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HYSTERESIS PHENOMENA IN MULTIPLE EFFECT
REFRIGERATING MACHINE.

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ABSTRACT

It is found theoretically and proved experimentally that the temperature of the delivery gas of the multiple effect refrigerating machine describes a hysteresis loop against the variation of separator pressure. Utilising this phenomena, the best separator pressure of the multiple effect cycle can be found very easily without calculations, while the machine is in actual operation. It is shown that, with the improper separator pressure, the losses in the refrigerating capacity and the efficiency are very great, but they may be avoided by the knowledge of this phenomena.

It was pointed out previously in one of the writer's paper⁽¹⁾ that the observed temperature of the delivery gas of the multiple effect refrigerating machine did not, in some cases, agree with that found from the theoretical calculations. After further studies upon this question he found that, with the variation of the multiple effect separator pressure, the said temperature would show a hysteresis-like phenomena. Experiments were performed to prove this phenomena on a CO₂ refrigerating machine of a single acting type having a cylinder diameter of 1 $\frac{7}{8}$ inches and a stroke of 5 inches. The results of these experiments are given in Table I. The separator pressure was raised and lowered only a few times during the trial while the other conditions were kept as constant as possible. A slight variations in the delivery pressure were, however permitted for, in order to keep it constant, it was necessary to charge or discharge the gas into the system, which delayed considerably

(1) "Theory and Experiments on Vapour Compression Refrigerating Machine", Jour. Soc. Mech. Eng., Tokyo, Vol. 27, No. 90, Oct. 1924, p. 876.

the experiments. The observed temperatures were, therefore, corrected afterwards to those corresponding to the mean delivery pressure. Then they were plotted against the separator pressure as shown in Fig. 1; and the curves drawn through the consecutive points, I to VI, exhibited, as it was expected, a shape just like a hysteresis loop.

The thermal quantities of the gases before and after the multiple effect mixing are related by,

$$V_{A''} = (1-x)V_{A'}, \quad I_{A''} = xI_{A'} + (1-x)I_A + V_{A''}(P_{A''} - P_{A'})/J, \quad \text{and} \quad P_{A''} = P_{A'}$$

where A denotes the suction gas, A' the separator gas, A'' the gas in the cylinder just after the multiple effect injection, x the fraction of the refrigerant circulated in the separator circuit, P_A the pressure of the suction gas, V_A the specific volume of the suction gas, I_A the total heat of the suction gas, etc. If we assume, as in the previous paper, that the multiple effect injection gas A' is dry and saturated, the equations will give a unique solution for the separator pressure $P_{A'}$. For any given separator pressure, there will be, however, two points of A' with different qualities satisfying these equations. To verify this, Table II is given, showing these solutions for a case corresponding to the mean condition prevailed during the actual trial. Owing to a slight over-regulation of the injection port, the area of the port was too small to make $P_{A''}$ equal to $P_{A'}$, and the measured separator pressure $P_{A'}$ was always higher than the pressure $P_{A''}$ obtained from the indicator cards. The relation of $P_{A''}$ and $P_{A'}$ during the actual trial is shown in Fig. 2, which was used for the calculations, instead of the equation $P_{A''} = P_{A'}$. The notations in the Table are the same as in the previous paper, and they may be easily understood by comparing the corresponding signs in the $\phi-I$ chart of Fig. 3. From the values obtained in Table II, the loci of the points A' and A'' are drawn on the $\phi-I$ chart as in Fig. 3. They are made up of three discontinuous sections. For the first sections, $A_1'A_2'$ and $A_1''A_2''$, both A' and A'' are located in the superheated region. For the second sections, $A_2'A_3'$ and $A_2''A_3''$, A' is in the wet region, but A'' in the superheated region. And, lastly, for the third sections, $A_3'A_4'A_5'$ and $A_3''A_4''A_5''$, both A' and A'' are in the wet region. The same fact exists when the separator pressure is low and some gaseous refrigerant, as indicated by the point E' in Fig. 3, is circulated in the evaporator. There will also be two points of A' , one saturated and the other wet, satisfying the equations. They are calculated for the separator pressure of 33.8 kg/cm² in Table III,

