OPTIMIZATION OF MULTI-STAGE VAPOUR COMPRESSION SYSTEM USING OZONE FRIENDLY REFRIGERANT R290*

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ABSTRACT

Considerable work has been in the field of optimization by various experts. This certainly puts a question on the need of this work .The emphasis of this work will be on ozone friendly refrigerants. The work has been systematically conducted keeping in mind intified ozone friendly refrigerant property .This will be followed by evaluation of optimum operation parameter.

It will enables to operate system using minimum energy.Tremendous emphasis has been laid on the use of R-134a is the height of being ozone friendly having 0 ODP(zero, ozone depletion potential) ,but its GWP (Global Warming Potential) is 1300 as compared to 3 of propane .More ever COP of R-290 is almost the same as that of R-134a.Hence optimization for determination of optimum inter-stage pressure corresponding to maximum COP.

Keywords: *COP (Coefficient of Performance), Optimum pressure (Popt), flash intercooler.*

I. INTRODUCTION

One of the design issues in multistage compression is the selection of suitable intermediate pressure. the increase system complexity adds at least two more variables to the thermodynamic optimization of the refrigeration cycle. the inter stage pressure & temperature here three situationshave been considered in order to obtain the inter-stage pressure to give maximum cop. these are:-

1. OPTIMUM INTER-STAGE PRESSURE BASED ON IDEAL GAS.
2. FLASH CHAMBER WITH COMPRESSED VAPOUR OF LOW PRESSURE COMPRESSOR

BEING COOLED IN THE FLASH CHAMBER & SATURATED VAPOUR FROM THE FLASH CHAMBER IS AGAIN COMPRESSEDIN THE HIGH PRESSURE COMPRESSOR (HP)

ALSO REFERRED TO AS FLASH INTERCOOLER (EXACT ANALYSIS).

3. AN APPROXIMATE METHOD OF DETERMINATION OF OPTIMUM INTER-STAGE PRESSURE

II. OPTIMUM INTER-STAGE PRESSURE BASED ON IDEAL GAS

For air compressors with intercooling to the initial temperature, the theoretical work input to the system will be minimum when the pressure ratios are equal for all stages. This also results in equal compressor discharge temperatures for all compressor. Thus for a two-stage air compressor with intercooling, the optimum intermediate pressure, $P_{i,\,opt}$ is:

$$P_{i,opt} = \sqrt{P_{low.}P_{high}} \tag{1.1}$$

where P_{low} and P_{high} are the inlet pressure to the low-stage compressor and exit pressure from the high-stage compressor, respectively. The above relation is found to hold good for ideal gases.

For refrigerants, correction factors to the above equation are suggested, for example one such relation for refrigerants is given by:

$$P_{i,opt} = \sqrt{P_l . P_h \frac{T_h}{T_l}} \quad (1.2)$$

whereP$_h$ and P$_l$ are the evaporator and condenser pressures, and T$_h$ and T$_l$ are condenser and evaporator temperatures (in K).

III. MULTI STAGE COMPRESSION WITH FLASH INTERCOOLER

As the discussion, the compressed vapour from LP compressor being cooled in the flash chamber showing in Fig.3.1 (a) and (b) . To obtain COP, one needs to get mass flow through HP compressor per unit mass flow through the L-P compressor,

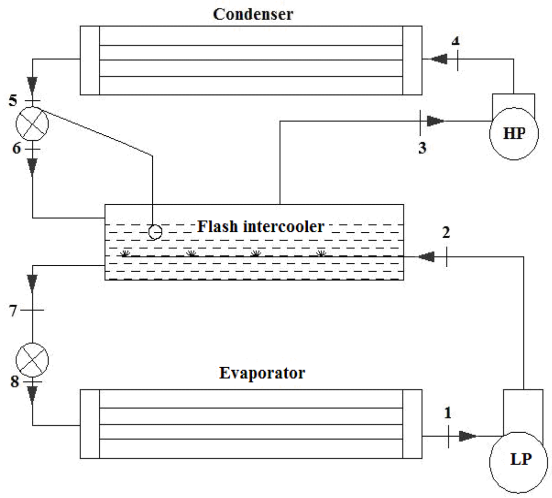


Fig- 3.1 (a) Multistage vapour-compression with flash intercooler.

