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RESEARCH ARTICLE

PERFORMANCE EVALUATION OF CONVENTIONAL DOMESTIC REFRIGERATOR RETROFITTED WITH WATER COOLED CONDENSER

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ABSTRACT

Basically domestic refrigerator uses two heat exchangers in the form of evaporator and condenser. Evaporator gives refrigeration affect and take heat on the other hand, condenser relies that heat and work as heat pump. This heat is realized by water cooled condenser to increase the coefficient of performance (COP) besides providing warm water. In this paper performance COP, refrigeration capacity (TR), condensation effect and compressor work done of domestic refrigerator is studied through an experimental set up where air cooled condenser is replaced by water cooled condenser.

INTRODUCTION

A vapour compression cycle is used in most household refrigerators. In the experiment air cooling coil (condenser coil) of domestic refrigerator situated at the back side of the refrigerator is retrofitted with water cooled condenser by positioning on top of the refrigerator to utilize the low grade energy of refrigerant given out to the water for domestic usage but the temperature of water will be limited. The design of condenser is of open tray type in which a net of the cooling coil with equidistant extra fins is fitted. In the tray water is filled for cooling the refrigerant flowing through the condenser tube. Refrigerant gives out its latent heat and change its phase from vapor to liquid by giving out heat for water.

LITERATURE REVIEW

Vapour compression refrigeration system

In this cycle, a circulating refrigerant such as R134a enters a compressor as low pressure vapour at or slightly above the temperature of the refrigerator interior. The vapour is compressed and exits the compressor as high pressure superheated vapour. The superheated vapour travels under pressure through coils or tubes comprising the condenser, which are passively cooled by exposure to air in the room in air cooled condenser or water in water cooled condenser. The condenser cools the vapour to liquefy. As the refrigerant leaves the condenser, it is still under pressure but is now only slightly above room temperature. This liquid refrigerant is forced through a throttling device to an area of much lower pressure. The sudden decrease in pressure results in explosive-like flash evaporation of about half of the liquid. The latent heat absorbed by this flash evaporation is drawn mostly from adjacent still-liquid refrigerant, a phenomenon known as auto-refrigeration. This cold and partially vaporized refrigerant continues through the coils or tubes of the evaporator unit. Refrigerant leaves the evaporator, now fully vaporized and slightly heated, and returns to the compressor inlet to continue the cycle. The cycles considered so far are internally reversible and no change of refrigerant state takes place in the connecting pipelines. The figure 1 shows an actual vapour compression cycle compared with a basic cycle.

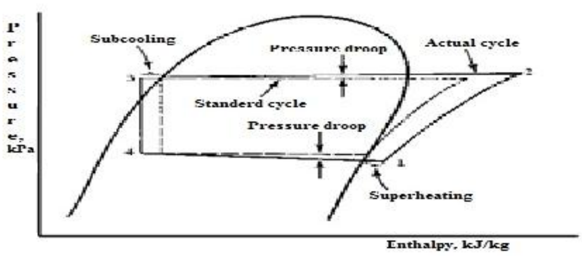

Figure 1 Actual vapor compression p-h diagram

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The COP of actual refrigeration systems is sometimes written in terms of the COP of Carnot refrigeration system operating between the condensing and evaporator temperatures (COP_{carnot}), cycle efficiency (η_{cycle}), isentropic efficiency of the compressor ($\eta_{isentropic}$) and efficiency of the electric motor (η_{motor}), as given by the equation shown below:

$$\mathbf{COP_{actual} = \eta_{cycle}\ \eta_{isentropic}\ \eta_{motor}\ COP_{carnot}}$$

Refrigerants

A refrigerant is a medium of heat transfer through phase change such as evaporation at low temperature and pressure, of course with some exceptions where the sensible energy occurs. The refrigerant used for performance analysis is R-134a i.e. Tetrafluoroethane (CF3CH2F). If system components are not changed 10% less R134a charge are needed in comparison to R12. When exposed to the environment the boiling temperature of R-134a is -26.1°C. R134a can escape through minor leaks than R12. Therefore higher standards in soldering operations, in sealing the circuit and in leak detection are needed.

Fabrication Of Experimental Set Up

An experimental set up of domestic refrigerator is fabricated using primary & secondary components along with measuring instruments such as pressure gauge, temperature gauge, rota-meter, ammeter, watt meter and voltmeter. Before physical measurement of space to be cooled is determined to find out the capacity of domestic refrigerator body under analysis the detail study of components is done as explained under:

Primary Components

Compressor

The compressor is the "heart" of the refrigeration system. It pumps heat through the system in the form of heat-laden refrigerant vapour. A compressor can be considered as a vapour pump. The displacement and dynamic compressors are commonly used for refrigeration. In order to lubricate the moving parts of the compressor, oil is added to the refrigerant during installation or commissioning. The type of oil may be mineral or synthetic to suit the compressor type, and also chosen so as not to react with the refrigerant type and other components in the system. There are many types of compressor in refrigeraton industries, the one used in this analysis is of LG company compressor model: **MA53LJJG. Specification:** Application for R134a, type: hermetically sealed compressor, electrical circuit: CSIR, 220V, 5Hz, single phase, power 1/6 h.p. The copper tube for suction and discharge line used for compressor is ¼".

Condenser

The superheated refrigerant vapour enters the condenser to dissipate its heat. There are several methods of dissipating the rejected heat into the atmosphere by condenser. These are water cooled, air cooled or evaporative condensers. In the water cooled condenser there are several types viz. shell and tube, shell and coil, tube in tube etc.

The condenser used in the analysis is shell and tube type water cooled condenser and positioned on top of the body of refrigerator. The condenser is situated on top of the refrigerator in a shell of stainless steel (590 mm*540 mm*200 mm), total capacity = 63.00 liter (55 liter working), tube = 2 rows, 10 tube in each row, 510 mm long each tubes, total length of tube = 10.20 metre long, ¼ inch diameter.

Filter drier

Filter drier is highly capable of keeping the system to low level of dryness. The excellent quality of desiccants used which have the best properties to remove moisture, acid and foreign contaminants. The main job of the drier is to protect the metering device from clogging either by ice (moisture) or blockage by particles. In the present analysis adsorbent type filter drier (Working pressure = 500 psi or 34.01bar) is used which will attract moisture, on to the total surface area of the desiccant. Specific desiccant that are widely used in a refrigeration systems filter drier are silica gel (adsorbent), molecular sieve (adsorbent), lithium chloride (adsorbent) and lithium bromide (adsorbent).

