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Use of Acetone & Water Combination as Refrigerant in Vapour Compression Refrigeration System (VCRS): A Process Development &Validation

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Abstract: Synthetic refrigerants contributes to global warming & depletion of ozone layer. Investigations over last few decades solicit natural substances to take over the present challenge. The present work was a manoeuvre to find out the possibility of Acetone and water solution in sharply estimated ratio as natural refrigerant in vapour compression refrigeration system with pros and cons. The process development and validation was investigated in comparison to halogenated refrigerants especially R-134a.The refrigerant parameters were measured in terms of $(COP)_{ref}$, nontoxic character ,reasonable compression ratio, work input, flammability, durability and stability & environment friendliness. While comparing with synthetic refrigerants the present refrigerant rationalized as an environmental friendly, better performance, and non corrosive with greater thermally and chemically stable stuff for domestic refrigeration, air conditioning, and heat pumps.

Keywords: Vapour Compression Refrigeration System, Acetone & Water Solution, designed ratio, process development, validation.

I. INTRODUCTION

Present generation of refrigeration and air conditioning devises vapor compression systems in refrigeration, air conditioning, heat pump and water chiller units. The working fluids are grouped in to six categories in the context of technological evolution of refrigeration and air conditioning listed as: hydrocarbons (HC), hydroflurocarbons (HFC), HFC/HC, hydrochloroflurocarbons, (HCFC), carbon dioxide (R744) and ammonia (R717). In last few decades use of halogenated refrigerants were imperative in vapor compression systems reasoning its good thermodynamic and thermo-physical properties. However their toxic environmental properties vitiates the ozone depletion potential (ODP) and global warming potential (GWP). Stringent norms of international refrigerant protocol standard (Montreal and Kyoto) refrains halogenated refrigerants in the vapor compression refrigeration systems. However it does not embraces hydrochloroflurocarbons (HCFC) till 2040, in developing countries like India outgrown by 2030 [1]. Significance of HCFC as refrigerant recently drops down in developed nations. United Nations Framework Convention on Climate Change (UNFCCC) mandates minimizing emission of six categories of green house gas contributed by hydroflurocarbon (HFCs) refrigerants [2]. In this context right combination of environment-friendly mixture finds new way of investigation. Investigating combination of HC and HFC mixtures infer reduced GWP. However the combined mixture is instantly inflammable that restrains its use in bigger capacity units [3]. Smaller units prefer HC refrigerant mixtures for domestic purpose that requires lower volume of refrigerants. HFC mixtures are ozone-friendly associated with significant GWP and immiscible to mineral oil, which require synthetic lubricants (such as polyolester). The presence of synthetic stuffs in HFC are hygroscopic in nature, expensive, causes itching in contact with skin and provides way to several service problems in overhauling [4]. Problems associated with HC and HFC refrigerant mixtures are overcome by blending hydrocarbons with HFC that facilitates miscibility (with mineral oil) and reduces flammability [5]. Basing on investigations HFC/HC mixtures are miscible with mineral oil with one-third GWP than HFC, when used alone. Hence HFC/HC mixtures can replace halogenated refrigerants [6].Use of natural working fluids as refrigerants have been reported in VCR and VAS [7].Use of different pure HC refrigerants have been reportedly experimented [8].Evolutionary development of pure refrigerants from early use to the present has been reported [9]. Investigations on environment-friendly alternatives reported that refrigerant mixtures are the replacement for halogenated refrigerants [10].

In present context no specific or very little investigations have been reported on refrigerant mixtures. Hence, the present work more broadly investigates the performance of new refrigerant mixture: Acetone water with special focus on its possibility as an environmental friendly refrigerant. Moreover, the study involves estimation of echo friendly impact, economy of use in fraternity with retrofitting, forecasting of refrigerant properties in the scenario of refrigeration and air-conditioning segment with technical pros and cons.