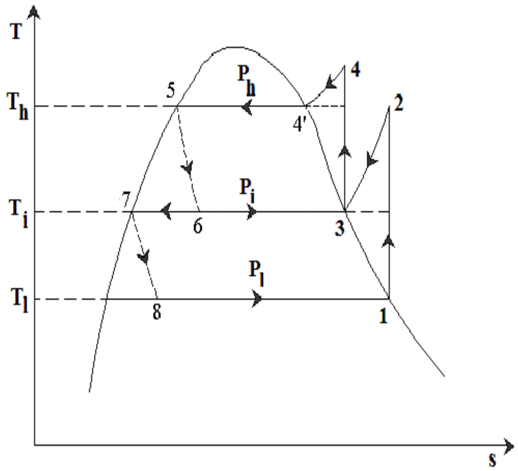


Fig- 3.1 (b) T-s diagram of multistage vapour compression system with flash intercooler from the mass conservation for the flash chamber it in seen as :

$$m_5 + m_2 = m_3 + m_7$$

but $m_7 = m_2 = 1$ (unit mass)
$m_5=m_3$(1.3)
The energy conservation across the flash chamber and simplification yields.
$m_5 h_5 + h_2 = m_3 h_3 + h_7$ (1.4) from (1.3) & (1.4)

$m_5=m_3\dfrac{(h_2-h_7)}{h_3-h_5}$(1.5)

The work Input to the system is seen to be

$$\begin{aligned}|w| &= |w_{LP}|+|w_{HP}| \\ &=(h_2-h_1)+m_3(h_4-h_3) \qquad (1.6)\\ |w| &=(h_2-h_1)+\frac{(h_2-h_7)(h_4-h_3)}{(h_3-h_5)}\end{aligned}$$

The refrigeration effect is given by
$q_c=h_1-h_7$(1.7)

Then, The COP is expressed as

$$\begin{aligned}COP &= \frac{q_c}{|w|} \qquad (1.8)\\ &= \frac{(h_1-h_7)(h_3-h_5)}{(h_2-h_1)(h_3-h_5)+(h_2-h_7)(h_4-h_3)}\end{aligned}$$

The enthalpies, h_2& h_4 of the out going vapours from LP & HP compressors respectively are evaluated assuming adiabatic condition from
$h_2 = h_3 + x_3(T_2 - T_3)$ (1.9)

we have for isentropic compression process
1-2 $S_1 = S_2$

& for process 2-3, (constant Pressure)

$s_2 = s_3 + x_3\ln\dfrac{T_2}{T_3}$ (1.10)

$$\begin{aligned}&\Rightarrow x_3\ell n\frac{T_2}{T_3} = s_2 - s_3\\ &\Rightarrow \frac{T_2}{T_3} = \left[\exp\frac{(s_2-s_3)}{x_3}\right] \qquad (1.11)\\ &\Rightarrow T_2 = T_3\left[\exp\frac{(s_2-s_3)}{x_3}\right]\end{aligned}$$

From (1.9) & (1.11) we get

$$h_2 = h_3 + x_3\left\{T_3\left[\exp\frac{(s_2 - s_3)}{x_3}\right] - T_3\right\} \qquad (1.12)$$

$$h_2 = h_3 + x_3\,T_3\left\{\exp\frac{(s_2 - s_3)}{x_3} - 1\right\}$$

Similarly

$$h_4 = h_4^{'} + x_4^{'}\,T_4^{'}\left\{\exp\frac{(s_4^{'} - s_3)}{x_4^{'}} - 1\right\} \qquad (1.13)$$

x_3 and $x_4^{'}$ are the specific heats at constant pressure.

Since COP Temperature, besides condensing & evaporating Temperature.