Expansion device

The high-pressure liquid from the condenser is fed to evaporator through expansion device to pass maximum possible liquid refrigerant. The throttling device is a pressure-reducing device and a regulator for controlling the refrigerant flow. Capillary tube is one of the expansion devices is a long, narrow tube of constant diameter. Typical tube diameters of refrigerant capillary tube range from 0.5 mm to 3 mm and the length ranges from 1.0 m to 6 m. The pressure reduction in a capillary tube occurs due to the frictional resistance offered by tube walls to the refrigerants.

Figure 2 Components of experimental setup

Table 1 Performance observation table of refrigerator while using air cooled condenser

1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.
Time (Min)	$P_{Absolute}$ (P_1), bar	$T_{Sat.}$ T_{s1} ^OC	$P_{Absolute}$ (P_2)bar	T_{Sat} Ts_2 ^OC	$T_{Eva.}$ t_1 ^OC	$T_{Cond.}$ t_2 ^OC	$T_{Cond.}$ t_3 ^OC	$T_{Eva.}$ t_4 ^OC	Enthalpy (kJ/kg) h_1	Enthalpy (kJ/kg) h_2	Enthalpy (kJ/kg) h_3
000	5.44	18.41	05.44	18.41	31.9	32.7	32.6	29.4	421.12	421.92	421.82
010	1.22	-21.99	17.55	61.82	28.6	81.6	52.1	08.0	427.06	452.93	411.04
020	1.29	-20.71	17.55	61.82	24.1	81.1	53.1	04.6	422.94	452.30	412.79
030	1.16	-23.13	17.41	61.48	23.0	83.9	55.7	01.9	422.25	456.05	417.62
040	1.16	-23.13	17.28	61.16	22.1	86.1	56.7	-0.2	421.47	458.98	419.64
050	1.02	-26.00	16.67	59.64	21.8	84.9	54.5	-1.9	421.51	458.53	418.28
060	1.02	-26.00	16.46	59.10	21.8	84.9	54.9	-3.1	421.51	458.87	419.58
070	1.02	-26.00	16.39	58.93	21.2	85.5	55.3	-3.7	420.99	459.71	420.39
080	0.88	-29.00	15.78	57.34	21.1	83.2	53.3	-4.8	421.20	457.94	419.38
090	0.88	-29.00	15.65	57.00	18.2	83.2	53.5	-5.2	418.70	458.16	420.07
100	0.88	-29.00	15.65	57.00	17.4	82.4	52.9	-5.6	418.01	457.20	419.20
110	0.82	-30.69	15.24	55.90	15.6	81.0	52.3	-6.6	416.60	456.21	419.62
120	0.75	-32.56	15.03	55.32	15.0	79.1	51.5	-7.2	416.26	454.30	419.13
130	0.75	-32.56	15.03	55.32	09.2	79.2	52.5	-7.1	411.34	454.41	420.53
140	0.75	-32.56	14.83	54.78	09.1	78.8	51.7	-8.0	411.26	454.28	420.01
150	0.75	-32.56	14.83	54.78	08.9	78.7	52.0	-8.1	411.09	454.16	420.43
160	0.75	-32.56	14.90	54.97	07.8	79.1	52.2	-8.8	410.16	454.52	420.50
170	0.68	-34.56	14.90	54.97	06.9	78.5	51.8	-8.7	409.58	453.80	419.94
180	0.68	-34.56	14.49	53.83	06.6	75.0	49.6	-8.9	409.33	450.35	418.12
190	0.68	-34.56	13.74	51.68	05.8	75.7	49.2	-9.0	408.67	452.90	419.82
200	0.68	-34.56	13.74	51.68	04.8	76.1	49.0	-9.2	407.83	452.95	419.55
210	0.68	-34.56	13.81	51.88	03.3	77.1	49.2	-9.2	406.58	454.00	419.61
220	0.68	-34.56	13.81	51.88	01.5	76.7	49.1	-9.7	405.09	453.54	419.48
230	0.68	-34.56	13.95	52.29	01.0	77.0	48.9	-9.9	404.68	453.65	418.79
240	0.68	-34.56	13.95	52.29	-1.4	76.2	49.0	-9.9	402.70	452.71	418.93
250	0.68	-34.56	13.95	52.29	-2.9	76.8	48.9	-9.9	401.47	453.42	418.79
260	0.68	-34.56	13.95	52.29	-4.1	76.8	48.8	-9.9	400.48	453.42	418.66
270	0.68	-34.56	13.95	52.29	-3.1	76.9	49.0	-9.4	401.30	453.53	418.93
280	0.68	-34.56	13.95	52.29	-3.1	76.3	48.9	-9.8	401.30	452.83	418.79
290	0.68	-34.56	13.95	52.29	-3.9	75.9	48.3	-9.8	400.65	453.53	417.98
300	0.68	-34.56	13.95	52.29	-4.0	76.1	48.4	-9.9	400.57	452.60	418.11

R.E. = Refrigeration Effect (h_4- h_1) in kJ/kg, C.E. = Condensation Effect (h_2- h_3) in kJ/kg, W_{in} =(h_2- h_1) in kJ/kg, P_{in} = Electricity consumption by compressor in kW, Theoretical COP = R.E. in (kJ/kg) / W_{in} in (kJ/kg), Actual COP = R.E. in kW / P_{in} in kW, Relative COP = Actual COP / Theoretical COP, R.C. = Refrigeration Capacity in (TR) that is (R.E. in kW / 3.5 kW).

