Vapour Compression Refrigeration Technology for Sustainable Development

R.S. Mishra
Department of Mechanical Engineering , Delhi Technological University, Delhi, India

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Abstract

This paper mainly focus on CFCs and their alternatives to their use. The main critical issue in the field of green technologies is to develop the relationship between ODP and GWP and suggest new and alternative refrigerants which do not damage ozone layer and not to increase global warming. The first and second law thermodynamic analysis of vapor refrigeration system of 1.5 ton capacity for five eco-friendly refrigerants such as (R-1234yf, R-1234ze, propane (R-290), isobutene (R-600a), butane (R-600)) have been carried out in terms of performance parameters such as COP, Exegetic efficiency, ratio of exergy destruction in components such as condenser, compressor, throttle valve and evaporator. These performance parameters have been evaluated by varying condenser temperatures in the range from 300K to 327K and evaporator temperatures in the range from 274 K to 279K. It was observed that R-290 and R-600 (butane) and R-600a (isobutene) of zero ODP and zero GWP is best alternatives if its flammable problem will mitigate and R-1234ze (of zero ODP), are the next option of R-22 refrigerant.

1. Introduction

An eminent philosopher has defined Science as "TAPASAYA" and Technology as "Bhog" where as science is pure selfless and open to all search for truth where as technology is the exploitation of scientific knowledge for selfish purposes and profit motive and hence it tends to be secretive in this competititive world of today with a throat cutting environment. Sustainable Development is a process in which development can be sustained for generations. It also focuses attention on inter generational fairness in the exploitation of development opportunities while social development is a function of technological advancement, and also the technological advancement, in turn is a function of scientific know how for a streamlined development of the society. Technology is one of the crucial determinants of sustainable development. Technological import through collaborations has been one of the most important sources of technological inputs for Indian conditions. The use of technologies originating in rich countries often ten to create many social, ecological and resource problems in poor countries. The exploitation of the vast natural resources through progressive development of science, engineering and technology that has brought about the vast changes in the civilization and society from the stone age to the present high technology era. In facts, the mad race for industrialization and economic development has resulted in over exploitation of natural resources, leading to a situation where the two worlds of mankind- the biosphere, lithosphere and hydrosphere of his inheritance and the techno sphere of his creation, are out of balance with each other, indeed on a collision path. To facilitate optimal utilization of finite natural resources for ensuring a sustainable benefit steam for better quality of life on the one hand and to simultaneously keep in mind the conservation of natural resources on the other hand, it is essential that the technology conservation process must be made as efficient as possible. Therefore sustainable economic development depends on the careful choice of technologies and judicious management of resources for productive activities to satisfy the changing human needs without degrading the environment or depleting the natural resources base.

Corresponding Author,
E-mail address: professor_rsmishra@yahoo.co.in

2. Application of Ecofriendly Refrigerats in the Vapour compression Refrigeration Systems

The efforts under the Montreal protocol to protest the OZONE layer, the alternative refrigerants have been proposed as a substitutes for ozone depleting substances. HFCs (Hydrofluoro carbons) PFCs (Perfluro carbons) have zero ODP potential but they are producer of green house gases and are subjected to limitation and reduction commitments under UNFCC(United Nations Framework Convention on Climate change). With the entry into force of Kyoto protocol on 16th February 2005 developed countries have already planning and implementing rational measures intended to contribute towards meeting green house gas reduction targets during the first commitment period of Kyoto protocol (2008-2012). The countries have also started together with developing countries to size up projects that qualify under Kyoto clean development mechanism. As what lies behyond 20-12 all Governments will work together over next few years to decide on future intergovernmental action on the climate change. In this light, it is vital that there should be continuous work on the replacement options for ozone depleting substances in way that serve the aim of the Montreal protocol and UNFCC alike. In the developing countries the conversion of CFCs to alternate is still a major issue. In this paper the first law and second law analysis of various eco friendly refrigerants have been carried out which will help in deciding about the path to be followed to satisfy Montreal and Kyoto protocol. On the basis of theoretical analysis, an extensive experiment have been conducted in the Advanced centre for studies and research in green energy technologies of Delhi college of Engineeing, and It was observed thatR1234yf and R-1234ze refrigerant is the best alternatives for replacing R134a after 2030 due to its low ODP and GWP.