It may express mathematically as **[11].**
COP = $f\,(t_i\,,\,T_h,\,T_l\,)$ (1.14)

Using saturated properties from reference **[21].**

The optimum Inter stage pressure can be had from the stepwise evaluation of COP for various valves of intermediate pressures with
upper lower pressure limits fixed **[3].**

IV. AN APPROXIMATE METHOD OF DETERMINATION OF OPTIMUM INTER-STAGE PRESSURE

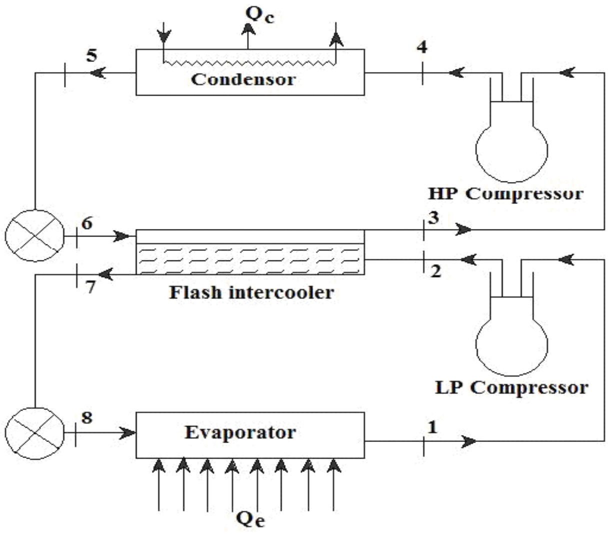


Fig- 3.2 (a) Approximate interstage pressure

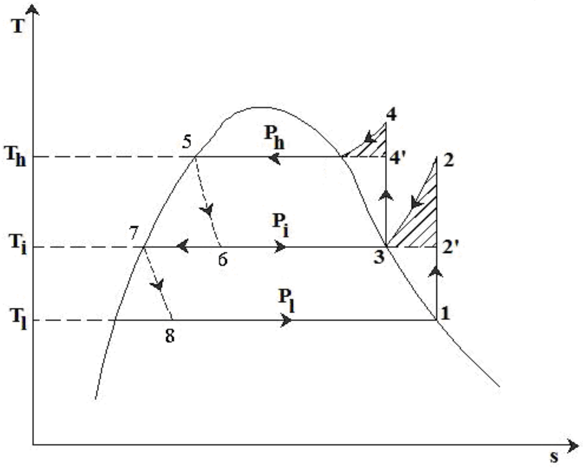


Fig- 3.2 (b) T-S diagram of Approximate interstage pressure.

In this method the superheat horn is ignored while making the analysis shown in Fig3.2(a) and (b) Then using approximate analysis, it is seen that

From the mass conservation for the flash chamber

$m_5+m_2=m_3+m_7$

But $m_7=m_2=1$

$m_5=m_3$

The energy conservation across the flash chamber and simplification yields.

$m_5 h_5 + h_2' = m_3 h_3 + h_7$

$$m_3 = \frac{(h_2' - h_7)}{(h_3 - h_5)}$$

$$T_{i'}.ds = h_2' - h_7$$

$$\Rightarrow T_i\,(s_2' - s_7) = h_2' - h_7 \quad (s_2' = s_1)$$

$$\Rightarrow T_i\,(s_1 - s_7) = h_2' - h_7$$

$$h_2' = T_i\,(s_1 - s_7) + h_7 \; (1.15)$$

where T_i is the Temperature corresponding to Inter-stage pressure.

Similarly

$$(s_4' = s_3)$$

$$h_4' = T_5\,(s_3 - s_5) + h_5 \; (1.16)$$

where T_5 is the condenser temperature

The compression work for the whole system is

$$w = \left(h_2^{'} - h_1\right) + m_3\left(h_4^{'} - h_3\right) (1.17)$$

$$\& COP = \left(h_1 - h_7\right) / w \, (1.18)$$

To get optimum inter-stage pressure, it is clear that in Equation (3.17 and 3.18) it is possible to obtain the expressions for h_7, h_3 and s_7 and s_3 as function of T_1 for assigned values of T_1 and T_h**[22]**.

TABLE I COMPUTATION OF VARIOUS RESULTS

The computed value of optimum inter-stage pressure for the multi-stage compression with the help of exact and approximate analysis given in above article. Here we have considered the different combination of

condenser& evaporator pressure (temperature). The optimum inter-stage pressure have calculated with the stepwise evaluation of COP for various value of intermediate pressure with the help of upper & lower (temperature) pressure limit fixed. The tables are given below.