13.	14.	15.	16.	17.	18.	19.	20.	21.	22.	23.
Enthalpy (kJ/kg) h_4	R.E. (kJ/kg)	R.E. kW	C.E. (kJ/kg)	W_{in} (kJ/kg)	P_{in} (kWh)	P_{in} (kW)	Theoretical COP	Actual COP	Relative COP	R.C. in (TR)
418.61	00.00	0.000	0.000	00.00	0.000	0.000	0.00	0.00	0.00	0.000
409.14	17.92	0.299	41.89	25.87	0.025	0.150	0.69	1.99	2.88	0.085
406.05	16.89	0.281	39.51	29.36	0.060	0.180	0.58	1.56	2.69	0.080
404.12	18.13	0.302	38.43	33.80	0.085	0.170	0.54	1.78	3.30	0.086
402.34	19.13	0.319	39.34	37.51	0.115	0.173	0.51	1.84	3.61	0.091
401.32	20.19	0.337	40.70	37.02	0.140	0.168	0.55	2.01	3.65	0.096
400.32	21.19	0.353	39.29	37.36	0.170	0.170	0.57	2.08	3.65	0.101
399.82	21.17	0.353	39.32	38.72	0.205	0.176	0.55	2.01	3.65	0.101
399.32	21.88	0.365	38.56	36.74	0.230	0.173	0.60	2.11	3.52	0.104
398.99	19.71	0.329	38.09	39.46	0.250	0.167	0.50	1.97	3.94	0.094
398.66	19.35	0.323	38.00	39.19	0.280	0.168	0.49	1.92	3.92	0.092
398.02	18.58	0.310	36.59	39.61	0.300	0.164	0.47	1.89	4.02	0.089
397.74	18.52	0.309	35.17	38.04	0.325	0.163	0.49	1.90	3.88	0.088
397.82	13.52	0.225	33.88	43.07	0.355	0.164	0.31	1.37	4.42	0.064
397.09	14.17	0.236	34.27	43.02	0.380	0.163	0.33	1.45	4.39	0.067
397.01	14.08	0.235	33.73	43.07	0.400	0.160	0.33	1.47	4.45	0.067
396.44	13.72	0.227	34.02	44.36	0.430	0.161	0.31	1.41	4.55	0.065
396.74	12.84	0.214	33.86	44.22	0.450	0.159	0.29	1.35	4.66	0.061
396.57	12.76	0.213	32.23	41.02	0.475	0.158	0.31	1.35	4.35	0.060
396.49	12.18	0.203	33.08	44.23	0.510	0.161	0.28	1.26	4.50	0.058
396.33	11.50	0.192	33.40	45.12	0.535	0.161	0.25	1.19	4.76	0.055
396.33	10.25	0.171	34.39	47.42	0.565	0.161	0.22	1.06	4.82	0.049
395.92	09.17	0.153	34.06	48.45	0.605	0.165	0.19	0.93	4.89	0.044
395.76	08.92	0.149	34.86	48.97	0.645	0.168	0.18	0.89	4.94	0.043
395.76	06.94	0.116	33.78	50.01	0.665	0.166	0.14	0.70	5.00	0.033
395.76	05.71	0.095	34.76	51.95	0.700	0.168	0.11	0.57	5.18	0.027
395.76	04.72	0.079	34.76	52.94	0.725	0.167	0.09	0.47	5.22	0.023
396.17	05.13	0.086	34.60	52.23	0.755	0.168	0.10	0.51	5.10	0.025
395.84	05.46	0.091	34.04	51.53	0.785	0.168	0.11	0.54	4.91	0.026
395.84	04.81	0.080	35.55	52.88	0.805	0.167	0.09	0.48	5.33	0.023
395.76	04.81	0.080	34.49	52.03	0.825	0.165	0.09	0.48	5.33	0.023

Table 2 Performance observation table of refrigerator while using water cooled condenser

1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.
Time (Min)	$P_{Absolute}$ (P_1), bar	$T_{Sat.}$ T_{s1} ^OC	$P_{Absolute}$ (P_2)bar	T_{Sat} T_{s2} ^OC	$T_{Eva.}$ t_1 ^OC	$T_{Cond.}$ t_2 ^OC	$T_{Cond.}$ t_3 ^OC	$T_{Eva.}$ t_4 ^OC	Enthalpy (kJ/kg) h_1	Enthalpy (kJ/kg) h_2	Enthalpy (kJ/kg) h_3
000	03.88	08.03	3.88	08.03	35.8	35.8	35.1	20.1	428.32	428.32	427.65
010	0.373	-46.07	7.14	27.39	30.3	61.5	28.8	-24.0	430.20	447.90	413.68
020	0.373	-46.07	7.14	27.39	30.4	61.9	28.6	-24.0	430.29	448.39	413.46
030	0.373	-46.07	7.14	27.39	30.5	62.2	28.5	-24.0	430.37	448.70	413.36
040	0.373	-46.07	7.14	27.39	30.5	62.8	28.5	-24.0	430.37	449.32	413.36
050	0.373	-46.07	7.14	27.39	30.5	63.0	28.4	-25.0	430.37	449.53	413.25
060	0.373	-46.07	7.14	27.39	30.5	63.0	28.4	-24.0	430.37	449.53	413.25
070	0.339	-47.79	7.14	27.39	30.5	63.1	28.3	-25.0	430.44	449.63	413.14
080	0.339	-47.79	7.14	27.39	30.5	63.1	28.3	-25.0	430.44	449.63	413.14
090	0.339	-47.79	7.14	27.39	30.5	63.5	28.3	-25.0	430.44	450.05	413.14
100	0.339	-47.79	7.14	27.39	30.4	63.6	28.2	-25.0	430.35	450.15	413.03
110	0.339	-47.79	7.14	27.39	29.3	63.5	28.2	-26.0	429.40	450.05	413.03
120	0.339	-47.79	7.07	27.06	29.8	63.6	28.0	-26.0	429.83	450.26	413.01
130	0.339	-47.79	7.07	27.06	30.0	63.6	28.0	-27.0	430.00	450.26	413.01
140	0.339	-47.79	7.07	27.06	29.9	63.5	28.0	-27.0	429.92	450.16	413.01
150	0.339	-47.79	7.07	27.06	29.8	63.9	27.9	-27.0	429.83	450.67	412.90
160	0.339	-47.79	7.00	26.72	29.5	63.8	27.9	-26.0	429.57	450.58	413.09
170	0.339	-47.79	7.00	26.72	29.2	63.5	27.9	-27.0	429.31	450.27	413.09
180	0.339	-47.79	7.00	26.72	29.3	63.5	28.0	-27.0	429.40	450.27	413.20
190	0.339	-47.79	7.00	26.72	29.3	64.3	28.0	-27.0	429.40	451.10	413.20
200	0.339	-47.79	7.00	26.72	29.2	64.0	28.1	-27.0	429.31	450.79	413.30
210	0.339	-47.79	7.00	26.72	29.2	64.2	27.9	-27.0	429.31	450.99	413.09
220	0.339	-47.79	7.00	26.72	29.1	64.4	28.3	-28.0	429.22	451.20	413.52
230	0.339	-47.79	7.00	26.72	29.0	64.9	28.1	-28.0	429.14	451.72	413.30
240	0.339	-47.79	7.00	26.72	28.9	65.5	26.7	-28.0	429.05	452.34	411.80
250	0.339	-47.79	7.00	26.72	28.8	65.4	27.8	-28.0	428.96	452.23	412.98
260	0.339	-47.79	7.00	26.72	28.7	65.7	28.5	-28.0	428.88	452.54	413.73
270	0.339	-47.79	7.00	26.72	28.6	65.3	28.3	-29.0	428.79	452.13	413.52
280	0.339	-47.79	7.00	26.72	28.5	65.7	28.3	-29.0	428.70	452.54	413.52
290	0.339	-47.79	7.00	26.72	28.4	66.1	28.2	-29.0	428.62	451.92	413.41
300	0.339	-47.79	7.00	26.72	28.4	66.5	28.7	-29.0	428.62	453.37	413.95

