0 \right)$$

(6.2)

for the three stage ARC system the component wise the exergy balance equation can be written as follows
(a) for compressor:

Compressor work: \[ w_c = m \left( h_2 - h_1 \right) \] (6.3)

where

\[ m = m_{RI} + m_{RII} + m_{RIII} \]

The exergy at inlet: \[ \psi_1 = m \left( h_1 - T_0 s_1 \right) + w_c \] (6.4)

The exergy at outlet: \[ \psi_2 = m \left( h_2 - T_0 s_2 \right) \] (6.5)

The exergy loss (due to irreversibility) in the compressor

\[ l_{comp} = m \left( h_1 - T_0 s_1 \right) + w_c - m \left( h_2 - T_0 s_2 \right) \] (6.6)

(b) for air cooled condenser:

heat removed at air cooled condenser,

\[ Q_{ACC} = m \left( h_2 - h_3 \right) \] where \[ m = m_{RI} + m_{RII} + m_{RIII} \] (6.7)

The exergy at inlet: \[ \psi_2 = m \left( h_2 - T_0 s_2 \right) \] (6.8)

The exergy at outlet: \[ \psi_3 = m \left( h_3 - T_0 s_3 \right) \] (6.9)

The exergy loss (due to irreversibility) in the air cooled condenser

\[ l_{ACC} = m \left( h_2 - T_0 s_2 \right) - m \left( h_3 - T_0 s_3 \right) - Q_{ACC} \left( 1 - \frac{T_0}{T_{ACC}} \right) \] (6.10)
(c) for condenser-I (cascade condenser-I: hot fluid flow):

heat removed at condenser-I,

\[ Q_{\text{condenser-I}} = m_{RII} + RIII \left( h_4 - h_5 \right) \]  \hspace{1cm} (6.11)

The exergy at inlet :

\[ \psi_4 = m_{RII} + RIII \left( h_4 - T_0 s_4 \right) \]  \hspace{1cm} (6.12)

The exergy at outlet :

\[ \psi_5 = m_{RII} + RIII \left( h_5 - T_0 s_5 \right) \]  \hspace{1cm} (6.13)

The exergy loss (due to irreversibility) in the condenser-I

\[ I_{\text{condenser-I}} = m_{RII} + RIII \left( h_4 - T_0 s_4 \right) - m_{RII} + RIII \left( h_5 - T_0 s_5 \right) \]

\[ = Q_{\text{condenser-I}} - I \left[ 1 - \frac{T_0}{T_{\text{condenser-I}}} - I \right] \]  \hspace{1cm} (6.14)

(d) for condenser-II (cascade condenser-II: hot fluid flow):

heat removed at condenser-II,

\[ Q_{\text{condenser-II}} = m_{RIII} \left( h_6 - h_7 \right) \]  \hspace{1cm} (6.15)

The exergy at inlet :

\[ \psi_6 = m_{RIII} \left( h_6 - T_0 s_6 \right) \]  \hspace{1cm} (6.16)

The exergy at outlet :

\[ \psi_7 = m_{RIII} \left( h_7 - T_0 s_7 \right) \]  \hspace{1cm} (6.17)
The exergy loss (due to irreversibility) in the condenser-II

\[ I_{condenser} = II = m_{RIII} \left( h_{6} - T_{0} s_{6} \right) - m_{RIII} \left( h_{7} - T_{0} s_{7} \right) \]

\[- Q_{condenser} = II \left( 1 - \frac{T_{0}}{T_{condenser}} \right) \]

(6.18)

(e) for thermostatic expansion valve-I:

The exergy at inlet: \( \psi'_{8} = m_{RI} \left( h_{8} - T_{0} s_{8} \right) \) (6.19)

The exergy at outlet: \( \psi'_{9} = m_{RI} \left( h_{9} - T_{0} s_{9} \right) \) (6.20)

The exergy loss (due to irreversibility) in the thermostatic expansion valve-I

\[ I_{TEV} - I = m_{RI} \left( h_{8} - T_{0} s_{8} \right) - m_{RI} \left( h_{9} - T_{0} s_{9} \right) \] (6.21)

Since the enthalpy is constant during the expansion process, we know that \( h_{8} = h_{9} \), the above equation can be written as

\[ I_{TEV} - I = m_{RI} T_{0} \left( s_{9} - s_{8} \right) \] (6.22)

(f) for thermostatic expansion valve-II:

The exergy at inlet: \( \psi'_{11} = m_{RII} \left( h_{11} - T_{0} s_{11} \right) \) (6.23)

The exergy at outlet: \( \psi'_{12} = m_{RI} \left( h_{12} - T_{0} s_{12} \right) \) (6.24)
The exergy loss (due to irreversibility) in the thermostatic expansion valve-II

\[ I_{TEV} - II = m_{RII} \left( h_{11} - T_0 s_{11} \right) - m_{RII} \left( h_{12} - T_0 s_{12} \right) \]  \( \text{(6.25)} \)

Since the enthalpy is constant during the expansion process, we know that \( h_{11} = h_{12} \), the above equation can be written as

\[ I_{TEV} - II = m_{RII} T_0 \left( s_{12} - s_{11} \right) \]  \( \text{(6.26)} \)

(g) for thermostatic expansion valve-III:

The exergy at inlet : \( \psi_7 = m_{RIII} \left( h_7 - T_0 s_7 \right) \)  \( \text{(6.27)} \)

The exergy at outlet : \( \psi_{15} = m_{RIII} \left( h_{15} - T_0 s_{15} \right) \)  \( \text{(6.28)} \)