II. MATERIALS AND METHODS

A. Selection of Materials

The UNFCC mandates phases-out pure halogenated refrigerants. A very narrow range of pure fluids exists in nature that exhibits parallel properties to halogenated refrigerants. Hence mixture of two or more refrigerants that shows adjustment of properties and behaves as a single substance is desirable. Azeotropic mixtures evaporate and condense as a single substance with their properties being different from those of constituents. Boiling point of azeotropes is lower than either of their constituents used as refrigerants. Acetone water solution was azeotropic in operating range of temperature and pressure. However further increase in temperature and pressure made it nearly azeotropic mixture. Nearly azeotropic mixtures are having very low temperature glide in the range between 0.2 and 0.61^0 C that does not affect the hardware design. So in present investigation azeotropic mixture of Acetone to water in the ratio ranging from 54: 1 to 76:1was trialed. The range of ratio was designed basing on unwieldy iterative trial and error with evaluation of properties.

B. Material Characterization

Acetone commercially known as propanone, is an organic compound with the formula $(CH_3)_2CO$. It is the simplest and smallest ketone, colourless, volatile, flammable liquid with a characteristic odour. Acetone is miscible with water. Acetone is produced and disposed of in the human body through normal metabolic processes. The other chemical identity specifications were given in Table.1.

Table.1: Chemical identity specifications

IUPAC Name	Preferred IUPAC Name	Other Names
Acetone	Proan-2-One	Dimethyl ketone
		Dimethyl carbonyl
		β-Ketopropane
		Dimethyl formaldehyde
		Pyroacetic spirit (archaic)
		Ketone propane

C. Process Development and Validation

The Acetone water refrigerant in designed ratio was retrofitted to a test rig using R-134a as baseline refrigerant. The COP of both refrigerants was recorded for comparison. The technical specifications of the test rig were: Model UPSON, Model number-URF-M5, Rated voltage 240V, Electricity consumption 0.5kWh/24h & Power 90W, and Weight 19kg, Volume 47L coupled with engineering equation solving software (EES).The major feature of EES is the high accuracy thermodynamic property database that is provided for hundreds of substances in a manner that allows it to be used with the equation solving capability. Refrigerants retrofitted alternately were R-134a and Acetone water. The flow diagram of the refrigerant test rig was depicted in Fig.1.

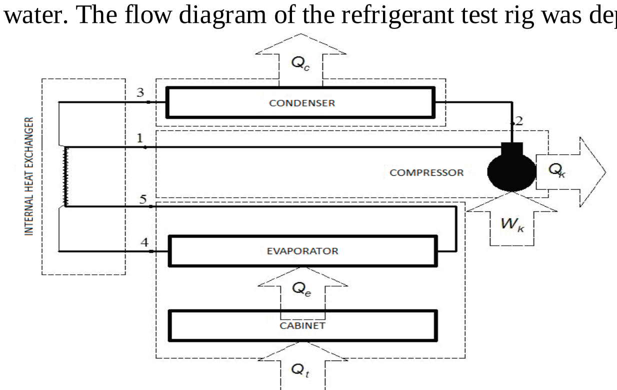

Fig.1 Flow diagram of the refrigerant test rig

1) *Rig Thermodynamic Processes*
a) *Process: 1-2(Compression):* The process was adiabatic. Work was done on refrigerant (*W=v. dp*) by energy input. Compression was dry, wet or super heated depending upon the phase of the refrigerant at that instant.
b) *Process: 2-3(Condensation):*The process was isobaric rejection of heat from refrigerant to atmosphere.

$$Q_1=W_{C+}Q_2$$

c) *Process: 3-4(Expansion):* The process was adiabatic retrofitted with capillary tube expansion valve.
d) *Process: 4-5(Evaporation):* The process was isobaric heat addition from desired cooling space to the evaporator flooded with refrigerant. Figure.2 shows the flow diagram of different processes with phase change.

$$Q_2=m.c_p.dt$$

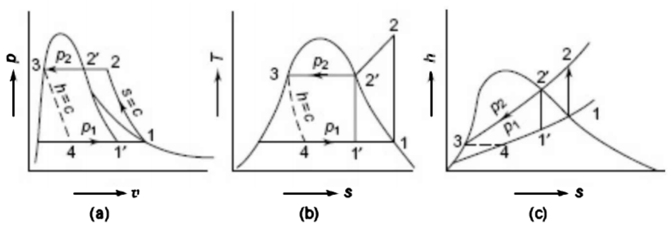

Figure.2 Flow diagram of different processes

2) *Refrigerant Mixture:* The research evolutionary gestation period of R134a emerged out with discovery of the damaging effect of CFCs and HCFCs refrigerants to the ozone layer. It is known as Tetrafluoroethane (CF3CH2F) of HFC refrigerant family. Present generation of refrigeration and air conditioning rampantly use it as CFCs and HCFCs replacement in centrifugal, rotary screw, scroll and reciprocating units. It is safe for normal handling as it is non-toxic, non-flammable and non-corrosive. Currently automotive sectors use it in interior air conditioning. The properties of R134a were summarized in Table.2.