R.E. = Refrigeration Effect (h_4- h_1) in kJ/kg, C.E. = Condensation Effect (h_2- h_3) in kJ/kg, W_{in} = (h_2- h_1) in kJ/kg, P_{in} = Electricity consumption by compressor in kW, Theoretical COP = R.E. in (kJ/kg) / W_{in} in (kJ/kg), Actual COP = R.E. in kW / P_{in} in kW, Relative COP = Actual COP / Theoretical COP, R.C. = Refrigeration Capacity in (TR) that is (R.E. in kW / 3.5 kW).

13.	14.	15.	16.	17.	18.	19.	20.	21.	22.	23.
Enthalpy (kJ/kg) h_4	R.E. (kJ/kg)	R.E. kW	C.E. (kJ/kg)	W_{in} (kJ/kg)	P_{in} (kWh)	P_{in} (kW)	Theoretical COP	Actual COP	Relative COP	R.C. in (TR)
413.33	00.00	0.000	00.00	00.00	0.000	0.000	0.00	0.00	0.00	0.000
385.65	44.55	0.743	34.22	17.70	0.015	0.090	2.52	8.26	3.28	0.212
385.65	44.64	0.744	34.93	18.10	0.025	0.075	2.47	9.92	4.02	0.213
385.65	44.72	0.745	35.34	18.33	0.040	0.080	2.44	9.31	3.82	0.213
385.65	44.72	0.745	35.96	18.95	0.060	0.090	2.36	8.28	3.51	0.213
384.88	45.49	0.758	36.28	19.16	0.075	0.090	2.37	8.42	3.55	0.217
385.65	44.72	0.745	36.28	19.16	0.090	0.090	2.33	8.28	3.55	0.213
385.01	45.43	0.757	36.49	19.19	0.100	0.086	2.39	8.80	3.68	0.216
385.01	45.43	0.757	36.49	19.19	0.115	0.086	2.37	8.80	3.71	0.216
385.01	45.43	0.757	36.91	19.61	0.130	0.087	2.32	8.70	3.75	0.216
385.01	45.34	0.756	37.12	19.80	0.145	0.087	2.29	8.69	3.79	0.216
384.24	45.16	0.753	37.02	20.65	0.160	0.087	2.19	8.66	3.95	0.216
384.24	45.59	0.760	37.25	20.43	0.170	0.085	2.23	8.94	4.01	0.217
383.47	46.53	0.776	37.25	20.26	0.180	0.083	2.30	9.35	4.07	0.222
383.47	46.45	0.774	37.15	20.24	0.195	0.084	2.29	9.21	4.02	0.221
383.47	46.36	0.773	37.77	20.84	0.210	0.084	2.22	9.20	4.14	0.221
384.24	45.33	0.756	37.49	21.09	0.220	0.083	2.16	9.11	4.22	0.216
383.47	45.84	0.764	37.18	20.96	0.235	0.083	2.19	9.20	4.20	0.218
383.47	45.93	0.766	37.07	20.87	0.250	0.083	2.20	9.23	4.20	0.219
383.47	45.93	0.766	37.90	21.70	0.260	0.082	2.12	9.34	4.41	0.219
383.47	45.84	0.764	37.49	21.48	0.270	0.081	2.13	9.43	4.43	0.218
383.47	45.84	0.764	37.90	21.68	0.285	0.081	2.11	9.43	4.47	0.218
382.74	46.48	0.775	37.68	21.98	0.300	0.082	2.11	9.33	4.42	0.221
382.74	46.36	0.773	38.42	22.58	0.315	0.082	2.05	9.30	4.54	0.221
382.74	46.27	0.771	40.54	23.20	0.335	0.084	1.99	9.18	4.61	0.220
382.74	46.22	0.770	39.25	23.27	0.345	0.083	1.99	9.28	4.66	0.220
382.74	46.14	0.770	38.81	23.66	0.355	0.082	1.95	9.39	4.82	0.220
387.95	41.65	0.694	38.61	23.34	0.365	0.081	1.78	8.57	4.81	0.198
387.95	40.75	0.679	39.02	23.84	0.380	0.081	1.71	8.38	4.90	0.194
387.95	40.67	0.678	48.91	23.30	0.395	0.082	1.75	8.27	4.73	0.194
387.95	40.67	0.678	39.42	24.75	0.405	0.081	1.64	8.37	5.10	0.194

This leads to some pressure drop, and the liquid refrigerant flashes (evaporates) into mixture of liquid and vapour as its pressure reduces. The density of vapour is less than that of the liquid. Hence, the average density of refrigerant decreases as it flows in the tube. The mass flow rate and tube diameter (hence the area) being constant, the velocity of refrigerant increases since $m = \rho VA$. The increase in velocity or acceleration of the refrigerant also requires pressure drop. Several combinations of length and bore are available for the same mass flow rate and pressure drop. Once a capillary tube of some diameter and length has been installed in a refrigeration system, the mass flow rate through it will vary in such a manner that the total pressure drop through it matches with the pressure difference between condenser and the evaporator. Its mass flow rate is totally dependent upon the pressure difference across it; it cannot adjust itself to variation of load effectively. The 31 gauge capillary tube used as an expansion device has 1.5 mm diameter and length 3.6 metre.