3. Thermodynamic Analysis of Vapour Compression Refrigeration systems

Thermodynamic processes in refrigeration system releases large amount of heat to the environment. Further, heat transfer between the system and the surrounding environment takes place at a finite temperature difference, which is a major source of irreversibility for the cycle and also responsible for the system performance degradation. The losses in the cycle need to be evaluated considering respective individual thermodynamic processes by applying first and second laws. Energy analysis (First Law) is still the most commonly used method in the analysis of thermal systems which only concern with the conservation of energy, and gives no information on how, where, and how much the system performance is degraded. On the other hand, second law is used to describe the quality of energy of materials. The first law optimization results in maximizing the coefficient of performance (COP) thus providing maximum heat removal from minimum power input; while the second law optimization is used for maximizing the exergy efficiency and minimizing entropy generation within the system, hence providing maximum cooling for the smallest distraction of available energy (exergy).

The exergy method, known as the second law analysis calculates the exergy loss caused by irreversibility which is an important thermodynamic property that measures the useful work that can be produced by a substance or the amount of work needed to complete a process. Thus exergy analysis is powerful tool in the design, optimization, and performance evaluation of energy systems. The principles and methodologies of exergy analysis are well established [1-4]. An exergy analysis is usually aimed to determine the maximum performance of the system and identify the sites of exergy destruction. Exergy analysis of a complex system can be performed by analyzing the components of the system separately. Identifying the main sites of exergy destruction shows the direction for potential improvements. An important objective of exergy analysis for system that consume work such as refrigeration, liquefaction of gases, and distillation of water is to find the minimum work required for a certain desired result [5].

There are several studies on the exergy analysis of refrigeration system [6, 7]. Bejan [7] showed that the exergetic efficiency decreases as the refrigeration temperature decreases. He offered two simple models to explain this trend. In his model, thermodynamic imperfections are explained largely by the heat transfer irreversibility. The behaviour of two stage compound-cycle with flash intercooling, using refrigerant R22 has been investigated by Nikolaidis and Probert [8] using exergy method. A computational model based on the exergy analysis is presented by Yumrutas et. al [9] for the investigation of the effects of the evaporating and condensing temperatures on the pressure losses, exergy losses, second law of efficiency, and the COP of a vapour compression cycle.

In the present research work, exergy analysis is performed on the operating data of vapour compression refrigeration cycle of an industrial ice plant. The expressions for the exergy losses (lost works) for the individual processes of the cycle as well as the coefficient of performance (COP) and second law efficiency for the entire cycle has been obtained. Effect of variation of condensing and evaporating temperatures on exergy losses, second law efficiency and COP has been investigated. The concept of structure coefficient (coefficient of structure bond) is used to explain the relation between irreversibilities of system & its component. The main components of an refrigeration are compressor, expansion valve, condenser and evaporator (brine chiller connected with ice box). Ice tank is made of mild steel plates and having heavy insulation of granulated corks around 300 mm in thickness. The tank is filled with recirculated brine in which cans filled with water are immersed. The tank is provided with piping for blowing air into ice cans to create agitation. In the present analysis, single stage vapour compression system has been used for ice production. Reverse osmosis water is being used in the system for production of ice cubes.The corresponding temperature versus entropy diagram for this system. At the starting point , the circulating refrigerant enters the compressor as a saturated vapour. From firstpoint to secondpoint , the refrigerant vapour is isentropically compressed and exits the compressor as a superheated vapour. From second point to point third', the superheated vapour travels through part of the condenser which removes the superheat by cooling the vapour.Between third point ' and fourth point , the vapour travels through the remainder of the condenser and is condensed into a saturated liquid. The condensation process occurs essentially at constant pressure. Between fourthpoints and fifth point, the saturated liquid refrigerant passes through the expansion valve and undergoes an abrupt decrease of pressure. This process results in the adiabatic flash evaporation and causes auto-refrigeration of a portion of the liquid refrigerant (typically, less than half of the liquid flashes). The adiabatic flash evaporation process is isenthalpic (i.e., occurs at constant enthalpy) in nature. Between fifth points and first point , the cold and partially vaporized refrigerant travels through the coil or tubes in the evaporator where it is totally vaporized by the warm water (from the space being refrigerated) that circulates across the coil or tubes in the evaporator. The evaporator operates at essentially constant pressure. The resulting saturated refrigerant vapor returns to the compressor inlet at the first point to complete the thermodynamic cycle

4. Eco Friendly Referants used in vapour compression refrigeration systems

The performance of Vapour compression refrigeration systems of 1.5 tons refrigerating capacity are given using following ecofriendly refrigerants.