Table.2: properties of R134a

Sl No	Properties	R-134a
1	Boiling Point	-14.9°F or -26.1°C
2	Auto-Ignition Temperature	1418^0 F or 770^0 C
3	Ozone Depletion Level	0
4	Solubility In water	O.11% by weight at 77^0 F or 25°C
5	Critical Temperature	252^0 F or 122°C
6	Cylinder Colour Code	Light Blue
7	Global warming Potential	1200

However UNFCCC mandates use of HCFC till 2040, in developing countries like India outgrown by 2030 [1]. The combined mixture is instantly inflammable and raises Global warming potential (GWP) that restrains its use in bigger capacity units [3]. Hence in present context the search for an environmental friendly refrigerant was prevalent focusing on proximal COP. Acetone water mixture in designed ratio 54: 1 to 76:1was such a nearly azeotropic refrigerant on which attention of investigation was concentrated to find its possibility as an environmental friendly refrigerant. A summary of chemical properties, structure and thermo chemistry of Acetone to be used as primary component of refrigerant mixture was given in Table.3.

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Table.3: chemical properties, structure and thermo chemistry of Acetone.

Properties	
Chemical formula	C_3H_6O
Molar mass	58.080 g·mol^{-1}
Appearance	Colourless liquid
Odor	Pungent, irritating, floral, cucumber like
Density	0.7845 g/cm^3 (25 °C)
Melting point	−94.7 °C (−138.5 °F; 178.5 K)
Boiling point	56.05 °C (132.89 °F; 329.20 K)
Solubility in water	Miscible
Solubility	Miscible in benzene, diethyl ether, methanol, chloroform, ethanol.
log *P*	-0.16
Vapour pressure	9.39 k Pa (0 °C) 30.6 k Pa (25 °C) 374 k Pa (100 °C) 2.8 m Pa (200 °C)
Acidity (p K_a)	19.16 (H_2O)
Magnetic susceptibility (χ)	−33.78·10^{-6} cm^3/mol
Refractive index (n_D)	1.3588 (V_D = 54.46)
Viscosity	0.295 m Pa (25 °C)
Structure	
Coordination geometry	Trigonal planar at C2
Molecular shape	Dihedral at C2
Dipole moment	2.91 D
Thermo chemistry	
Heat capacity (*C*)	125.45 J/(mol· K)
Std molar entropy ($S^{\ominus}_{298}$)	200.4 J/(mol· K)
Std enthalpy of formation ($\Delta_f H^{\ominus}_{298}$)	(−250.03) – (−248.77) kJ/mol
Std enthalpy of combustion ($\Delta_c H^{\ominus}_{298}$)	−1.772 MJ/mol
Flash point	−20 °C (−4 °F; 253 K)
Auto ignition temperature	465 °C (869 °F; 738 K)
Explosive limits	2.6–12.8%
Threshold limit value (TLV)	1185 mg/m^3 (TWA), 2375 mg/m^3 (STEL)

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III. RESULT AND DISCUSSION

A. *Selection of Materials*

Acetone was preferred as primary constituent of novel nearly azeotropic mixture refrigerant considering its ball-beam structure, dimensional structural formula & bond order configuration. The structural geometry was shown in fig.3