RESULT AND DISCUSSION

With certain assumption keeping environmental consideration i.e. average $S_{urrounding}$, average humidity φ, constant air flow etc fixed and for unit mass flow of refrigerant the observations noted for water cooled condenser replacing existing air cooled condenser (shape, size, length of coil and diameter; etc remains same instead additionally water as medium and fins on condenser coils for water cooled condenser) are depicted below:

A. It is observed that in the case of water cooled condenser, there are drop in condenser pressure as well as evaporator pressure relative to air cooled condenser.
B. In case of water cooled condenser, power consumption of compressor decreases relative to the air cooled condenser.
C. We have seen that the temperature of refrigerant after giving out its latent heat to condenser is very high and further increases with time and because of this condenser pressure also increases in case of air cooled condenser whereas in case of water cooled condenser there are no such trend of increase in refrigerant temperature and thus condenser pressure remain same until change in condenser temperature or change in flow of refrigerant.
D. The analysis reveals that sub-cooling is effective in case of air cooled condenser but in case of water cooled condenser sub-cooling is not possible.
E. In case of air cooled condenser sub-cooling of refrigerant is possible because of saturation temperature at corresponding condenser pressure is much higher than saturation temperature at corresponding atmospheric pressure of air i.e.
F. $\Delta T_{aircooled\ condenser} = T_{sat\ at\ cond\ press} - T_{sat.\ at\ atm.\ press}$, whereas in case of water cooled condenser is not possible because $\Delta T_{watercooled\ condenser} \ll \Delta T_{aircooled\ condenser}$ as state of condensate is saturated liquid and the same passes through expansion device.
G. Temperature of water in submerged water cooled condenser tray will remain same so long free convection is possible as tray is uncovered but for hot water usage tray needs to be covered then in that case temperature of water will moderately increase.
H. It is observed that refrigeration effect in case of water cooled condenser is quite higher in comparison to air cooled condenser.

The observations enable a strong basis to give out reasons and possible causes for a comparative study and analysis of water cooled condenser over air cooled condenser in a domestic refrigerator are given below:

Condenser pressure and temperature

In air cooled condenser, condenser side pressure measured is 16.46 bar with corresponding saturation temperature is $59.1^{O}C$. This condenser pressure will be same from compressor outlet to the capillary inlet under assumption that there is no pressure loss in high pressure side. The temperature of high pressure side of compressor outlet and condenser discharge is $84.9^{O}C$ and $54.9^{O}C$ respectively. The high compressor discharge temperature will produce large quantity of high specific volume superheated refrigerant causing high vapour pressure. On the other hand the difference of actual condenser discharge temperature and condenser saturation temperature i.e. $4.2^{O}C$ ($59.1 - 54.9 = 4.2^{O}C$) will be the degree of sub-cooling so this liquid refrigerant will have low specific volume causing low liquid pressure.

The saturated liquid refrigerant after condensing gets collected in the remaining part of condenser coil and travels through capillary tube without any extraction of heat through this travel period. Because of this collection of liquid refrigerant, the condenser side pressure decreases to 7.14 bar with corresponding saturation temperature $27.39^{O}C$. This is because of Dalton's law of partial pressure. The compressor discharge temperature and condenser discharge temperature noted are $63^{O}C$ and $28.4^{O}C$ respectively. The compressor discharge temperature of the refrigerant in water cooled condenser set up is lower than the compressor discharge temperature in the air cooled condenser set up at different condenser pressures but due to higher degree of superheat i.e. $34.6^{O}C$, the refrigerant will have low mass flow rate in water-cooled condenser set up.
The figure 3 shows the variation of evaporation pressure (p1) and condenser pressure (compressor discharge pressure, p_2) / compressor discharge temperature (p_2) with run time of experimental set up. While water cooled condenser is used the exit pressure of compressor remains constant whereas while air cooled condenser is used the exit pressure of compressor initially droops down drastically and remains almost constant for remaining period. The reason is varying temperature of circulating air with time in air cooled condenser so the amount of condensed liquid and vapour refrigerant changes causing variation of condenser pressure while in water cooled condenser temperature of cooling medium i.e. water is hardly changing means invariant with time because of large water storage having natural evaporation so negligible change in condenser pressure occur.

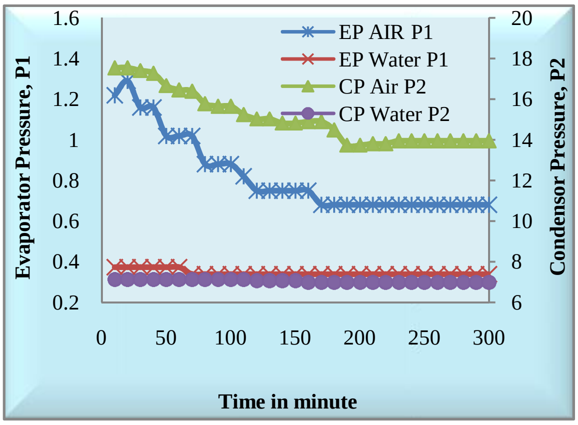

Figure 3 Variation of Evaporator pressure (p1)/ Condenser pressure (p2) while using Air/ Water cooled condenser v/s Time

Similarly, while water cooled condenser is used the exit temperature of compressor gradually increases with time but while air cooled condenser is used the exit temperature of compressor initially increases and then drops. The reason for this is that in case of water cooled condenser large quantity of liquid refrigerant stored in the condenser coil resulting the drop in condenser pressure so causing corresponding low compressor discharge temperature in contrary to air cooled condenser where compressor works against high pressure resulting high compressor discharge temperature.

The figure 4shows that the variation of condenser discharge temperature (t_3) in air cooled condenser and water cooled condenser of a domestic refrigerator. The exit temperature of condenser remains constant throughout the period of tests while water cooled condenser used but while air cooled condenser is used the exit temperature of condenser initially fluctuates up and down. The reason is that because of fluctuation in circulating air temperature of air cooled condenser condensate temperature also accordingly fluctuates.

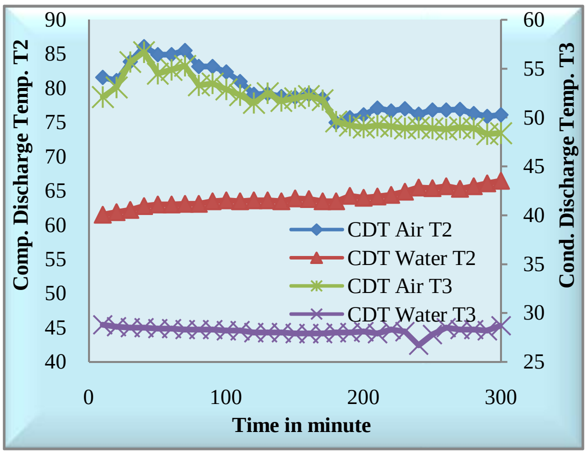

Figure 4 Variation of Compressor discharge temperature (t2)/ Condenser discharge temperature (t3) while using Air/ Water cooled condenser v/s Time.