R-410a: is a azeotropic mixture of HFC-32 and HFC-125 in the proportions 50%, 50% by weight with 2% tolerance allowed for each of the components. It has very low temperature glide around 0.1K and its vapor pressure is roughly 50% higher than that of HCFC22.

R-32/124a: R-32 is a near azeotropic mixture of HFC-32 (Difluromethane) and R-124a in the proportions of 30% and 70% by weight.

R-134a: is a member of the family of HFC refrigerants. The HFC refrigerants are similar composition to CFCs and HCFCs and they have become the primary focus of the refrigeration and air conditioning industries as a long term substitute for traditional refrigerants. HFCs are not miscible with traditional mineral oil so alternative synthetic lubricants are recommended synthetic polyester either alkyl benzene or polyalkylen glycol

R-407c: is a mixed zoetrope refrigerant consisting of three HFC components such as R-32, R-125 and R-134a in the proportions 23%, 25% and 52% by a weight +_ 2% tolerances allowed for each of the components. R-407c has properties very similar to R-22 which was replaced in air conditioning applications in terms of both its operating pressures and its performance in dry expansion air conditioning systems.

Propane (R-290) can be used as substitute for R-11, R12 and R22 because of zero ODP and GWP. The pressure levels and refrigerating capacity are similar to R-22 and R-502 along with its temperature behavior is as favorable as with R-22 & R-502. There is no material problems in compressor of hermetic and semi hermetic types in air conditioning units and heat pumps. The first law and second law performances in terms of variation of condenser and evaporator temperatures with COP, Exergy Destruction Ratio(EDR), exegetic efficiency, exergy destruction in each components of vapor compression refrigeration system of 1.5 tons capacity using R-290 refrigerant for 298K of ambient temperature.

Propylene (R-1270) can be used as substitute because of good refrigerant by higher volumetric refrigeration capacity and low boiling temperature however higher pressure level and discharge gas temperature have to be taken into consideration which restricting the possible application range. R-1270 is also easily inflammable and due to chemical double linkage it is relatively reaction friendly and there is a danger of polymerization at higher pressure and temperature levels. The component dimensions have to be altered when using R-1270 refrigerant due to higher volumetric refrigeration capacity along with lower compressor displacement. Because of higher vapor density , the mass flow rate is almost the same as for R-290 and liquid density is nearly identical for the liquid volume in circulation.

5. Modelling of vapour compression refrigeration system using ecofriendly refrigerants

The major disadvantage of hydrocarbon refrigerants is their inflammability therefore system must be designed by consideration of flame proof regulations however with open compressors additional safety devices may be required. For practically mass flow rate of refrigerant may be low as 55% to 60% approximately as compared to R-22 and internal heat exchanger between the suction and liquid line is improved the refrigeration capacity along with COP. Due to good solubility with mineral oils, it may be necessary to use an oil it lower mixing characteristics or increasing viscosity for higher suction pressure, the use of internal heat exchanger is advantageous because it leads to higher oil temperatures to lower solubility improves its viscosity. Due to favorable temperature behavior of R-290, the single stage compressor is used down to approximately 233K evaporator temperature respectively and can also be considered as a direct substitute for R-502. For the thermodynamic analysis of the industrial ice plant working on vapour compression system, the principles of mass conservation, first and second laws of thermodynamics are applied to each component of the system. Each component can be treated as control volume with inlet and outlet streams, heat transfer and work interactions. For the system, the mass conservation is governed by following equation:

$$\sum m_i - \sum m_o = 0 \qquad (1)$$

Where m is the mass flow rate and suffix i and o represents inlet and outlet of the component.