Table- 1.1(a) P_1=0.7 bar (-50°C) and P_2= 17.1 bar (50°C) by exact analysis.

P_i	**Ti(^{0}C)**	**s_7**	**s_3**	**h_7**	**h'_2**	**h_3**	**h'_4**	**m_3**	**w**	**COP**
0.9	-45	0.578	2.456	93.582	525.41	522.06	661.5	2.3457	336.46	1.2557
1.2	-38	0.646	2.436	109.37	538.5	530.42	655.2	2.2298	300.64	1.3528
1.4	-34	0.684	2.426	118.5	545.78	535.17	652	2.1667	282.8	1.4059
1.7	-30	0.722	2.417	127.71	552.89	539.91	649.1	2.1054	266.65	1.4565
2	-26	0.76	2.409	137.02	559.89	544.63	646.4	2.0461	252.1	1.5036
2.3	-22	0.797	2.402	146.42	566.72	549.33	644	1.9885	238.91	1.5472
2.6	-18	0.835	2.395	155.92	573.41	554	641.8	1.9325	227.04	1.5863
3	-14	0.872	2.389	165.52	579.95	558.63	639.8	1.8781	216.33	1.6204
3.5	-10	0.909	2.383	175.23	586.38	563.23	638	1.8252	206.78	1.6483
3.9	-6	0.945	2.378	185.05	592.65	567.78	636.4	1.7736	198.2	1.6702
4.5	-2	0.982	2.373	194.99	598.78	572.28	634.8	1.7233	190.49	1.6856
5	2	1.018	2.369	205.05	604.79	576.73	633.5	1.6742	183.71	1.693
5.3	**4**	**1.036**	**2.367**	**210.12**	**607.73**	**578.93**	**632.9**	**1.65**	**180.64**	**1.6937**
5.7	6	1.055	2.365	215.23	610.66	581.12	632.3	1.6262	177.74	1.6927
6.4	10	1.091	2.362	225.55	616.4	585.43	631.1	1.5794	172.48	1.6844
7.1	14	1.127	2.359	236.01	622	589.67	630.1	1.5335	167.9	1.6681
7.9	18	1.163	2.356	246.62	627.48	593.82	629.1	1.4886	163.99	1.6431

8.8	22	1.199	2.353	257.38	632.8	597.87	628.2	1.4444	160.6	1.6108
9.8	26	1.235	2.35	268.31	638.02	601.81	627.4	1.4013	157.77	1.5704
10.8	30	1.272	2.348	279.41	643.1	605.62	626.5	1.3588	155.44	1.5225
11.9	34	1.308	2.345	290.7	648.08	609.3	625.7	1.3171	153.64	1.4669
13.1	38	1.344	2.342	302.18	652.93	612.81	624.9	1.2762	152.23	1.4051
14.3	42	1.381	2.34	313.88	657.64	616.14	624	1.2358	151.26	1.3368
15	44	1.399	2.338	319.81	659.95	617.72	623.5	1.2158	150.93	1.3004
15.7	46	1.417	2.337	325.8	662.22	619.26	623	1.196	150.67	1.2628
16.4	48	1.436	2.335	331.85	664.47	620.73	622.5	1.1763	150.51	1.224
17.1	50	1.454	2.333	337.97	666.68	622.14	622	1.1568	150.42	1.1841