Evaporator pressure and temperature

Figure 5 and 6 show the comparison of p-h diagram and T-s diagram of air/ water cooled condenser. In case of air cooled condenser, compressor has to work more to maintain high pressure in condenser coils so there is low flow rate of vapour refrigerant through the compressor. Refrigerant after condensing will expand through capillary tube and some of them vaporise after expansion. Now there maintain a positive evaporator pressure as evaporator pressure is some of partial pressure of liquid refrigerant and partial pressure of vapour refrigerant. As in case of air cooled condenser, condenser discharge temperature is very high (about 52.1^{O}C) so that after expansion about 8.0^{O}C in primary condition and fall down to -10^{O}C after 300 minutes.

In case of water cooled condenser when saturated liquid refrigerant pass through the capillary tube it expends and vaporises some of the liquid refrigerant. In this case condenser discharge temperature is very low and so that refrigerant expends through capillary tube to very low temperature about -24^{O}C and reaches to -29^{O}C after 300 minutes of run. In this case because large amount of liquid refrigerant is stored in condenser and overall volume of refrigerator circuit is constant so when remaining refrigerant circulate through the evaporator there are drop in evaporator pressure and condenser pressure, but there is no change in compressor volume flow rate but only drop in compressor work. In the case of water cooled condenser there is large temperature difference with cooling medium, compared to air cooled condenser (about 32^{O}C to 19^{O}C after 300 minutes run, more in case of water cooled condenser). Because of this extra temperature deference refrigerant extract more heat from evaporator (more than 2.5 times extra).

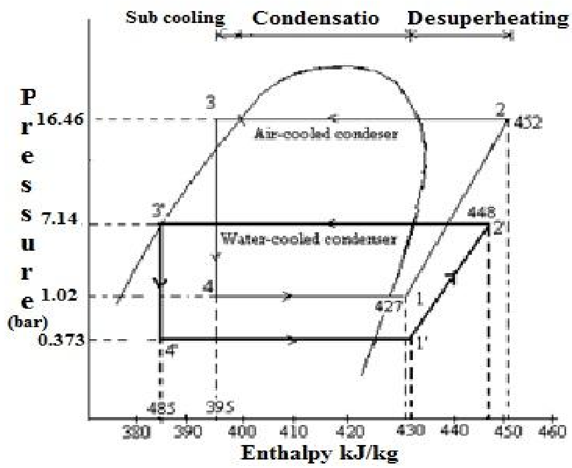

Figure 5 Comparison of p-h diagram of Air/ Water cooled condenser

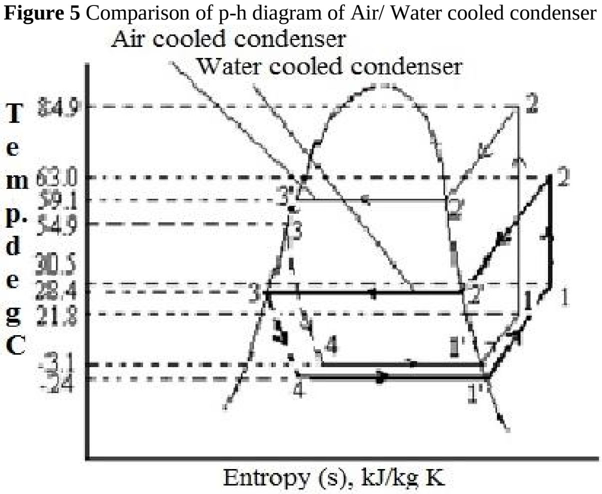

Figure 6 Comparison of T-s diagram of Air/Water cooled condenser

In this case refrigerant leaving the evaporator is superheated to $30^{O}C$ because of low condenser pressure i.e. 7.14 bar and it is seen low condenser pressure is helpful for good refrigeration effect as at low evaporator pressure latent heat of vaporisation is greater and decreasing with increase in pressure.

The figure 7shows the variation of capillary discharge temperature (t_4). It is seen that while water cooled condenser is used the exit temperature of capillary tube slowly decreases with time but remain same after 260 minutes run while in case of air cooled condenser the exit temperature of capillary tube gradually decrease to 190 minutes run and then remain unchanged for remaining period of times. The reason is that in case of air cooled condenser because of high condenser pressure and high discharge temperature relative to water cooled condenser after expansion through capillary tube temperature drops more in case of water cooled condenser.

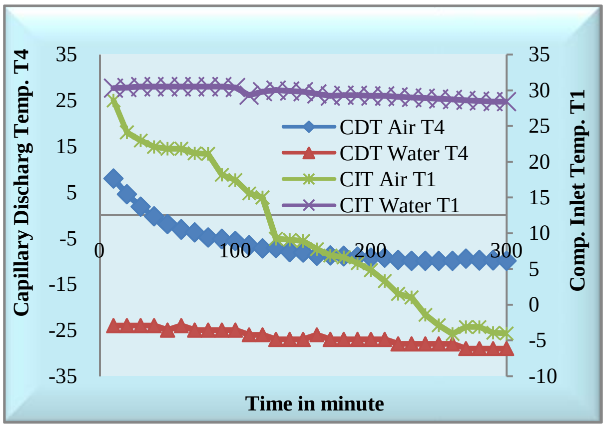

Figure7 Variation of Capillary discharge temperature (t4)/ Compressor inlet temperature (t1) while using Air/ Water cooled condenser v/s Time

The figure 7 also shows the variation of condenser discharge temperature (t_1). The trend shown in the figure and the reason is because of high evaporator pressure there is low temperature difference in evaporator surrounding and refrigerant in case of air cooled condenser compared to water cooled condenser so that there are large drop of evaporator outlet temperature as rate of heat transfer decreases in air cooled condenser but while water cooled condenser used because of more temperature difference more heat transfer and outlet temperature remains high and unchanged.

Compressor work and power consumption

The p-v diagram for a reciprocating compressor is shown in figure 8.

The stroke or swept volume or piston displacement is, V_p = (V_1-V_3) = $\frac{\pi D^2}{4}$ L, where D is the bore or diameter and L is the stroke.

The work done for compression for the cycle is given by the cycle integral of pdV. Hence

$$W = \oint pdV = \int_1^2 pdV + \int_2^3 pdV + \int_3^4 pdV + \int_4^1 pdV$$
$$= \int_1^2 pdV + p_2 (V_3-V_2) + \int_3^4 pdV + p_1 (V_1-V_4)$$
$$= \text{area 1-2-3-4}$$

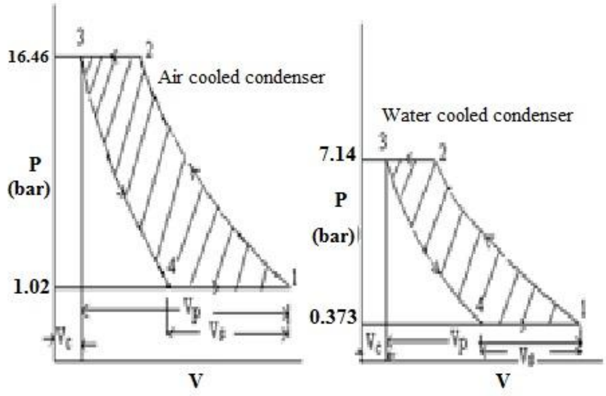

Figure 8 Work done in Air/ Water cooled condenser on p-v diagram.

