EXERGETIC ASSESSMENT OF A SIMPLE VAPOUR COMPRESSION REFRIGERATION SYSTEM

J. M. Joshi[1], R.B.Shah[2]
[1]Assistant Professor, Mechanical Engineering Department, VGEC-Chandkheda , Ahmedabad, Gujarat
[2]Assistant Professor, Mechanical Engineering Department, GEC- Modasa, Gujarat

Abstract:

This paper presents a comprehensive investigation of a Simple vapour compression refrigeration system using conventional and advanced exergy analysis. The conventional exergy analysis helps us identify various locations of exergy destruction in the system and splitting the exergy destruction into avoidable/unavoidable and endogenous/exogenous parts provides additional useful information and helps us improve the overall system's efficiency. The paper presents conventional as well as advance exergetic analysis of VCR system with the use of different working fluids, R717, R134a, and R1234yf.

1. LITERATURE REVIEW

The following literature review focuses on the exergy, conventional exergy analysis and advanced exergy analysis. A representative collection of works and their related findings are presented, with greater emphasis on papers from the past decade.

A basic definition of exergy also referred to as work potential and available work is the potential of a substance to do work. While in thermodynamic equilibrium with its surroundings, a substance has no potential to do work, and therefore its exergy is zero. Sciubba and Wall [1] defined exergy as the maximum theoretical useful work obtained if a system S is brought into thermodynamic equilibrium with the environment by means of processes in which S interacts only with this environment. Unlike an energy based analysis, an exergy analysis allows one to identify the location, magnitude, and origin of thermodynamic inefficiencies. This additional information is useful for improving the efficiency and cost-effectiveness of a system, and providing means of comparing multiple systems.
The idea of available work can be traced back almost two hundred years. According to Sciubba and Wall [1], Carnot (1824) first stated that the work that can be extracted from a heat engine is proportional to the temperature difference between the hot and the cold reservoir. However, Clapeyron (1832, 1834), Rankine (1851), Thomson (1852), and Clausius (1850, 1867) all contributed to the establishment of the principle.The earliest mention of the term available work was by Gibbs [2] in 1873. Gibbs modelled an arbitrary substance as a triangular surface. He said that the surface is made up of three points, the properties of the substance: volume, energy, and entropy. The surface is acted upon by the two other properties, temperature and pressure. When the substance is in thermodynamic equilibrium with its surroundings, the triangular surface is tangent to the plane; if it is not, then it is shifted, and its coordinates change. The movement is parallel to the respective axis of each property. The coordinates for which the surface is tangent to the plane, and the substance is in thermodynamic equilibrium with its surroundings, will be referred to as at the dead state. Exergy is basically a measure of the distance between the coordinates of the old and new vertices of the triangular surface. Therefore the work potential equals the sum of these three distances, with the sign of the entropy term being negative.

Kaushik et al [3] conducted an in-depth review of the energy and conventional exergy analysis as applied to coal and gas power plants, noting the method of splitting the exergy destruction into endogenous and exogenous components as a potential improvement.

In her dissertation, Kelly [4] presented a complete method and application of an advanced exergy analysis which splits the exergy destruction into its exogenous and endogenous parts, and its avoidable and unavoidable parts. Kelly et al [5] further described the method for splitting exergy destruction into exogenous and endogenous components, which illustrate the component irreversibilities, as well as the irreversibilities of a component due to the entire system design. These parameters were be split a second time to illustrate the avoidable and unavoidable irreversibilities. The unavoidable irreversibilities are due to technological limitations such as availability and cost of materials and components, however, this value is somewhat arbitrary as the limitations must be estimated. Nevertheless, the advanced exergy analysis provides deeper insight into system performance and component interactions. In [6], Morosuk and Tsatsaronis outlined the strengths and limitations of the advanced exergy analysis.

