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Numerical estimation of main parameters for realistic two-stage ammonia refrigerating systems

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Abstract

Two-stage ammonia systems, one with a flash intercooler only while the other with a precooler and a flash intercooler, are analysed with the objective function as COP. Correlations of main design parameters, inter-stage pressure and refrigerating efficiency, have been developed and presented for optimum performance. The effect of precooling on system performance is described.

Key words: Two-stage ammonia systems, refrigerating system, precooling.

1. Introduction

The performance of a multi-stage refrigeration system is affected by a suitable selection of a working fluid, inter-stage pressure, degree of subcooling of HP condensate and superheating of LP vapour inside the evaporatoı.

Ammonia is one of the refrigerants which are usually preferred in a multi-stage system due to their availability at comparatively cheaper rates and production of maximum coefficient of performance. To reduce power consumption of such a system, the common practice is that COP should be treated as an objective function and optimized with respect to inter-stage pressure. Simultaneously, degree of subcooling and superheating should be selected up to that level only where they yield additional refrigerating effect with insignificant power enhancement for compression. Further improvement in both the performance and piston displacement may be realized if the flash tank, incorporated in a multi-stage system, is made to act as an intercooler as well as a subcooler. A system having such an arrangement, as shown in fig. 1, would require

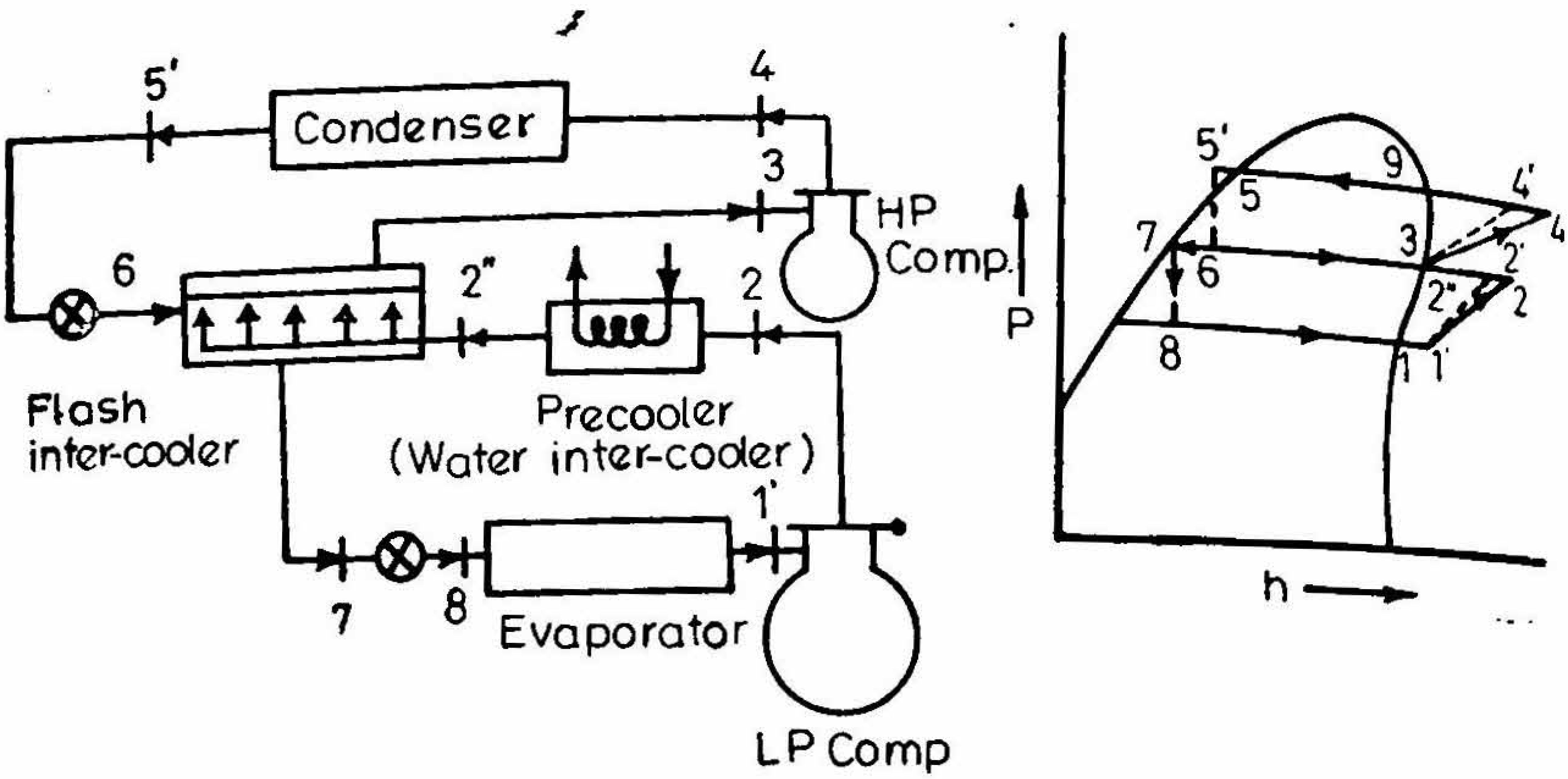

FIG. 1. Two-stage system with flash and water inter-coolers.

a water-cooled intercooler, since it is desirable to reject heat directly from the system whenever possible, but would follow it with a flash intercooler. The relatively warm liquid at point 6 from the high side of the system and the gas from the water intercooler at point 2" are cooled by the evaporation of a part of liquid in the flash intercooler until a condition of thermal equilibrium is established and the contents, liquid and vapour at points 7 and 3, respectively, coming out of the flash intercooler are in a saturated state. When the saturated vapour is further compressed in the HP cylinder up to the condenser pressure corresponding to point 4, lesser work is required. Observing this advantageous effect, it would always be desirable to provide a water-cooled intercooler (hereinafter named as precooler) for cooling the LP-compressed vapour before it enters the flash chamber, provided that the temperature of the LP vapour is considerably higher than the ambient temperature.