and plotted in Fig. 3 as A_6' , A_6'' and A_7' , A_7'' . The delivery temperatures calculated are represented in dotted lines against the abscissa of the separator pressure as shown in Fig. 1; in which 1-2 corresponds to the first sections of the loci $A_1'A_2'$ and $A_1''A_2''$ in Fig. 3, 2-3 to the second sections $A_2'A_3'$ and $A_2''A_3''$, and 3-4-5 to third sections $A_3'A_4'A_5'$ and $A_3''A_4''A_5''$. 2-6 and 4-7 in Fig. 1 correspond to $A_2''A_6''$ and $A_4''A_7''$ in Fig. 3.

When the point A' is situated on the section of the loci $A_2'A_3'$ in Fig. 3, a slight increase in the separator pressure will make both x and $V_{A'}$ smaller, then the total volume of the injection gas will be insufficient to fill the cylinder space, and, consecutively, wet gas will be injected into the cylinder. This will make A' more wet, and the unbalance will be accelerated. A final balance is established when the point A' is shifted further into the section $A_3'A_4'A_5'$ of the curve. On the contrary, a slight decrease in the separator pressure will make both x and $V_{A'}$ larger, and this will make the dry gas to circulate, as indicated by E' in Fig. 3, into the evaporator. The point A'' will be shifted on to the curve $A_2''A_6''$ in this case. The points on the sections of the curves $A_2'A_3'$ and $A_2''A_3''$ in Fig. 1 are, therefore, in states of unstable equilibrium, and does not exist in actual cases. That the points on the curves 4-7 in Fig. 1 and $A_4''A_7''$ in Fig. 3 are also unstable, will be proved without much difficulties. Lastly, the sections of the curves $A_1'A_2'$, $A_1''A_2''$ in Fig. 3 and 1-2 in Fig. 1 do not exist in actual cases, unless we have some means to superheat the separator gas A' . The delivery temperature will change, therefore, along 2-6 and 3-4-5 as indicated in the thick dotted lines in Fig. 1. It will be seen that the points II, III, and IV obtained from experiments are located nearly along the curve 3-4-5, and V and VI along 2-6. The point I is between these curves. Joining these points in consecutive order, we have a hysteresis loop as in Fig. 1.

The multiple effect injection of the wet gases as A_3' , A_4' and A_5' of Fig. 3, followed by the compression of wet gases as A_4'' and A_5'' , will cause the losses in volume efficiency and coefficient of performance, due to the effect of the compressor cylinder wall in evaporating very easily the wet vapour during the injection and successive compression. This is proved experimentally as shown in Table I, for they, η_{vol} and γ_a , are very low for the points II, III and IV of the wet injection, and high for the points V and VI of the dry injection. In addition to these disadvantages, the effect of the clearance in reducing the effective suction

stroke is also large for the wet compression, for the later part of the expansion curve of the indicator card extends into the wet region in this case, causing the re-evaporation of the wet vapour. These facts are also varified by the figures given in Table I, and from the shapes of the indicator cards shown in Fig. 4. Fig. 5 gives the compression curves of the indicator cards transformed on the $\phi-I$ chart, and show how the wet compression deviates from the ideal adiabatic line of the constant entropy, resulting in the loss of the coefficient of performance.

From what has been described, the most suitable separator pressure of the multiple effect refrigerating machine can be found experimentally by raising and lowering several times the separator pressure, and observing the temperature of the delivery gas. The theoretical calculations determining the most suitable separator pressure involves a tedious trial and error method, and a slight variation in the condition of the refrigerant will have a comparatively large effect upon the best pressure. We can, therefore, well to utilise these hysteresis phenomena to check the calculated separator pressure whether it is suitable or not to the actual running condition of the machine.