The vapour compression refrigeration systems face a number of difficult challenges over the coming decade, the most prominent being a possible ban of fluorocarbon refrigerants, increasing energy prices, and growing environmental concerns. A possible solution to enhance performance of a simple vapour compression refrigeration system is changing the refrigerant. Evaluating the performance of the system can however be a difficult task. Implementing exergy analysis is without a doubt a powerful tool for developing, evaluating and improving thermal systems. An exergy analysis helps us identify the location, magnitude and the cause of thermodynamic inefficiencies. It also enhances our understanding about the operations in energy conversion processes and thus helps engineers dealing with improvement of these systems and processes.

Exergy analysis is relevant in identifying and quantifying both the consumption of useful energy used to drive a process as well as the irreversibility or exergy destruction and the losses of exergy. The latter are true inefficiencies and therefore an exergy analysis can highlight the areas of improvement of a system. Exergy measures any material's true potential to cause a change. Throughout the years such analysis has been extensively discussed and applied to a wide variety of energy conversion systems.

All real processes are irreversible due to effects such as chemical reaction, heat transfer due to a finite temperature difference, mixing of different matter at different composition or states, unrestrained expansion and friction [7]. A conventional exergy analysis identifies the system components with the highest exergy destruction and the processes that cause them. Efficiencies within a system can hence be improved by reducing the exergy destruction in individual components.

However due to certain technical limitations part of the exergy destruction may be unavoidable, part maybe due to the exergy destruction occurring within the other components of the energy conversion system being considered, and hence it may be worthwhile to improve the other components and not just the component with the highest exergy destruction. A detailed exergy analysis in which the exergy destruction is split into the previously mentioned parts is hence called advanced exergy analysis. Such analysis facilitates the improvement of an energy conversion system from the viewpoint of thermodynamics, environment and economy.

2. EXERGY ANALYSIS: CONVENTIONAL AND ADVANCED

Splitting the exergy destruction into parts (e.g., avoidable and unavoidable, or endogenous and exogenous) improves the quality of the conclusions from an exergy analysis and an exergoeconomic evaluation [8]. An exergy analysis, in which the exergy destruction is split into these distinct parts, is called advanced exergy analysis, and is a much more detailed version of the conventional exergy analysis.The most important application of an advanced exergy analysis is the exergoeconomic evaluation conducted to improve the cost effectiveness of an energy conversion system. The value of the total exergy destruction in the kth component can be determined through an exergy balance for this component.

3.1 Conventional Exergy Analysis

A conventional exergetic analysis identifies the magnitude, location, and causes of thermodynamic inefficiencies [9]. It mainly helps identify the component with the highest exergy destruction by using thermodynamic analysis of each component in the energy conversion system. The exergy balance for the overall system is

$$\dot{E}_{F,tot} = \dot{E}_{P,tot} + \dot{E}_{D,tot} + \dot{E}_{L,tot} = \dot{E}_{P,tot} + \sum_n \dot{E}_{D,k}\, \dot{E}_{L,tot} \quad (1)$$

Where as for the k^{th} component, we write,

$$\dot{E}_{F,k} = \dot{E}_{P,k} + \dot{E}_{D,k} \quad (2)$$

The variables $E_{D,k}$ and $E_{L,tot}$ are absolute measures of the thermodynamic inefficiencies. In evaluating the performance of a system one needs, in addition to absolute measures, relative measures that indicate (a) the efficiency with which the fuel exergy is converted in exergy of the product and (b) the reduction in overall efficiency associated with each thermodynamic inefficiency. Relative measures include the exergetic efficiency,

$$\epsilon_{tot} = \frac{\dot{E}_{P,tot}}{\dot{E}_{F,tot}} = 1 - \sum_n y_k - \frac{\dot{E}_{L,tot}}{\dot{E}_{F,tot}} \quad (3)$$

Or

$$\epsilon_k = \frac{\dot{E}_{P,k}}{\dot{E}_{F,k}} = 1 - \frac{\dot{E}_{D,k}}{\dot{E}_{F,k}} \quad (4)$$

The exergy destruction ratio,

$$y_{D,k} = \frac{\dot{E}_{D,k}}{\dot{E}_{F,tot}} \quad (5)$$

And, for the overall system, the exergy loss ratio,

$$y_L = \frac{\dot{E}_{L,tot}}{\dot{E}_{F,tot}} \quad (6)$$

3.2. Advanced Exergy Analysis

The interactions among different components of the same system can be estimated and the quality of conclusions obtained from an exergetic evaluation can be improved, when the exergy destruction in each important component is split into endogenous/exogenous and avoidable/unavoidable components. We call such an analysis which is based on splitting the exergy destruction, advanced exergy analysis.