2. System analysis and optimization

Referring to fig. 1, the temperature T_2 of ammonia vapour at the end of LP compression is evaluated from :

$$T_2 = T_3 + [(h_{2'} - h_{1'})/\eta_{c1} + h_{1'} - h_3]/X_3 \tag{1}$$

If T_2 is greater than $T_{2''}$ ($= T_a + 5 \cdot 0$), the enthalpy of the LP-compressed vapour at the exit of the precooler is calculated from :

$$h_{2''} = h_3 + X_3 (T_{2''} - T_3) \tag{2}$$

where X_3 is the specific heat at constant pressure (p_3) and is found out from the functional relationship given in ref. [1] as :

$$X = 2 \cdot 543 + 0 \cdot 004643 (T - 283 \cdot 15) + 0 \cdot 05015 (T - 283 \cdot 15)^2 \tag{3a}$$
$$\text{for } 283 \cdot 15 \leqslant T \leqslant 333 \cdot 15 \text{ K}$$

and, $X = 2 \cdot 14375 + 0 \cdot 00396916\,[(T - 228 \cdot 15) + 0 \cdot 0000600638\,(T - 228 \cdot 15)^2]$ (3b)

for $213 \cdot 15 \leqslant T < 283 \cdot 15$ K.

The compressor efficiency[2], η_c, is correlated within $\begin{matrix} +\,2 \cdot 70 \\ -\,1 \cdot 30 \end{matrix}\,\%$ as :

$$\eta_c = 0 \cdot 976695 - 0 \cdot 0366432\, r + 0 \cdot 00133798\, r^2 \tag{4}$$

with r as the compression ratio.

The pressure is correlated in terms of saturated temperature as :

$$p = 4 \cdot 46558 + 0 \cdot 166907\, t + 24 \cdot 3664\, (t/100)^2 + 16 \cdot 1561\, (t/100)^3 + 3 \cdot 42760\, (t/100)^4 \tag{5}$$

where $t = \mathrm{T} - 273 \cdot 15$.

The mass flow of refrigerant through HP side per unit mass flow through LP side is obtained by :

$$m_3 = (h_{2''} - h_7)/(h_3 - h_{5'}). \tag{6}$$

Coefficient of performance (COP) and refrigeration efficiency (η_R) are found from :

$$\mathrm{COP} = (h_{1'} - h_7)/(h_{1'} - h_2) + m_3\,(h_3 - h_4) \tag{7}$$

$$\eta_R = \mathrm{COP}\,(T_h - T_l)/T_l \tag{8}$$

Since COP depends upon temperature limits (T_h, T_l), inter-stage temperature (T_i)' degrees of subcooling and superheating (ΔT_c and ΔT_s), and desired degree of precooling (ΔT_p), it may mathematically be expressed as :

$$\mathrm{COP} = F\,(T_i\,;\; T_h,\; T_l,\; \Delta T_c,\; \Delta T_s,\; \Delta T_p) \tag{9}$$

To have maximum COP one would need to satisfy :

$$\left(\frac{\partial F}{\partial T_i}\right) = 0 \tag{10}$$

under the given values of the constraints T_h, T_l, ΔT_c, ΔT_s or ΔT_p, as the case may be.