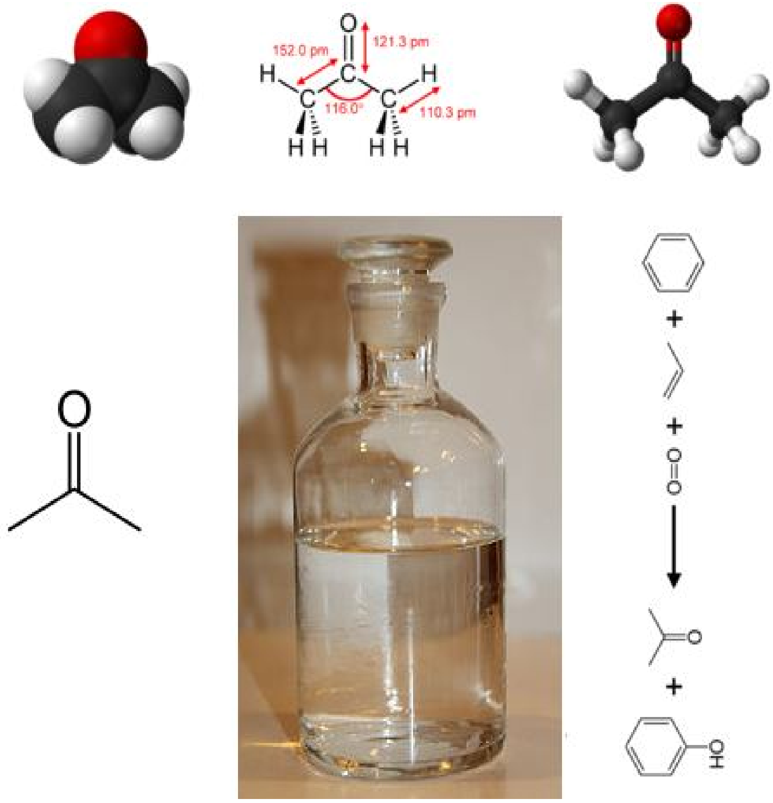

Figure.2 Structural geometry of Acetone

The structural geometry contributes to : thermal and chemical stability, low density(low pumping work to circulate), assessable range of boiling point(not achieved in halogenated refrigerants),non toxic nature, comparatively higher emissivity & refractive index than conventional refrigerant(low compressor work), low freezing point of -78^{o}c(superior cooling effect), stoechiometric pressure impact on conduit walls(latent heat transfer),better lubrication property(no scaling inside copper conduit at elevated temperature & pressure), odorous(easy leakage detection) and negligible GWP & ODP.

However its high inflammability, low density and low specific heating value were imperative issues to be addressed before considering its possibility as primary constituent of refrigerant mixture. High flammability restrains its use in bigger units, low density increases possibility of leakage in conduit and valves when compressed and low specific heating value is not tolerable.

The associated problems were addressed by mixing water with Acetone to form a nearly azeotropic refrigerant solution in the ratio of 54:1 to 76:1.

Mixing of water increased its density and specific heat thus decreasing chances of leakage and manages the sharp increase in temperature while adding heat. It also moderates the flammability risk. The mixing of water in designed ratio (54: 1 to 76:1) did not intervene any irregularity in nearly azeotropic behaviour of the mixture refrigerant over a wide temperature range as it was readily soluble to Acetone. So, the solution of Acetone & Water (54: 1 to 76:1) holds optimized characteristics of a refrigerant. However the designed ratio (54:1 to 76:1) was to be fairly maintained, any violation may cause serious damages to the system. Excess water causes corrosion, valve choking and seizure of piston or vanes of compressor unit. It also impairs heat absorbing & radiating nature and compressibility of refrigerant mixture causing decreased $COP_{ref.}$.

Fair maintenance of designed optimal ratio (54:1 to 76:1) was the investigation objective of present research endeavour to develop a better ever refrigerant mixture. The experimental thermodynamic behaviour of the refrigerant solution was presented in table.4.