Endogenous exergy destruction is the part of exergy destruction within a component obtained when all other components operate ideally and the component being considered operates with the same efficiency as in the real system [10].The exogenous part of the variable is the difference between the total exergy destruction and the endogenous exergy destruction, i.e. the sum of the endogenous and exogenous exergy destructions is the total exergy destruction of that component being considered.

$$\dot{E}_{D,k} = \dot{E}_{D,k}^{EN} + \dot{E}_{D,k}^{EX} \quad (7)$$

Further, the part of exergy destruction which cannot be avoided or reduced due to technological limitations such as availability and cost of materials and manufacturing methods is called unavoidable exergy destruction, consequently the difference between the total exergy destruction and unavoidable giving the avoidable exergy destruction in a component [11].

$$\dot{E}_{D,k} = \dot{E}_{D,k}^{UN} + \dot{E}_{D,k}^{AV} \quad (8)$$

Finally, combining both these split components can give us better results in terms of analysis. Such combination gives analysts an opportunity to calculate,

- The avoidable endogenous exergy destruction ($E^{AV,EN}{}_{D,k}$), which can be reduced by improving the k^{th} component from the exergetic point of view, and
- The avoidable exogenous exergy destruction ($E^{AV,EX}{}_{D,k}$) that can be reduced by a structural improvement of the overall system, or by improving the efficiency of the remaining components.

$$\dot{E}_{D,k} = \dot{E}_{D,k}^{UN,EN} + \dot{E}_{D,k}^{UN,EX} + \dot{E}_{D,k}^{AV,EN} + \dot{E}_{D,k}^{AV,EX} \quad (9)$$

In order to summarize the data obtained from the above splitting of exergy destruction, the variable sum of the avoidable exergy destruction is used. This variable represents the sum of the avoidable endogenous exergy destruction within the k^{th} component and the avoidable exogenous exergy destructions within the remaining components caused by the k^{th} component.

$$\dot{E}_{D,k}^{AV,\Sigma} = \dot{E}_{D,k}^{AV,EN} + \sum_{\substack{r=1 \\ r \neq k}}^{n} \dot{E}_{D,r}^{AV,EX,k} \quad (10)$$

the avoidable endogenous exergy destruction within the k^{th} component and the avoidable exogenous exergy destructions within the remaining components caused by the k^{th} component.

This summation of avoidable exergy destructions is used for determining the importance of the k^{th} component of an energy conversion system from the thermodynamic viewpoint. The advanced exergy analysis hence gives us a detailed analysis of the exergy destruction by splitting it into avoidable/unavoidable and endogenous/exogenous parts which can be combined and effective analysis about the energy conversion system can be made. All the options to split the exergy destruction in the k^{th} component can be described as below shown in the figure 1.

4. ENERGY CONVERSION SYSTEM

The energy conversion system we have taken into account to carry out the conventional and advanced exergy analysis is a Simple Vapour Compression Refrigeration system, commonly used for various domestic and industrial applications. A vapour compression refrigeration system is an improved type of refrigeration system in which a suitable working substance, termed as refrigerant is used. It condenses and evaporates at a temperature and pressure close to atmospheric conditions. The refrigerant used, does not leave the system, but is circulated throughout the system alternatively condensing and evaporating.