The first law of thermodynamics yields the energy balance of each component of the system as follows:

$$\sum(mh)_i - \sum(mh)_o + [\sum Q_i - \sum Q_o] + W = 0 \qquad (2)$$

The overall energy balance of the system requires that the sum of the evaporator, condenser and compressor must be zero. The vapour compression system is assumed to be in steady state condition and further if the pump work for brine solution circulation and the environmental heat losses are neglected, the energy balance for the entire system can be written as

$$Q_0 = Q_c + W \qquad (3)$$

The energy balance equations of various components of a vapour compression system are given below:

Mass flow rate of circulated refrigerant can be calculated as

$$m_R = Q_c / (h_1 - h_4) \qquad (4)$$

For the compressor (by convention, the work done by compressor is presumed to be negative);

$$W_c = - m_R (h_2 - h_1)/\eta_m \eta_e \qquad (5)$$

Where η_m and η_e are mechanical and electric motor efficiencies respectively.

Heat transfer rate in the condenser (zone B) is given by

$$Q_0 = m_R (h_3 - h_2) \qquad (6)$$

Coefficient of performance of refrigeration is

$$COP = Q_c/W \qquad (7)$$

For state point 4 dryness fraction and specific entropy can be represented as:

$$x_4 = (h_3 - h_f) / (h_1 - h_f) \qquad (8)$$

Where h_f is the enthalpy of saturated liquid refrigerant at evaporator pressure.

Specific entropy is:

$$s_4 = s_f + x_4 (s_1 - s_f) \qquad (9)$$

Where s_f is the entropy of saturated liquid refrigerant at evaporator pressure. Second law analysis is a relatively new concept, which has been used for understanding the irreversible nature of real thermal processes and defining the maximum available energy. The second law analysis is based on the concept of exergy, which can be defined as a measure of work potential or quality of different forms of available energy relative to the environmental conditions. In other words, exergy can be defined as the maximum theoretical work derivable by the interaction for an energy resource with the environment.

Exergy analysis is applied to a system describes loses both in the components of the system and for the system as a whole. With the help of exergy analysis the magnitude of these losses or irreversibility's and their order of importance can be understood respectively. With the use of irreversibility, which is a measure of process imperfection, the optimum operating conditions can be easily determined. It is possible to say that exergy analysis throw an insight to indicate the possibilities of thermodynamic improvement for the process under consideration. The formulation for exergy analysis is described below:

The difference of the flow availability of a stream and that of the same stream at its restricted dead state is called flow exergy (ε) and by ignoring chemical exergy terms, flow exergy (ε) is given by

$\varepsilon = (h - T_0 s) + V^2/2 + gZ - (h_0 - T_0 s_0)$ (10)

Ignoring the potential and kinematic energy terms, Eq. (10) becomes

$\varepsilon = (h - T_0 s) - (h_0 - T_0 s_0)$ (11)

The exergy balance equation is given by

$E_w = \sum E_Q + \sum(m\varepsilon)_i - \sum(m\varepsilon)_o + T_0 S_{gen}$ (12)

In equation (12) the term T_0S_{gen} is defined as the irreversibility (I) and can be written as:

$I = T_0 S_{gen}$ (13)

The above exergy analysis formulation has been performed on each component of the vapour compression system shown in Figure 3, and corresponding irreversibility of each component is calculated. Using this formulation described below:

By carrying out an exergy-rate balance for the compressor, the irreversibility rate (zone A):

$I_A = W + E_1 - E_2$ (14)

The exergy-rate balance for the evaporator (zone D):

$I_D = E_4 - E_1 - E_Q^D$ (15)

where, for the evaporator

$E_Q^D = Q_C (T_0 - T_c)/T_c$ (16)

The exergy rate balance for the condenser, (zone B) is given by

$I_B = E_2 - E_3$ (17)

The exergy-rate balance in the throttling valve, (zone C) is given by

$I_C = E_3 - E_4$ (18)

Efficiency defect (δ_k) of k^{th} component of the system may be expressed as fractions of input which are lost through irreversibility

$\delta_k = I_k/W$ (19)

Where I_k is the irreversibility rate of the k^{th} component of the system under consideration.