Objective function 'F' has been optimized numerically satisfying eqn. (10) over condensing temperature range of $283 \cdot 15$ to $333 \cdot 15$ K and evaporating temperature range of $233 \cdot 15$ to $283 \cdot 15$ K, each with 5 K interval. But, the overall temperature difference between T_h and T_l has been kept $\geqslant 35$ K. The degree of subcooling of HP condensate and superheating of LP vapour inside the evaporator has been varied from 0 to 15 K and 0 to 20 K, respectively. The effect of precooling has been taken care of only when the LP vapour is warm enough, *i.e.*, $T_2 > (T_h + 5)$ K. Inter-stage temperatures and refrigeration efficiencies have been computed at the optimal points pertaining to various practical situations of interest. Tables I and II have been prepared only to depict the effect of precooling on the design parameters (T_i and η_R). The correlations of optimum inter-stage pressure and optimum refrigeration efficiency in terms of T_h, T_l, ΔT_c, ΔT_p have been developed by a regression analysis.

Table I

Optimum refrigeration efficiencies for two-stage ammonia systems

t_k, °C / t_l, °C	With precooler and flash intercooler			With flash intercooler only			Per cent increase
	20·0	40·0	60·0	20·0	40·0	60·0	
−35·0	79·33	73·53	67·75	76·80	70·35	63·98	2·49 to 5·89
−15·0	86·13	81·10	75·88	84·04	78·14	72·11	
5·0	...	86·40	81·80	...	84·01	78·37	

Table II

Optimum inter-stage pressures for two-stage ammonia systems

t_k, °C / t_l, °C	With precooler and flash intercooler			With flash intercooler only			Per cent decrease
	20·0	40·0	60·0	20·0	40·0	60·0	
−35·0	3·02	4·27	5·85	3·08	4·27	5·85	0·0 to 3·96
−15·0	4·61	6·41	8·64	4·80	6·59	8·77	
5·0	...	9·17	12·19	...	9·52	12·63	

3. Results and discussion

It is observed from Tables I and II that due to precooling p_{i0} decreases over lower values of $(T_k - T_l)$. However, reduction in p_{i0} over large values of $(T_k - T_l)$ becomes rather negligible. Lower p_{i0} would improve volumetric efficiency of LP compressor and its capacity.

Feasible operating ranges of the two-stage ammonia systems with and without a precooler have been determined and displayed graphically[3]. It was also established there that the power consumption at the optimum performance of the system with a precooler turns out to be more over smaller $(T_k - T_l)$ values than the large $(T_k - T_l)$ values. Since COP is directly linked with p_{i0} and power consumption, it increases almost uniformly over all values of $(T_k - T_l)$. On the other hand, the reduction in m_3 is not noticed to be that much pronounced over lower $(T_k - T_l)$ values as is seen over large values of $(T_k - T_l)$. Size of HP compressor, being governed by m_3, thus, becomes smaller without affecting cooling capacity of the system.

The change in refrigeration efficiency with $(T_h - T_l)$ is also seen similar to p_{io} (Tables I and II). It increases in the range 2·5 to 6·0% in the presence of a precooler over operating ranges considered. It implies that inclusion of a precooler in an ammonia system would bring about (i) smaller p_{io}, and (ii) better refrigeration efficiency and hence better COP. The extra cost of a precooler would be compensated by smaller size HP compressor.

The correlations which have been searched out for main design parameters of ammonia systems are given below.

Case I (System with a flash intercooler only)

Optimum inter-stage pressure

Saturation,

$$p_{io} = [35{\cdot}77023 - 38{\cdot}90097\,(T_l/100) + 11{\cdot}77831\,(T_l/100)^2 - 0{\cdot}387111\,(T_l/100)^3]\,[2{\cdot}24883 - 2{\cdot}28122\,(T_h/100) + 0{\cdot}59511\,(T_h/100)^2] \qquad (11$$

within $\begin{matrix} +2{\cdot}96 \\ -1{\cdot}26 \end{matrix}\,\%$.