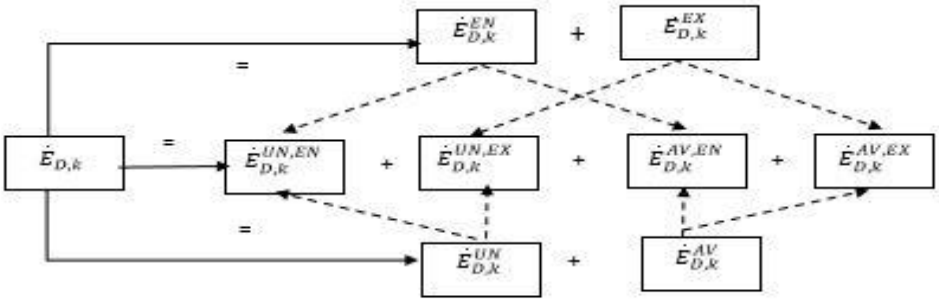


Figure 1: Alternatives for splitting the exergy destruction in the k^{th} componen

In evaporating, the refrigerant absorbs its latent heat from the brine which is used for circulating it around the cold chamber. While condensing, it gives out its latent heat to the circulating water of the cooler. The vapour compression system is therefore also referred to as a latent heat pump, as it pumps its latent heat from the brine and delivers it to the cooler [12]. The vapour compression system is nowadays widely used in real life application for all purpose refrigeration. It is generally used for all industrial purposes from a small domestic refrigerator to a big air conditioning plant. Hence, analysis and optimisation of this system is a topic of interest for engineers and this can be effectively done using exergy analysis. A simple vapour compression system consists of the following major components:

Compressor: The low pressure and temperature refrigerant from the evaporator is drawn into the compressor through the inlet or suction valve, and is compressed to high temperature and pressure. This high pressure and temperature refrigerant is delivered to the condenser through the delivery valve.

Condenser: The condenser consists of coils of pipe in which the high temperature and pressure vapour refrigerant is cooled and condensed. The refrigerant while passing through the condenser gives up its latent heat to the surrounding condensing medium which is normally air or water.

Expansion valve: Also called as throttle valve, the function of this component is to allow the liquid refrigerant under high pressure and temperature to pass at a controlled rate after reducing its pressure and temperature. Some of the liquid refrigerant evaporates as it passes through the expansion valve, but the greater portion is vaporised in the evaporator at the low pressure and temperature.

Evaporator: An evaporator consists of coils of pipes in which the liquid-vapour refrigerant at low pressure and temperature is evaporated and changed into vapour refrigerant at low pressure and temperature. In evaporating, the liquid vapour refrigerant absorbs its latent heat of vaporisation from the medium which is to be cooled.

The schematic diagram of a VCR system showing all of its key components is shown in Figure 2.

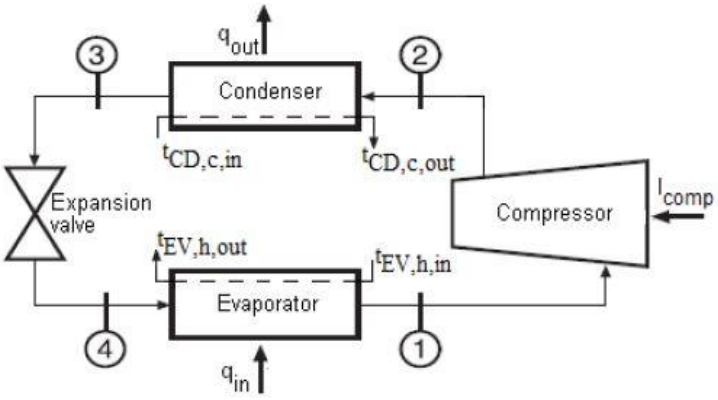


Figure 2: Flow diagram of a simple vapour compression refrigeration system

5. Results and Discussion

A MATLAB code is developed to carry out exergy and advanced exergy analysis of VCR system with three different refrigerant i.e., R717, R134a, R1234yf. The exergy destruction for each component is calculated in the conventional exergy analysis and this exergy destruction is further split into four components during advanced exergy analysis. The results of conventional and advanced exergy analysis obtained for different refrigerant are presented in table 1 to 6.