In concluding the paper, the writer wishes to express his hearty thanks to the Mechanical Engineering Department, Faculty of Engineering, Tokyo Imperial University, in permitting him to experiment upon the refrigerating machine of their Department, and to the students of the same College who have very ably assisted him in conducting these experiments.

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Fig. 4.

SCALE OF PRESSURE., kg/cm²

Fig. 5.

Table I.

(Experiments on Dec. 12, 1925)

No. of Experiment	I	II	III	IV	V	VI	Mean
Time	h pm 2:13	h pm 5:55	h pm 8:15	h pm 9:23	h pm 10:18	h pm 11:27	—
Mean temp. of brine, C.	-5.35	-6.29	-5.90	-5.69	-5.40	-4.80	-5.70
Temp. diff. of brine, C.	4.69	3.99	4.19	4.69	4.79	5.20	—
Quantity of brine, litre/mn	21.0	20.3	21.5	20.5	20.2	20.0	—
Sp. gr. of brine	1.1960	1.1963	1.1962	1.1961	1.1961	1.1959	—
Sp. heat of brine	0.7220	0.7210	0.7213	0.7215	0.7215	0.7221	—
Rev. per mn of compressor	158.5	160.0	159.5	159.0	162.0	158.2	159.5
Refrigeration, kcal/h	5105	4190	4670	4983	5014	5395	—
I.H.P. from indicator card.	3.27	3.20	3.27	3.30	3.24	3.28	—
Suct. pr., P_A , kg/cm ²	23.9	24.3	24.4	23.9	23.9	23.6	24.0
Temp. of suct. gas, T_A , C.	-12.5	-12.8	-12.2	-13.4	-12.3	-12.3	-12.6
Sp. vol. of suct. gas, V_A , litre/kg	16.63	16.29	16.29	16.53	16.72	17.01	16.58
Total heat of suct. gas, I_A , kcal/kg	57.65	57.35	57.70	57.30	57.80	57.85	—
Separator pres, $P_{A'}$, kg/cm ²	40.5	44.0	41.9	38.2	34.7	38.2	—
$P_{A''}$, kg/cm ²	35.5	37.6	36.7	35.3	32.7	34.6	—
Delv. pr. by gauge, $P_{B'g}$, kg/cm ² abs.	83.6	79.4	81.6	83.6	85.8	83.3	82.9
Delv. pr. by indicator, $P_{B'i}$, kg/cm ² abs.	84.4	81.6	83.3	86.5	85.8	85.8	84.4
Delv. temp, $T_{B'}$, C., observed	70.0	46.0	52.3	68.0	80.0	76.0	—
Delv. temp, $T_{B'}$, corrected	70.5	50.0	53.5	67.0	79.0	75.6	—
Total heat of delv. gas, $I_{B'}$, kcal/kg	67.00	55.40	58.20	65.90	71.00	69.60	—
$I_{A''}$, kcal/kg	57.95	49.15	51.20	56.90	60.10	59.75	—
$V_{A''}$, litre/kg	11.08	8.71	9.24	10.74	14.26	11.99	—
$V_{A''}/V_A = 1-x$	0.6660	0.5345	0.5673	0.6493	0.7784	0.7050	—
$w = 10 V_{A''}(P_{A''} - P_A)/427$, kcal/kg	3.01	2.07	2.66	2.88	2.78	3.08	—
$I_{A'} = \{I_{A''} - (1-x)I_A - w\}/x$, kcal/kg	49.50	33.88	36.57	47.97	55.72	53.90	—
T_C , C.	29.5	29.6	29.4	29.1	29.8	29.8	29.4
I_C , kcal/kg.	19.90	20.75	20.20	19.30	19.65	20.00	—
$I_E = I_{A'} - (I_{A'} - I_C)/(1-x)$	5.03	9.31	7.71	3.82	9.40	5.70	—
$R' = I_{A''} - I_C - w = (1-x)(I_A - I_E)$	35.04	25.67	28.34	34.72	37.67	36.59	—
$W' = I_{B'} - I_{A''}$	9.05	6.25	7.00	9.00	10.90	9.75	—
$\Sigma W = W' + w$	12.06	8.98	9.66	11.88	13.68	12.81	—
Theoretical coef. of perf., $\gamma_t = \frac{R'}{\Sigma W}$	2.905	2.859	2.934	2.922	2.752	2.855	—
$R'/V_{A''}$, refrig. per litre	3.162	3.061	3.069	3.233	2.640	3.050	—
Vol. coef. due to clearance, η_c	0.911	0.890	0.880	0.898	0.906	0.906	—