It is seen that this area is also expressed by the term $-\oint Vdp$. Hence, $W = \oint_1^2 pdV = -\oint_1^2 Vdp = m\oint_1^2 pdv = -m\oint_1^2 vdp$, where m is the mass of the suction vapour. Thus, the specific work in a reciprocating compressor is given by $W = \oint_1^2 pdv = -\oint_1^1 vdp$

In both cases that is air cooled condenser as well as in water cooled condenser power consumptions are increasing with time but it is revealed that in air cooled compressor work consumption is always more than water cooled condenser because work transfer is a function of specific heat and outlet-inlet temperature difference of compressor that is always less in case of water cooled condenser. In case of air cooled condenser, compressor works against high pressure and temperature compared to water cooled condenser so that compressor work is high in case of air cooled condenser. Here in this analysis the compressor power consumption is calculated with the help of watt meter and work done by enthalpy difference (h_2-h_1) in kJ/kg. Compressor work done = $C_p\Delta t$ The figure 9 shows the variations of compressor work in air cooled condenser and water cooled condenser of a domestic refrigerator. It is seen that while water cooled condenser is used the compressor work linearly increases with time but while air cooled condenser is used the compressor work increases in fluctuating manner at same atmospheric conditions for remaining period of times. In this whole period of time compressor work is always high (about 80% extra) while using air cooled condenser. The reason for this is because drop in evaporator discharge temperature there are increase in temperature difference of compressor outlet and inlet, which is greater in case of air cooled condenser compare to water cooled condenser and so that increasing in power consumption.

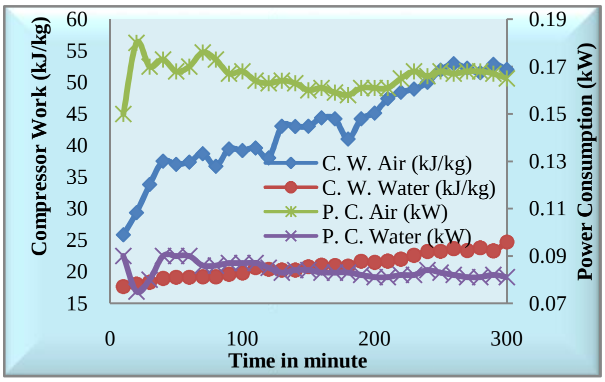

Figure 9 Variation of Compressor work (kJ/kg) and Power consumption (kW) while using Air/ Water cooled condenser v/s Time.

The figure 9 also shows that while water cooled condenser is used the compressor power consumption is small while in case of air cooled condenser this compressor power consumption is higher for same period of time interval.

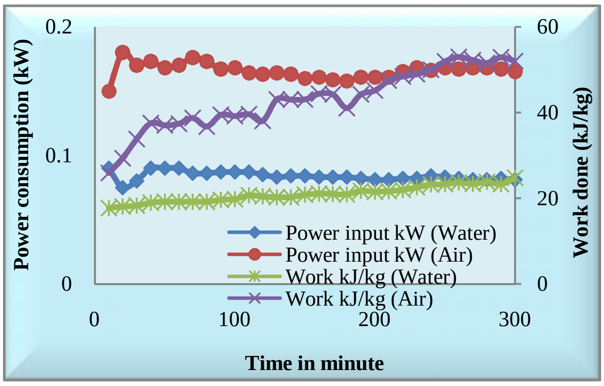

Figure 10 Variation of Compressor power consumption (kW) and Work done (kJ/kg) while using Air/ Water cooled condenser v/s Time.

The figure 10 shows the variation of power consumption by compressor in kW and work done in kJ/kg in case ofair cooled condenser and water cooled condenser of a domestic refrigerator. It is seen that initially till 30 to 40 minute there is fluctuation in power consumption and then slightly decrease in continuous manner throughout the experiment for both air/water cooled condenser is used. On the other hand work done continuously increases, linearly in case of water cooled condenser and zig-zag manor in case of air cooled condenser.

Refrigeration effect, Condensation effect and Coefficient of performance

In case of water cooled condenser compressor power consumption reduced to half that of air cooled condenser and it is seen that COP will be higher in case of water cooled condenser domestic refrigerator.

The figure 11shows the variation of evaporation effect in air cooled condenser and water cooled condenser of a domestic refrigerator. It is seen that while water cooled condenser is used the evaporation effect remains small increases with some fluctuation till 260 minute and then drop in refrigeration effect to 40 throughout the period of tests but while air cooled condenser is used the refrigeration effect initially fluctuates up and then down in fluctuating manner for remaining period of times.

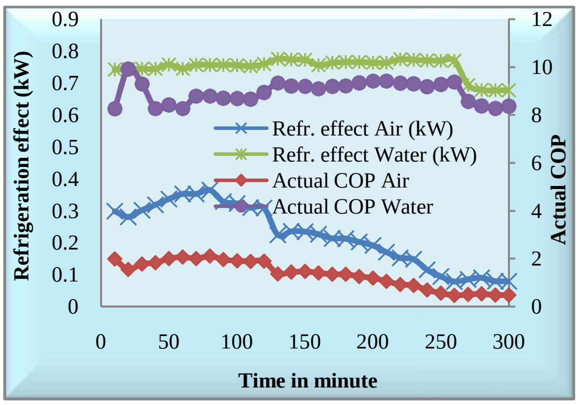

Figure 11 Variation of Refrigeration effect and Actual COP while using Air/ Water cooled condenser v/s Time.

The reason for this is that because of high evaporator discharge temperature and very low capillary discharge temperature, evaporation effect is very high in case of water cooled condenser but opposite in air cooled condenser and because of change in several parameters as pressure, capillary discharge temperature and evaporator discharge temperature, refrigeration effect decreases with time in both cases but more in case of air cooled condenser.