Table- 1.1(b) P1=0.7 bar (-50°C) and P2 =17.1 bar (50°C).by approximate analysis

		Enthalpy at state Points(kJ/kg)				**W_c (kJ/kg)**	**Q (kJ/kg)**	**COP**	**m_3**
Pi (bar)	**Ti(^{0}C)**	**h_2**	**h_3**	**h_4**	**h_7**				
0.9	-45	525.7	522.06	662.66	93.582	339.6902	422.494	1.244	2.3474
1.2	-38	538.88	530.415	656.03	109.37	303.1673	406.711	1.342	2.2318
1.4	-34	546.21	535.173	652.71	118.5	285.0555	397.58	1.395	2.1689
1.7	-30	553.39	539.913	649.7	127.71	268.7289	388.363	1.445	2.1079
2	-26	560.43	544.633	646.96	137.02	254.0069	379.055	1.492	2.0488
2.3	-22	567.34	549.329	644.47	146.42	240.7341	369.654	1.536	1.9915
2.6	-18	574.1	553.996	642.21	155.92	228.7988	360.155	1.574	1.9358
3	-14	580.73	558.63	640.17	165.52	218.0725	350.554	1.608	1.8816
3.5	-10	587.21	563.226	638.32	175.23	208.4649	340.845	1.635	1.8289
3.9	-6	593.55	567.779	636.64	185.05	199.8721	331.026	1.656	1.7775
4.5	-2	599.77	572.283	635.1	194.99	192.2012	321.09	1.671	1.7275
5	2	605.83	576.731	633.72	205.05	185.409	311.031	1.678	1.6786
5.3	**4**	**608.8**	**578.93**	**633.1**	**210**	**182.32**	**305.955**	**1.68**	**1.65**

6	8	614.66	583.285	631.89	220.37	176.692	295.703	1.674	1.6072
6.7	12	620.36	587.563	630.81	230.76	171.7806	285.313	1.661	1.5609
7.5	16	625.94	591.758	629.8	241.3	167.5132	274.78	1.64	1.5156
8.4	20	631.39	595.859	628.85	251.98	163.8515	264.096	1.612	1.4712
9.3	24	636.69	599.855	627.97	262.83	160.7583	253.251	1.575	1.4276
10.3	28	641.87	603.733	627.13	273.84	158.1887	242.237	1.531	1.3848
11.3	32	646.93	607.478	626.28	285.03	156.104	231.045	1.48	1.3428
12.5	36	651.83	611.072	625.47	296.42	154.4873	219.661	1.422	1.3014
13.7	40	656.63	614.495	624.6	308	153.2908	208.074	1.357	1.2607
15	44	661.3	617.723	623.69	319.81	152.5027	196.269	1.287	1.2207
16.4	48	665.86	620.728	622.69	331.85	152.0937	184.227	1.211	1.1812

V. RESULT AND DISCUSSION

Table- 1.2(a) P1=0.7bar (-50o C) and P2 = 13.7 bar (40o C).by exact analysis

		Enthalpy at state Points kJ/kg				**W_c**KJ/Kg	**q_c**kJ/Kg	**(COP)**	**m_3**
P_i(bar)	**T_i**(^{0}C)	**h_2**	**h_3**	**h_4**	**H_7**				
0.9	-45	525.73	522.06	651.35	93.582	270.6616	422.494	1.561	2.019
1.2	-38	538.88	530.415	644.92	109.37	243.9415	406.711	1.6672	1.931
1.4	-34	546.21	535.173	641.7	118.5	230.7052	397.58	1.7233	1.883
1.7	-30	553.39	539.913	638.78	127.71	218.7941	388.363	1.775	1.836
2	-26	560.43	544.633	636.13	137.02	208.0812	379.055	1.8217	1.789
2.3	-22	567.34	549.329	633.72	146.42	198.4567	369.654	1.8626	1.744
2.6	-18	574.1	553.996	631.53	155.92	189.8422	360.155	1.8971	1.7
3	-14	580.73	558.63	629.55	165.52	182.1462	350.554	1.9246	1.657
3.5	-10	587.21	563.226	627.76	175.23	175.3044	340.845	1.9443	1.614
3.9	-6	593.55	567.779	626.14	185.05	169.2422	331.026	1.9559	1.572
4.2	-4	596.67	570.037	625.38	190	166.4818	326.073	1.9586	1.552
4.5	**-2**	**599.77**	**572.283**	**624.65**	**194.99**	**163.8931**	**321.09**	**1.9591**	**1.532**
4.7	0	602.8	574.514	623.98	200	161.4857	316.076	1.9573	1.511