Theoret. capacity of ref., kcal/h	6200	5745	5800	6260	5760	5965	—
Vol. efficiency, η_{vol}	0.823	0.735	0.798	0.796	0.870	0.903	—
Actual coef. of perf., γ_a	2.435	2.045	2.226	2.354	2.413	2.565	—
Relative eff., γ_a/γ_t	0.834	0.716	0.759	0.805	0.877	0.898	—

Table II.

	1	2	3	4	5
Separator pres., P_A , kg/cm ²	43.6	39.9	38.7	39.9	43.6
$P_{A''}$, kg/cm ²	37.5	35.7	35.0	35.7	37.5
Suction pres., P_A , kg/cm ²	24.0	24.0	24.0	24.0	24.0
Sp. vol. of suct. gas, V_A , litre/kg	10.35	10.35	10.35	10.35	10.35
Temp. of suct. gas, T_A , C	-12.6	-12.6	-12.6	-12.6	-12.6
Delivery pres., $P_{B'}$, kg/cm ²	84.0	84.0	84.0	84.0	84.0
T_C , C°	29.4	29.4	29.4	29.4	29.4
I_G , kcal/kg	20.0	20.0	20.0	20.0	20.0
$I_{A'}$, kcal/kg	—	—	46.27	42.00	34.00
$I_{A'S}$, kcal/kg (saturation)	54.80	55.48	—	—	—
I_E , kcal/kg	7.45	5.65	5.07	5.65	7.45
$1-x$	0.735	0.712	0.638	0.605	0.528
$V_{A''}$, litre/kg	12.17	11.80	10.58	10.04	8.77
$w=10V_{A''}(P_{A''}-P_A)/427$	3.81	3.23	2.72	2.74	2.75
$I_{A''}$, kcal/kg	62.85	60.21	56.22	54.19	49.21
$I_{A'}=\{I_{A''}-(1-x)(I_A-I_{A'})-w\}/x$	63.00	—	—	—	—
$T_{B'}$, C	84.7	77.0	66.0	61.0	51.0

Table III.

	6	7		6	7
Separator pres., P_A , kg/cm ²	33.8	33.8	$I_{A'}$, kcal/kg	—	41.5
$P_{A''}$, kg/cm ²	32.3	32.3	$I_{A'S}$, kcal/kg (saturation)	56.40	—
Suction pres., P_A , kg/cm ²	24.0	24.0	I_E , kcal/kg	10.40	10.40
Sp. vol. of suct. gas, V_A , litre/kg	10.35	10.35	$1-x$	0.790	0.691
Temp. of suct. gas, T_A , C°	-12.6	-12.6	$V_{A''}$, litre/kg	13.11	11.47
Delivery pres., $P_{B'}$, kg/cm ²	84.0	84.0	$w=10V_{A''}(P_{A''}-P_A)/427$	2.52	2.21
T_C , C°	29.4	29.4	$I_{A''}$, kcal/kg	59.87	54.83
I_G , kcal/kg	20.0	20.0	$T_{B'}$, C°	79.5	64.0