Subcooling,

$$p_{io,c}/p_{io} = 1{\cdot}00 - 0{\cdot}437433\,(\triangle T_c/100) + 2{\cdot}05689\,(\triangle T_c/100)^2 = FP_c$$

within $\begin{matrix} +3{\cdot}53 \\ -3{\cdot}65 \end{matrix}\,\%$. (12)

Superheating,

$$p_{io,s}/p_{io} = 1{\cdot}00 - 0{\cdot}287878\,(\triangle T_s/100) + 0{\cdot}949318\,(\triangle T_s/100)^2 = FP_s \qquad (13)$$

within $\pm 3{\cdot}50\%$

Subcooling and superheating

$$p_{io,cs} = p_{io}\,.\,FP_c\,.\,FP_s \qquad (14)$$

within $\begin{matrix} +3{\cdot}53 \\ -5{\cdot}96 \end{matrix}\,\%$.

Optimum refrigerating efficiency

Saturation,

$$\eta_{RO} = [-\,302{\cdot}11 + 3{\cdot}09750\,T_l - 0{\cdot}824381\,(T_l/10)^2 + 7{\cdot}51613\,(T_l/100)^3]\,[2{\cdot}37371 - 0{\cdot}0378930\,(T_h/100) - 0{\cdot}254555\,(T_h/100)^2 + 0{\cdot}0410755\,(T_h/100^3)] \qquad (15)$$

within $\begin{matrix} +1{\cdot}47 \\ -1{\cdot}31 \end{matrix}\,\%$.

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within $\begin{matrix} +1{\cdot}47 \\ -1{\cdot}31 \end{matrix}\%$.

Subcooling,

$$\begin{aligned}\eta_{RO,C}/\eta_{RO} &= 1\cdot 00 + 0\cdot 249787\,(\Delta T_c/100) - 0\cdot 224193\,(\Delta T_c/100)^2\\ &= FE_c\end{aligned} \tag{16}$$

within $\begin{matrix}+1\cdot 51\\ -1\cdot 39\end{matrix}\,\%$.

Superheating,

$$\begin{aligned}\eta_{RO,S}/\eta_{RO} &= 1\cdot 00 - 0\cdot 134049\,(\Delta T_s/100) + 0\cdot 0553376\,(\Delta T_s/100)^2\\ &= FE_s\end{aligned} \tag{17}$$

within $\begin{matrix}+1\cdot 64\\ -1\cdot 31\end{matrix}\,\%$.

Subcooling + superheating,

$$\eta_{RO,CS} = \eta_{RO}\,.\,EF_C\,.\,EF_S. \tag{18}$$

within $\begin{matrix}+1\cdot 64\\ -1\cdot 54\end{matrix}\,\%$.

Case II ***(System with a precooler and flash intercooler)***

Optimum inter-stage pressure

Saturation,

$$\begin{aligned}p_{io,p}/p_{im} = {}& 1\cdot 16085 - 0\cdot 095180\,(T_h T_l/10000) + 0\cdot 0172437\\ & (T_h T_l/10000)^2 - 0\cdot 0009729501\,(T_h T_l/10000)^3\end{aligned} \tag{19}$$

within $\begin{matrix}+4\cdot 73\\ -0\cdot 65\end{matrix}\,\%$.

Subcooling,

$$p_{io,cp}/p_{io,p} = FP_c \tag{20}$$

within $\begin{matrix}+4\cdot 73\\ -3\cdot 03\end{matrix}\,\%$.

Superheating,

$$p_{io,sp}/p_{io,p} = FP_s \tag{21}$$

within $\begin{matrix}+4\cdot 73\\ -2\cdot 89\end{matrix}\,\%$.

Subcooling and superheating,

$$p_{io,csp} = p_{io,p}\,.\,FP_c\,.\,FP_s \tag{22}$$

within $\begin{matrix}+5\cdot 33\\ -4\cdot 73\end{matrix}\,\%$.