Table 1: Conventional exergy analysis (for R-717)

Component	Exergy of Fuel, kW	Exergy of Product, kW	Exergy Destruction, kW	Exergetic Efficiency, %
Compressor	43.26	37.34	5.91	86.32
Condenser	14.93	2.40	12.531	15.82
Throttling Valve	22.28	18.08	4.20	81.15
Evaporator	18.21	14.68	3.53	80.60
Overall System	43.26	14.68	28.58	33.93

Table 2: Advanced exergy analysis (for R-717)

Component	Total ExD., kW	Unav. ExD. kW	Av.ExD., kW	End.ExD., kW	Exo.ExD., kW
Compressor	5.919	0.79 (13.5%)	5.119 (86.5%)	3.92 (66.3%)	1.99 (33.7%)
Condenser	12.531	4.07 (32.4%)	8.46 (67.6%)	8.04 (64.2%)	4.49 (35.8%)
Throttling Valve	4.202	1.69 (40.4%)	2.50 (59.6%)	1.716 (40.8%)	2.48 (59.2%)
Evaporator	3.531	3.01 (85.5%)	0.51 (14.5%)	3.53 (100%)	0
Overall system	26.183	9.58 (36.6%)	16.59 (63.4%)	17.21 (65.7%)	8.97 (34.3%)

Table 3: Conventional exergy analysis (for R-134a)

Component	Exergy of Fuel, kW	Exergy of Product, kW	Exergy Destruction, kW	Exergetic Efficiency, %
Compressor	46.38	38.21	8.17	82.31
Condenser	9.76	2.45	7.31	25.16
Throttling Valve	30.68	20.61	10.07	67.17
Evaporator	18.25	11.53	6.72	63.17
Overall System	46.38	11.53	34.85	24.85

Table 4: Advanced exergy analysis (for R-134a)

Component	Total ExD., kW	Unav. ExD. kW	Av.ExD., kW	End.ExD., kW	Exo.ExD., kW
Compressor	8.17	1.10 (13.5%)	7.06 (86.5%)	4.79 (58.6%)	3.38 (41.4%)
Condenser	7.31	2.24 (30.7%)	5.06 (69.3%)	5.81 (79.5%)	1.50 (20.5%)
Throttling Valve	10.07	4.21 (41.8%)	5.85 (58.2%)	4.01 (39.9%)	6.05 (60.1%)
Evaporator	6.72	2.56 (38.2%)	4.15 (61.8%)	6.72 (100%)	0
Overall system	34.85	9.86 (28.3%)	24.98 (71.7%)	21.36 (61.3%)	13.48 (38.7%)

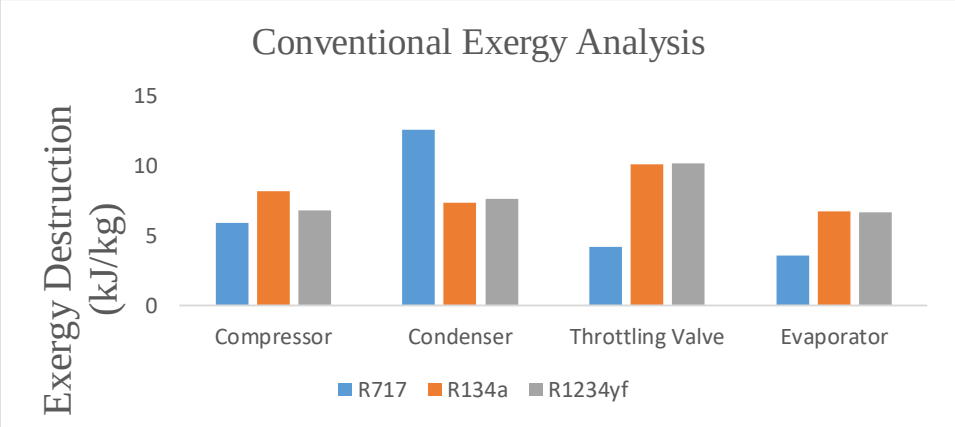
Table 5: Conventional exergy analysis (for R-1234yf)