The total irreversiblitities of the system components is expressed as

$I_t = I_A + I_B + I_C + I_D$ (20)

The relative irreversibility of the k^{th} component of plant is $= I_k/I_t$ (21)

Structural coefficients are used in the study of the system structure, optimization of plant components and product pricing in multi-product plants. The change of local irreversibility rates and exergy fluxes in relation to the overall plant's irreversibility rate is effectively expressed by the coefficient of structural bonds (CSB) which is defined by

$\sigma_{k,i} = [\partial I_t/\partial x_i]/[\partial I_k/\partial x_i]$ (22)

Where x_i is the i^{th} parameter of the system which produces the changes in k^{th} component.

The effect of a change in x_i on the system would be to alter the rate of exergy input while leaving the output constant. This acceptance confirms to the usual practice of specifying a plant in terms of its output rather than its input. From the exergy balance of the system

$E_{IN} = E_{OUT} + I_t$ (23)

But E_{OUT} = constant, thus

$\Delta E_{IN} = \Delta I_t$ (24)

As seen from equation (24) changes in the irreversibility of the system are equivalent to changes in the exergy input. In general, the ratio of the rates of exergy output to exergy input is less than unity. This ratio denotes the degree of thermodynamic perfection of the process and is called the rational efficiency(η_R).

$\eta_R = E_{OUT}/E_{IN}$ (25)

Plant rational efficiency $\eta_{R,\,plant} = 1 - \sum\delta_k$ (26)

6. Results & Discussions

The computation modeling of vapor compression refrigeration systems was carried out with the help of engineering equation solver of Hon'ble Dr. S.A. Klein (2002) for first and second law analysis in terms of energetic analysis i.e. COP (First law analysis) and exegetic analysis in terms of exergetic efficiency, exergy destruction ratio (EDR) and percentage exergetic destruction in each components (second law analysis). In this analysis we assumed negligible pressure losses and heat losses. The comparative performance of 4.75 KW window air conditioner is evaluated for condenser temperature varying between 300K to 327K with increment of 3 and evaporator temperature is varying from 274K to 278 K with increment of 1. The energy and exergy change in vapour compression refrigeration cycle have been calculated for various eco friendly refrigerants such as R-1234yf, R-1234ze, R404a, R-290 (propane), R600 (butane), R-600a (isobutene) for environmental temperature of 298K. The variation of fist law efficiency in terms of cop and second law eficiency in terms of exergetic are shown in Table-1to Table 2 respectively. As condenser temperature increses the first law efficiency decreases while second law efficiency decreases. Similarly with increasing evaporator temperature, the first law efficiency increases while second law efficiency decreases. The effect of various eco friendly refrigerants for condenser temperature of 321 (K) and Evaporator temperature of 277 K is also shownin table 3. Respectively.

Table: 2a. First Law Performance Of Vapour Compression Refrigeration System With Evaporator Temperatures Using Ecofriendly Refrigerants (Tcond=321 K Tamb=300 K)

Evaporator Temp (K)	**COP** R1234yf	**COP** R1234ze	**COP** R600a	**COP** R290	**COP** R600
274	2.27	5.214	2.514	2.424	2.623
275	2.345	5.466	2.592	2.498	2.703
276	2.423	5.738	2.675	2.576	2.787
277	2.505	6.034	2.76	2.658	2.874
278	2.591	6.358	2.851	2.743	2.966
279	2.681	6.712	2.946	2.833	3.061

Table: 2b: Second law Performance of Vapour Compression Refrigeration System With Evaporator Temperatures Using Ecofriendly Refrigerants (Tcond=321 K Tamb=300 K,)

Eva. Temp(K)	Second LawEff $_{R1234yf}$	Second LawEff	Second LawEff $_{R600a}$	SecondLaw Eff $_{R290}$	Second LawEff $_{R600}$
274	0.8507	0.8791	0.8555	0.8538	0.8574
275	0.6926	0.7505	0.7023	0.6988	0.7061
276	0.5247	0.6132	0.5392	0.5340	0.5447
277	0.2356	0.4661	0.3647	0.3573	0.3720
278	0.1535	0.3077	0.1772	0.1678	0.1864
279	0.0	0.1364	0.0	0.0	0.1420