Optimum refrigerating efficiency

Saturation,

$$\eta_{RO \cdot P}/\eta_{RO} = 0\cdot650290 + 0\cdot0950285\,(T_h T_l/10000) - 0\cdot00575658\,(T_h T_l/10000)^2$$

within $\begin{smallmatrix}+2\cdot62\\-1\cdot73\end{smallmatrix}\%$. (23)

Subcooling,

$$\eta_{RO \cdot CP}/\eta_{RO \cdot C} = FE_c \qquad (24)$$

within $\begin{smallmatrix}+2\cdot92\\-1\cdot97\end{smallmatrix}\%$

Superheating,

$$\eta_{RO \cdot SP}/\eta_{RO \cdot S} = FE_s \qquad (25)$$

within $\begin{smallmatrix}+2\cdot64\\-1\cdot73\end{smallmatrix}\%$

Subcooling and superheating,

$$\eta_{RO \cdot CSP} = \eta_{RO \cdot P} \cdot FE_c \cdot FE_s \qquad (26)$$

within $\begin{smallmatrix}+2\cdot98\\-1\cdot97\end{smallmatrix}\%$

For the FPS system, the above equations may be used if the temperature (t_F) in Fahrenheit is first converted into degree Kelvin by : $T = t_F/1\cdot8 + 255\cdot3722$. However, the pressure thus calculated using temperature, T, would be multiplied by a factor of 14·5085.

Illustration

A two-stage ammonia system incorporated with a precooler and a flash intercooler is to operate between condensing and evaporator temperatures of 313·15 K (40° C) and 243·15 K (– 30° C), respectively. LP vapour gets superheated by 15 degree K before it enters the LP compressor and HP condensate is subcooled by 5 K in the condenser. Determine optimum inter-stage pressure and optimum refrigeration efficiency of the system and compare them with the values obtained for the system which employs only a flash intercooler.

Using eqns. (11) to (18), for $T_h = 313\cdot15$ K, $T_l = 243\cdot15$ K, $\Delta T_c = 5$ K and $\Delta T_s = 15$ K, we get :

$$p_{is,cs} = 4\cdot758 \text{ bar} \; ; \quad \eta_{RO,CS} = 72\cdot63\%$$

For a system with a precooler and a flash intercooler, eqns. (19) to (26) produce :

$$p_{is,csp} = 4\cdot784 \text{ bar} \; ; \quad \eta_{RO,CSP} = 75\cdot54\%$$

Thus, due to the presence of a precooler, the per cent increase in optimum refrigerating efficiency and per cent increase in optimum inter-stage pressure are found to be 1·43% and 0·63%, respectively.

4. Conclusions

1. The correlations developed are quite simple and predict the various quantities of interest very near to the values as found by numerical technique for the optimum performance of the system.

2. Inclusion of a precooler brings about per cent increase in optimum refrigerating efficiency in the range 2·5 to 6%, while the per cent decrease in the optimum inter-stage pressure comes out to be in the range 0·0 to 4%, over the operating temperature limits considered.

Nomenclature

COP = Coefficient of performance
h = Enthalpy, kJ/kg
p = Pressure, bar
p_i = Inter-stage pressure, bar
p_{io} = Optimum inter-stage pressure for saturated case, bar
$p_{io,c}$ = Optimum inter-stage pressure with subcooling, bar
$p_{io,s}$ = Optimum inter-stage pressure with superheating, bar
$p_{io,cs}$ = Optimum inter-stage pressure with subcooling and superheating, bar
$p_{io,p}$ = Optimum inter-stage pressure with precooling, bar
$p_{io,cp}$ = Optimum inter-stage pressure with subcooling and precooling, bar
$p_{io,sp}$ = Optimum inter-stage pressure with superheating and precooling, bar
$p_{io,csp}$ = Optimum inter-stage pressure with subcooling, superheating and precooling, bar.
p_k, T_k = Condensing pressure (bar) and temperature (K), respectively
p_1, T_1 = Evaporator pressure (bar) and temperature (K), respectively
r = Compression ratio (p_i/p_1 or p_k/p_i)
t = Temperature, C
T = Tempearture, K
ΔT_c = Degrees of subcooling, K
ΔT_s = Degrees of superheat, K
X = Specific heat at constant pressure, kJ/kg–K
η_c = Compressor efficiency
η_R = Refrigerating efficiency
η_{RO} = Optimum refrigerating efficiency
$\eta_{RO,C}$ = Optimum refrigerating efficiency with subcooling
$\eta_{RO,S}$ = Optimum refrigerating efficiency with superheating
$\eta_{KO,CS}$ = Optimum refrigerating efficiency with subcooling and superheating
$\eta_{RO,P}$ = Optimum refrigerating efficiency with precooling
$\eta_{RO,CP}$ = Optimum refrigerating efficiency with subcooling and precooling
$\eta_{RO,SP}$ = Optimum refrigerating efficiency with superheating and precooling
$\eta_{RO,CSP}$ = Optimum refrigerating efficiency with subcooling, superheating and precooling.

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