The figure 11 also shows the variation of COP in air cooled condenser and water cooled condenser of a domestic refrigerator. The COP is higher while water cooled condenser is used the reasons being higher refrigeration affect and lower work done. COP is a function of several parameters as compressor work done (that is a function of compressor inlet and outlet temperature), refrigeration effect (that is function of evaporator inlet and outlet temperature) and indirectly depends on pressure so a small change in these parameters can affect more to the COP of the refrigerator in both cases.

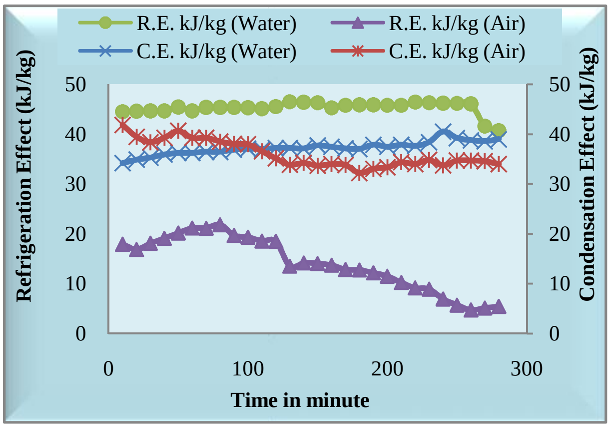

Figure 12 Variation of Refrigeration effect andCondensation effect while using Air/ Water cooled condenser v/s Time.

About retrigeration ettect ot a domestic retrigerator is discussed in figure 11.The figure 12shows the variation of condensation effect in air cooled condenser and water cooled condenser of a domestic refrigerator. It is seen that while water cooled condenser is used the condensation effect remain same with slightly increment throughout the experiment but in case of air cooled condenser there is continually decrement in condensation effect with fluctuation throughout the experiment.

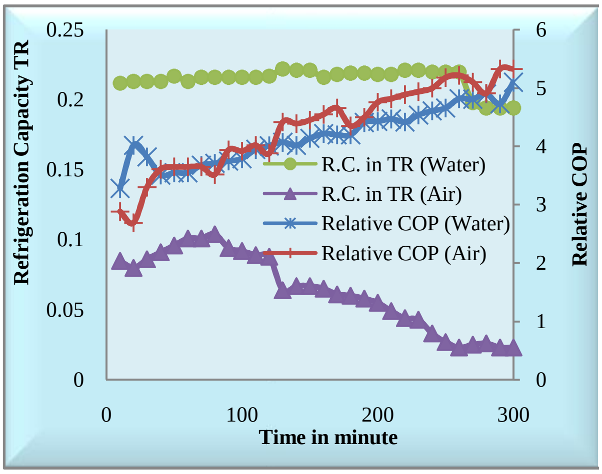

Figure 13 Variation of Refrigeration capacity (TR) andRelative COP while using Air/ Water cooled condenser v/s Time.

The figure 13shows the variation of refrigeration capacity (Tone of Refrigeration) in air cooled condenser and water cooled condenser of a domestic refrigerator. It is seen that whilewater cooled condenser is usedrefrigeration capacity is same without any variation with time till 270 minute and after that slightly decrease for remaining 30 minute. In case of air cooled condenser till 100 minute increase linearly and then decrease with some fluctuation for remaining 200 minute.

The figure 13 also shows the variation of relative COP in air cooled condenser and water cooled condenser of a domestic refrigerator. Relative COP is the ratio of actual COP to the theoretical COP.It is seen that while air orwater cooled condenser is used in both case relative COP is increasing with time, linearly in case of water cooled condenser and slightly varying with gape of time in case of air cooled condenser.

The figure 14shows the variation of actual COP and theoretical COPofair cooled condenser and water cooled condenser of a domestic refrigerator. Actual COP is discussed in figure 11. It is seen that while air or water cooled condenser is used the theoretical COP decreases linearly with little fluctuation. Theoretical COP in case of water cooled condenser is much more approximate 4 to 5 times higher than that of in case of air cooled condenser is used.

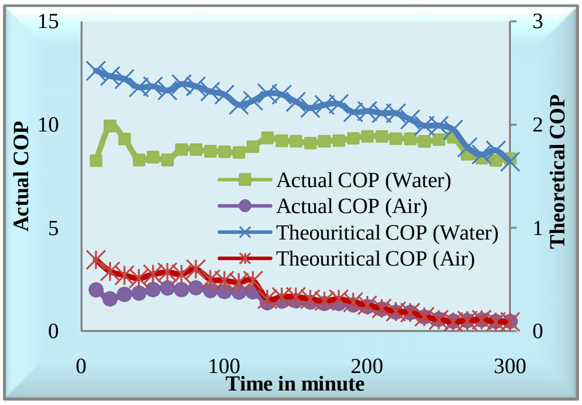

Figure 14 Variation of Actual COP and TheoreticalCOP while using Air/ Water cooled condenser v/s Time

Superheating and Sub-cooling

Sub-cooling is possible only in case of air cooled condenser. There are self sub-cooling because of cooling of refrigerant below its saturation temperature and sub-cooling by applying liquid vapour heat exchanger in which heat of condensed hot liquid will be transferred to the evaporator discharge low temperature vapour refrigerant.

The refrigerating effect is increased by adopting both the superheating and under-cooling process as compared to a cycle without them. In case of sub-cooling the liquid refrigerant by vapor refrigerant, the coefficient of performance of the cycle is reduced. Even with theoretical loss resulting from the above type of sub-cooling, there are many actual installations which adopt this process. In case of water cooled condenser sub cooling is not possible but due to low evaporator pressure evaporator discharge will be much more super heated than air cooled condenser or it can be said this is a self-sub-cooled and super-heated process.

CONCLUSION

The performance evaluation of domestic refrigerator using water condenser has been carried out and based as the results and discussion, in previous chapter the following concluding points have been drawn as under.

A. During performance analysis it is observed that when condenser is of air cooled then compressor work increase and work on about 220-250 psi but when we have use water cooled condenser then compressor work on about 110-120 psi.
B. For 150 minutes calculation we have see that compressor have take 0.390 kWh power In the case of air cooled condenser but in the case of water cooled condenser compressor work is 0.230 kWh in 145 minute.
C. The theoretical COP of the refrigerator is about 90% more in case of water cooled condenser. In case of air cooled condenser it slightly decrease compare to water cooled condenser.
D. After 22 hour running we have see that refrigerant outlet in water cooled condenser increased to 36^{o}C from 31^{o}C.
E. This analysis leads to further scope analysis by redesigning water tray, shape-size-orientation and compactness of condenser, using a circulation fan inside the evaporator to avoid frosting problem, using spray water on the condenser coils and fins.

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