Table.4: Thermodynamic behaviour of the refrigerant solution

T [K]	P [k Pa]	Thermal Conductivity [W/(m*K)]	State
288.70	98.000	0.1642	Liquid
288.70	4900.000	0.1667	Liquid
288.70	9800.000	0.1684	Liquid
311.20	98.000	0.1543	Liquid
311.20	4900.000	0.1581	Liquid
311.20	9800.000	0.1599	Liquid
338.10	4900.000	0.1469	Liquid
338.10	9800.000	0.1512	Liquid
340.50		0.01345	Vapour
340.50		0.0135	Vapour
340.50		0.0145	Vapour
359.00	4900.000	0.1352	Liquid
359.00	9800.000	0.1424	Liquid
362.00		0.01565	Vapour
362.00		0.01582	Vapour
362.00		0.0165	Vapour
372.30		0.01721	Vapour
372.30		0.0174	Vapour
372.30		0.01742	Vapour
391.00	4900.000	0.1239	Liquid
391.00	9800.000	0.1291	Liquid
397.00		0.0198	Vapour
397.00		0.01981	Vapour
397.00		0.01985	Vapour
423.00	4900.000	0.1112	Liquid
423.00	9800.000	0.1158	Liquid
436.70		0.0236	Vapour
436.70		0.0237	Vapour
454.30		0.02478	Vapour
454.30		0.0248	Vapour

454.30		0.0260	Vapour
463.90	4900.000	0.0966	Liquid
463.90	9800.000	0.1032	Liquid
470.00		0.02718	Vapour
470.00		0.0272	Vapour
488.50	4900.000	0.0894	Liquid
488.50	9800.000	0.0959	Liquid
494.30	4900.000	0.0898	Critical Point
494.30	9800.000	0.0965	Liquid
498.00		0.0307	Vapour
498.00		0.03071	Vapour
498.30	4900.000	0.0903	Critical Point
498.30	9800.000	0.0969	Liquid
502.40	4900.000	0.0921	Critical Point
502.40	9800.000	0.0956	Liquid
504.00		0.03085	Vapour
504.00		0.0311	Vapour
504.00	4900.000	0.0997	Critical Point
506.80	4900.000	0.1202	Critical Point
508.50	4900.000	0.1956	Critical Point
508.50	9800.000	0.0959	Liquid
509.90	4900.000	0.0939	Critical Point
513.80	4900.000	0.0697	Critical Point
516.80	4900.000	0.0566	Critical Point
522.40	4900.000	0.0544	Critical Point
522.60		0.0337	Vapour
522.60		0.03375	Vapour
534.60		0.0340	Vapour
534.60		0.0346	Vapour
535.70	4900.000	0.0471	Critical Point
548.50		0.0356	Vapour
548.50		0.0357	Vapour
553.70	4900.000	0.0498	Critical Point
557.90		0.0368	Vapour
557.90		0.0371	Vapour
571.70		0.03835	Vapour
571.70		0.0384	Vapour
571.70		0.0385	Vapour
572.70	4900.000	0.0544	Critical Point

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B. Material Characterization

Choosing Acetone as primary constituent of refrigerant mixture was rationalized to its lowest contribution to global warming, considering various hydrocarbons.Table.5 represents the contribution of various possible hydrocarbon refrigerants to global warming.

Table.5: Global warming potential of various hydrocarbons

Organic compound/study	GWP^{CH4}	GWP^{O3}	GWP
Ethane (C2H8)	2.9	2.6	5.5
Propane (C3H8)	2.7	0.6	3.3
Butane (C4H10)	2.3	1.7	4.0
Ethylene (C2H4)	1.5	2.2	3.7
Propylene (C3H6)	-2.0	3.8	1.8
Toluene (C7H8)	0.2	2.5	2.7
Isoprene (C5H8)	1.1	1.6	2.7
Methanol (CH3OH)	1.6	1.2	2.8
Acetalhyde(CH3CHO)	- 0.4	1.7	1.3
Acetone(C_3H_6O)	0.3	0.2	0.5

The other inference of identifying Acetone as primary constituent was its fairly change of phase with respect to designed range of temperature and pressure and thermodynamic behaviour as a refrigerant. The figure.3 explains the pressure and temperature oriented phase change and table.6 represents the thermodynamic behavioural comparison of Acetone with other refrigerants in critical range of pressure and temperature.