Table: 2a. Firstlaw Performance of Vapour Compression Refrigeration System with Condenser Temperatures Using Ecofriendly Refrigerants (TEVA=277 K, Tamb=300 K)

Condeser temperature (K)	COP $_{R1234yf}$	COP $_{R1234ze}$	COP $_{R600a}$	COP $_{R290}$	COP $_{R600}$
300	5.818	6.034	6.036	5.914	6.141
303	5.034	5.249	5.252	5.140	5.355
306	4.4080	4.624	4.629	4.521	4.737
309	3.894	4.113	4.12	4.0160	4.23
312	3.465	3.686	3.696	3.594	3.806
315	3.099	3.325	3.337	3.236	3.446
318	2.782	3.013	3.029	2.927	3.141
321	2.505	2.742	2.761	2.658	2.874
324	2.259	2.503	2.526	2.42	2.640
327	2.038	2.29	2.317	2.207	2.431

Table: 2b. Second Law Performance of Vapour Compression Refrigeration System with Condenser Temperatures Using Ecofriendly Refrigerants (TEVA=277 K Tamb=300 K)

Condeser temperature(K)	SECONDLAWETA $_{R1234yf}$	SECONDLAWETA $_{R1234ze}$	SECONDLAWETA $_{R600a}$	SECONDLAWETA $_{R290}$	SECONDLAWETA $_{R600}$
300	0.4629	0.4661	0.4661	0.4643	0.4676
303	0.4491	0.4533	0.4534	0.4512	0.4553
306	0.4345	0.44	0.4401	0.4375	0.4427
309	0.4191	0.4261	0.4263	0.4231	0.4296
312	0.4027	0.4116	0.412	0.4080	0.4160
315	0.3851	0.3963	0.3970	0.3921	0.4020
318	0.3661	0.3803	0.3812	0.3753	0.3873
321	0.3456	0.3633	0.3647	0.3573	0.3720
324	0.3231	0.3453	0.3472	0.3382	0.2504
327	0.2983	0.3261	0.3288	0.3177	0.3393

Table: 1a: Performance of Vapour Compression Refrigeration Systems Using Ecofriendly Refrigerants

Refrigerants	Q_{EVA}	W_{COMP}	Q_{CON}	COP_{ACTUAL}	COP_{CARNOT}	$EFFICIENCY_{SECOND}$
R717	1047	398.7	1445	2.625	5.383	0.4876
R407c	134.04	65.97	200	2.031	5.383	0.3774
R404a	90.03	45.01	139	2.089	5.383	0.3830
R123	128.6	48.12	176.7	2.672	5.383	0.4965
R152a	220.8	84.77	305.5	2.60	5.383	0.4838

Table: 1b: Performance Of Vapour Compression Refrigeration Systems Using Ecofriendly Refrigerants

Refrigerant	Q_{EVA}	W_{COMP}	Q_{CON}	COP_{ACTUAL}	COP_{CARNOT}	EFF_{SECOND}
R-1234yf	93.12	42.06	135.2	52.214	5.383	0.4113
R1234ze	117.8	47.93	165.8	2.459	5.383	0.4567
R134a	130.2	53.1	183.2	2.451	5.383	0.45540
R410a	148.6	63.83	212.4	2.329	5.383	0.4326
R600	259.7	100.9	360.6	2.574	5.383	0.4782
R-290	244.3	101.3	345.6	2.412	5.383	0.4481
R600a	224.1	91.56	315.7	2.448	5.383	0.4547

7. Conclusions and Recommendation

The analysis of the single stage vapour compression refrigeration system performance by the exergy method demonstrates how effective this method is for analyzing behavior. Employing the concepts of efficiency defect and exergetic efficiency has enabled the proportions of input lost through irreversibility's, in various refrigeration systems sub systems, to be evaluated easily. Using the technique of the coefficient of structural bond has demonstrated that a change in any component variable in a system component significantly influences the other component in the system as a whole, and a reduction of irreversibility's rate in a plant component give a greater reduction in the irreversibly rate of system as whole. The greater the value of condeser temperature, the greater the irreversibly. Because T_{cond} and T_{evap} affect the system exergetic efficiency, they need to be optimized each particularly heat transfer area chosen for the two heat exchanger in therefrigerating system.

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