Component	Exergy of Fuel, kW	Exergy of Product, kW	Exergy Destruction, kW	Exergetic Efficiency, %
Compressor	44.86	38.06	6.80	84.84
Condenser	10.08	2.46	7.61	24.43
Throttling Valve	29.20	19.05	10.15	65.23
Evaporator	18.15	11.53	6.62	63.52
Overall System	44.86	11.53	33.33	25.70

Table 6: Advanced exergy analysis (for R-1234yf)

Component	Total ExD., kW	Unav. ExD. kW	Av.ExD., kW	End.ExD., kW	Exo.ExD., kW
Compressor	6.80	1.06 (15.7%)	4.73 (84.3%)	4.71 (69.3%)	1.08 (30.7%)
Condenser	7.617	2.12 (27.9%)	5.49 (72.1%)	5.87 (77.1%)	1.74 (22.9%)
Throttling Valve	10.15	3.75 (37.0%)	6.39 (63.0%)	3.57 (35.3%)	6.57 (64.7%)
Evaporator	6.62	2.36 (35.7%)	4.25 (64.3%)	6.62 (100%)	0
Overall system	34.85	9.29 (26.6%)	25.55 (73.4%)	20.86 (59.8%)	13.98 (40.2%)

The comparison of exergy destruction in VCR system with different refrigerant is shown in Figure 3. The Figure 3 is a representation of the results obtained after carrying out conventional exergy analysis of the three refrigerants taken into consideration. Each component is analysed separately and the exergy destruction is plotted on the y axis. From the graph obtained by plotting the exergy destruction values of each component for the three refrigerants, we observe the exergy destruction for each component for R134a and R1234yf is almost similar. This can be explained due to similar thermodynamic properties of the refrigerants. Highest exergy destruction is observed in the condenser when R717 is used as the refrigerant, whereas for all other components



the exergy destruction is lower when R134a or R1234yf is used.

Figure 3: Exergy destruction in various components

6. Conclusion

After analysing the three refrigerants from their conventional analysis results, we conclude that exergy destruction is highest in throttling valve for R134a and R1234yf, whereas for system with R717 as the refrigerant, Condenser has the highest exergy destruction. The priority for improvement of the components with different refrigerant are as below.

For R717: Condenser, Compressor, Throttling Valve, Evaporator.

For R134a: Throttling Valve, Compressor, Condenser, Evaporator.

For R1234yf: Throttling Valve, Condenser, Compressor, Evaporator.

Our improvement efforts should focus on the values of avoidable endogenous and avoidable exogenous exergy destruction. The values of the avoidable endogenous exergy destruction demonstrate that the priorities for improving a compression refrigeration machine have only a very weak dependence on the working fluid [10]. In general the evaporator should be considered first. Since 100% of the exergy destruction in this component is endogenous, and since the evaporator significantly affects the exogenous avoidable exergy destruction associated with the remaining components, an improvement of this component leads to the highest possible thermodynamic savings [17].

R1234yf (2,3,3,3 tetrafluoropropene, HFO-1234yf) is a hydrofluoroolefin with the formula $CH_2{=}CFCF_3$. It is also designated R-1234yf as the first of a new class of refrigerants and is marketed under the name Opteon YF by Chemours and as Solstice YF by Honeywell. a relatively new refrigerant which is a potential replacement for the refrigerant being widely used currently, R134a [19]. The drawback associated with R134a lies in its high global warming potential (GWP). Almost all Thermodynamic properties, including the GWP of R1234yf are lower than that of R134a. Upon executing the exergy analysis for a simple VCR system with both these refrigerants simultaneously, we find that the exergetic efficiency obtained for all the components is almost similar and the exergy destruction in the compressor is lower for R1234yf system. This clearly means that R1234yf is a good alternative for R134a. However, the only problem with using R1234yf, which has a significantly lower GWP than R134a, lies within its safety concerns [20]. The refrigerant is mildly flammable

which not an ideal refrigerant property is. Researchers have been working on this factor to try and mitigate the flammability tendencies of R1234yf, after which it can be successfully replaced in place of R134a, which will help solve the global warming crisis worldwide.

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