5	2	605.83	576.731	623.31	205.05	159.2252	311.031	1.9534	1.491
5.7	6	611.74	581.118	622.11	215.23	155.1801	300.845	1.9387	1.452
6.4	10	617.53	585.434	621	225.55	151.7081	290.526	1.915	1.413
7.1	14	623.17	589.672	619.99	236.01	148.7737	280.065	1.8825	1.375
7.9	18	628.66	593.821	619.08	246.62	146.3451	269.457	1.8412	1.337
8.8	22	634.04	597.871	618.2	257.38	144.3753	258.694	1.7918	1.299
9.8	26	639.3	601.81	617.35	268.31	142.8407	247.766	1.7346	1.263
10.8	30	644.42	605.623	616.53	279.41	141.7184	236.664	1.67	1.226
11.9	34	649.38	609.295	615.75	290.7	140.9856	225.377	1.5986	1.19
13.1	38	654.27	612.806	614.9	302.18	140.6109	213.894	1.5212	1.155
13.7	40	656.63	614.495	614.5	308	140.5567	208.074	1.4804	1.137

From the previous computation of optimum inter-stage pressure for various ranges of temperature & pressure have been discussed by two analyses.

i – Exact analysis
ii – Approximate Analysis

The exact analysis is more complex than the approximate analysis because in this analysis the unknown properties at state point 2 & 4 (superheat region), fig- 3.1(b) T_2, h_2, & T_4, h_4, makes the analysis more complex by using the equation 1.12 and 1.14. Other properties like as entropy & specific heat at point 2& 4, obtained from the saturated state.
The entropy at point 2 and 4 obtained by the equating the entropy from the isentropic compression process 1-2, ($S_1 = S_2$) & isentropic compression process 3- 4 ($S_3 = S_4$) and the specific heat is obtain from constant pressure process 2 - 3 & 4 – 4'.

But the approximate analysis, there is no need to superheat value at state point 2and 4 fig-3.2(b), because super heat horn is ignored. All the properties at state points are easily available from the saturated stage. The enthalpy at state point 2 & 4 has been calculated using the equation 1.15 and 1.16. From the calculation we can see the optimum inter-stage pressures by both the analysis are very close for the different combination of evaporator &condenser temperature & pressure.

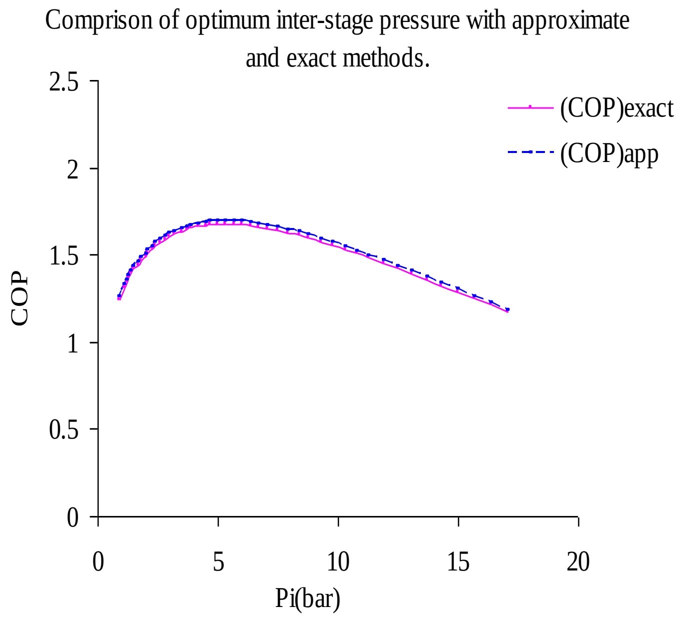
The computed values of optimum inter-stage pressure have been shown in tables 1.1(a) to 1.2 (b).

Table-1.2(b) P1=0.7 bar (- 50°C) and P2 =13.7 bar (40°C) by approximate analysis.