The exergy loss (due to irreversibility) in the thermostatic expansion valve-III

\[ I_{TEV} - III = m_{RIII} \left( h_7 - T_0 s_7 \right) - m_{RIII} \left( h_{15} - T_0 s_{15} \right) \]  \( \text{(6.29)} \)

Since the enthalpy is constant during the expansion process, we know that \( h_7 = h_{15} \), the above equation can be written as

\[ I_{TEV} - III = m_{RIII} T_0 \left( s_{15} - s_7 \right) \]  \( \text{(6.30)} \)
(h) for evaporator-III:

heat addition in evaporator-III,

\[
Q_{\text{evaporator}} - III = m_{RIII} \left( h_{14} - h_{15} \right)
\]  
(6.31)

The exergy at inlet :

\[
\psi_{15} = m_{RIII} \left( h_{15} - T_0 s_{15} \right) + Q_{\text{evaporator}} - III \left( 1 - \frac{T_0}{T_{\text{evaporator}} - III} \right)
\]  
(6.32)

The exergy at outlet :

\[
\psi_{14} = m_{RIII} \left( h_{14} - T_0 s_{14} \right)
\]  
(6.33)

The exergy loss (due to irreversibility) in the evaporator-III

\[
I_{\text{evaporator}} - III = m_{RIII} \left( h_{15} - T_0 s_{15} \right)
\]

\[
+ Q_{\text{evaporator}-III} \left( 1 - \frac{T_0}{T_{\text{evaporator}-III}} \right) - m_{RIII} \left( h_{14} - T_0 s_{14} \right)
\]  
(6.34)

(i) for evaporator-II (cascade condenser-II: cold fluid flow):

heat addition in evaporator-II,

\[
Q_{\text{evaporator}} - II = m_{RII} \left( h_{13} - h_{12} \right)
\]  
(6.35)

The exergy at inlet :

\[
\psi_{12} = m_{RII} \left( h_{12} - T_0 s_{12} \right) + Q_{\text{evaporator}} - II \left( 1 - \frac{T_0}{T_{\text{evaporator}} - II} \right)
\]  
(6.36)

The exergy at outlet :

\[
\psi_{13} = m_{RII} \left( h_{13} - T_0 s_{13} \right)
\]  
(6.37)
The exergy loss (due to irreversibility) in the evaporator-II

\[
I_{\text{evaporator II}} - II = m_{RII} \left( h_{12} - T_0 s_{12} \right)
\]

\[
+ Q_{\text{evaporator II}} \left( 1 - \frac{T_0}{T_{\text{evaporator II}}} \right) - m_{RII} \left( h_{13} - T_0 s_{13} \right)
\]

(6.38)

(j) for evaporator-I (cascade condenser-I: cold fluid flow):

heat addition in evaporator-I,

\[
Q_{\text{evaporator I}} - I = m_{RI} \left( h_{10} - h_9 \right)
\]

(6.39)

The exergy at inlet:

\[
\psi_9 = m_{RI} \left( h_9 - T_0 s_9 \right) + Q_{\text{evaporator I}} - I \left( 1 - \frac{T_0}{T_{\text{evaporator I}}} \right)
\]

(6.40)

The exergy at outlet:

\[
\psi_{10} = m_{RI} \left( h_{10} - T_0 s_{10} \right)
\]

(6.41)

The exergy loss (due to irreversibility) in the evaporator-I

\[
I_{\text{evaporator I}} - I = m_{RI} \left( h_9 - T_0 s_9 \right)
\]

\[
+ Q_{\text{evaporator I}} \left( 1 - \frac{T_0}{T_{\text{evaporator I}}} \right) - m_{RI} \left( h_{10} - T_0 s_{10} \right)
\]

(6.42)

The total exergy loss of the system is given by the correlation 6.43.

\[
I_{\text{Total}} = I_{\text{comp}} + I_{\text{ACC}} + I_{\text{condenser}} - I + I_{\text{condenser}} - II +
\]

\[
I_{\text{evaporator}} - I + I_{\text{evaporator}} - II + I_{\text{evaporator}} - III + I_{\text{TEV}} - I +
\]

\[
I_{\text{TEV}} - II + I_{\text{TEV}} - III
\]

(6.43)
The overall exergic efficiency of the system is defined as the ratio of exergy absorbed to the compressor work (or) the overall system exergetic efficiency ($\eta_x$) is the ratio of the exergy output ($\psi_{\text{output}}$) to exergy input ($\psi_{\text{input}} = w_c$). The exergy efficiency is given by

$$\eta_x = \frac{\psi_{\text{output}} - \psi_{\text{input}}}{w_c} = \frac{Q_{\text{evaporator-III}}}{w_c} \left( \frac{T_0}{T_{\text{evaporator-III}}} - 1 \right)$$  \hspace{1cm} (6.44)

For the three stage ARC system the component wise efficiency defect ($\delta_i$) is given by the ratio of exergy used in the corresponding component ($\psi_i$) to the exergy required to sustain the process (exergy through the compressor, $w_c$), or the ratio of exergy lost and compressor work. The values are calculated by means of the product of 'compressor work' and 'exergy lost' (Bukola O Bolaji, 2010) through the derived compressor work input and exergy lost.

$$\delta_i = \frac{\psi_i}{w_c}$$  \hspace{1cm} (6.45)

The overall performance of the three stage ARC system is determined by evaluating its COP and is calculated as the ratio between the refrigerating capacity ($Q_{\text{evaporator-III}}$) and the electrical power supplied to the compressor ($w_c$).

$$\text{COP} = \left( \frac{Q_{\text{evaporator-III}}}{w_c} - 1 \right)$$  \hspace{1cm} (6.46)