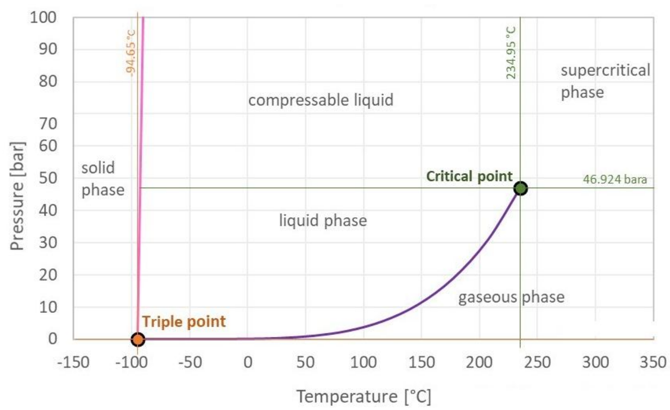

Figure.3 Phase change with temperature & pressure

Table.6: Thermodynamic behavioural comparison of Acetone with other refrigerants

Refrigerant	T_{boil}	P_{cond}	T_{crt}	P_{crt}	T_{max}	ODP	GWP	Type
Acetone	56	0.38	234.9	46	276	---	---	Wet
Ethanol	78	0.11	241.5	62.68	376	---	---	Wet
R11	23	1.26	197.9	44.07	351.8	1	4600	Isentrop ic
RE245fa2	28.89	1.04	171.7	34.33	226.8	0	825	Dry
R365mfc	39.82	0.69	186.8	32.66	226.8	0	825	Dry
R601a	27.4	1.09	187.2	33.78	226	0	˜20	Dry

The comparative thermodynamic behaviour investigated that Acetone inferred: high latent heat of vaporization, suction gas density, no excess pressure inside evaporator and condenser, chemically stable with water, non-corrosive, non-toxic and environment friendly. The flammability was moderated with adding water in designed ratio (54:1 to 76:1). Other favorable result was critical temperature and triple points were well beyond the designed range of working.

C. Process Development And Validation

The test rig was initially charged with R-134a as baseline refrigerant. Performance of R-134a was evaluated from the parametric conditions of compression, condensation, expansion and evaporation employing engineering equation solver software (EES) coupled with test rig [11]. Secondly the rig was retrofitted with presently developed acetone water solution refrigerant in optimal ratio 76:1 to record the software generated performance. The performances of both the refrigerant were compared considering R-134a as baseline refrigerant. Comparative results obtained were presented in Table.7.The parametric inputs were the working temperatures at superheating, sub cooling and compressor speed (Ta, T_{ff} & T_{fz}). Thus, for a given set of guessed values for P_e , P_c , h_1 and T_R , the compressor sub-model calculates h_2 , the condenser sub-model estimates h_3 and T_3=T(P_c,h_3), the internal heat exchanger sub-model calculates h_4 and T_1 , and the evaporator sub-model calculates h_5 and T_5 =T(P_e ,h_5).

Table.7: Comparative performances of R-134a and Acetone water mixture refrigerant.

Evaporator/ temperature set	Refrigerant	T_{fz} (0_C)	T_{ff}(0_C)	W_k(w)	P_e(bar)	P_c(bar)	COP
Original/Minimum	R-134a	-31.3	-12.5	93.3	0.6	10.9	1.06
	$C_3H_6O+H_2O$	-30.8	-11.4	92.7	0.4	10.1	1.0
Original/ standard	R-134a	-20	4.4	127.1	0.8	12.4	1.21
	$C_3H_6O+H_2O$	-19.6	4.0	126.8	0.7	11.9	1.18
EFA/Minimum	R-134a	-30	-11.6	92.8	0.5	10.8	1.04
	$C_3H_6O+H_2O$	-29.8	-10.9	92.3	0.5	10.6	1.02
EFA/standard	R-134a	-19.1	3.6	123.0	0.8	12.2	1.17
	$C_3H_6O+H_2O$	-18.9	3.4	122.8	0.7	11.9	1.08

IV. CONCLUSION

The present investigation validated a nuance in COP between R-134a and Acetone water mixture. The proximal COP of Acetone water mixture to prevailing used refrigerant R-134a was addressed to unwieldy process development in designing the ratio of mixing Acetone with water (54:1 to 76:1). The economical viability of using Acetone as primary constituent of presently developed refrigerant mixture was addressed to its lowest unit price than halogenated refrigerants. The GWP, ODP and flammability of the developed refrigerant was also moderated by designed ratio of mixing with water (54:1 to 76:1).More over the designed refrigerant was echo friendly, stable chemically & thermally, non toxic and non corrosive in nature.

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