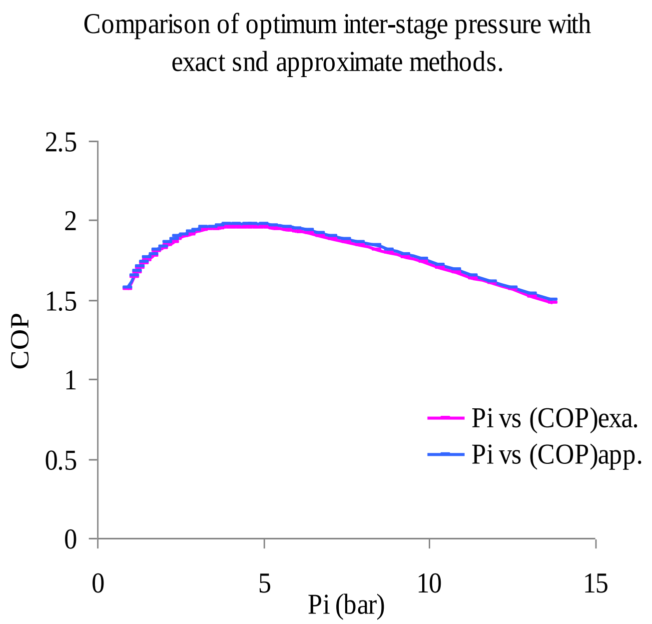
P_i	**Ti(^{0}C)**	**s_7**	**s_3**	**h_7**	**h'_2**	**h_3**	**h'_4**	**m_3**	**w**	**COP**
0.9	-45	0.5778	2.456	93.582	525.414	522.06	650.3	2.0174	268.04	1.57622
1.2	-38	0.6457	2.436	109.37	538.499	530.415	644.16	1.9294	241.89	1.68135
1.4	-34	0.684	2.426	118.5	545.78	535.173	641.07	1.8809	228.88	1.7371
1.7	-30	0.7221	2.417	127.71	552.89	539.913	638.25	1.8334	217.1	1.78888
2	-26	0.7598	2.409	137.02	559.885	544.633	635.68	1.787	206.51	1.83549
2.3	-22	0.7973	2.402	146.42	566.722	549.329	633.33	1.7416	196.95	1.87689

2.6	-18	0.8346	2.395	155.92	573.407	553.996	631.21	1.6971	188.37	1.91199
3	-14	0.8717	2.389	165.52	579.948	558.63	629.27	1.6535	180.67	1.94029
3.5	-10	0.9085	2.383	175.23	586.379	563.226	627.51	1.6109	173.86	1.96041
3.9	-6	0.9452	2.378	185.05	592.652	567.779	625.92	1.569	167.8	1.97279
4.2	-4	0.9635	2.376	190	595.736	570.037	625.16	1.5484	165.02	1.97597
4.5	**-2**	**0.9818**	**2.373**	**194.99**	**598.776**	**572.283**	**624.45**	**1.5279**	**162.4**	**1.97719**
4.7	0	1	2.371	200	601.801	574.514	623.79	1.5076	160.01	1.97533
5	2	1.0182	2.369	205.05	604.785	576.731	623.13	1.4875	157.73	1.97193
5.3	4	1.0364	2.367	210.12	607.727	578.933	622.54	1.4676	155.64	1.96579
6	8	1.0726	2.363	220.37	613.548	583.285	621.38	1.4283	151.88	1.94697
6.7	12	1.1088	2.36	230.76	619.218	587.563	620.34	1.3895	148.69	1.91881
7.5	16	1.145	2.357	241.3	624.741	591.758	619.37	1.3513	145.98	1.88226
8.4	20	1.1811	2.354	251.98	630.155	595.895	618.47	1.3136	143.73	1.83746
9.3	24	1.2172	2.351	262.83	635.441	599.855	617.62	1.2767	142.05	1.78285
10.3	28	1.2534	2.349	273.84	640.577	603.733	616.81	1.2401	140.72	1.72147
11.3	32	1.2896	2.346	285.03	645.602	607.478	615.99	1.204	139.78	1.65293
12.5	36	1.3258	2.344	296.42	650.529	611.072	615.21	1.1684	139.29	1.57701
13.7	40	1.3622	2.341	308	655.307	614.495	614.37	1.1332	139.09	1.49602

P_1=0.7 bar (-50°C) and P_2= 17.1 bar (50°C) by exact analysis.



P_1=0.7bar (-50° C) and P_2 = 13.7 bar (40° C).by exact analysis.



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