Task 2 : Transport Phenomena Survey

2. TRANSPORT PHENOMENA IN ABSORPTION HEAT PUMPS
Paper Survey

2.1 Introduction

The performance of an absorption machine is greatly affected by the characteristics of the transport phenomena represented by heat and mass transfer. Only a few reports have been published regarding cycle simulations that take the heat and mass transfer characteristics of each heat exchanger into consideration. The development of high performance heat pumps, however, will not be forthcoming unless a fundamental evaluation is made where both heat and mass transfer effects are considered.

For this reason, an effort has been made to review nearly one hundred recent papers related to transport phenomena in absorption machines.

2.2 Classification Criteria and Related Key Items

An absorption heat pump consists, as it is well known, of four major heat exchangers: evaporator, condenser, absorber and generator. The evaporator and condenser, which are also the essential components of conventional compression-type heat pumps, have already been the object of extensive research. Since the main purpose of this review is to gather up-to-date information that will contribute to the improvement of our knowledge of transport phenomena in absorption heat pumps and refrigerators, the focus has been on papers related to the absorber and the generator, where the behavior of an absorbent will have a great effect on the transport characteristics.

Transport phenomena such as momentum transfer, heat transfer, mass transfer and their respective interactions have been included in this review.

In order to set up a matrix of all the papers surveyed by international cooperation, classification criteria were selected for each component according to the following key items.

(A) Absorber

[1] Main Factors of Absorption Phenomena (4 subitems)

[2] Flow Patterns (7 subitems)
[3] Absorption Enhancement Techniques (5 subitems)
[4] Analytical Models for Absorption Phenomena (8 subitems)

(B) Generator

[1] Main Factors of Regenerative Phenomena (4 subitems)
[2] Flow Patterns (7 subitems)
[3] Regeneration Enhancement Techniques (5 subitems)
[4] Analytical Models for Absorption Phenomena (7 subitems)

2.3 Matrix Set-up

The surveyed papers have been classified according to the key items and subitems listed on Table 1. The asterisk marks on the right-hand column indicate the number of papers found on each subject and obey the following categorization:

sufficient information is available	(6 or more marks)
limited information is available	(5 to 3 marks)
little or no information is available	(2 or less marks)

Detailed matrices with specific information on each paper are presented on tables 2[A] and 2[B] for the Absorber and Generator, respectively. The bracketed numbers correspond to the items and the encircled numbers to the subitems listed on Table 1. The usage of the matrices is as follows:

A **search by subject** is started by identifying the appropriate alpha-numeric code on Table 1; Mist Flow, for example, is coded as (A) [2] ⑤ . The code is then entered into the research paper matrices (table 2), from the top of the columns whose alpha-numeric codes correspond to the subject codes on Table 1. The circle marks on the matrix relate papers on each subject to their respective authors. A **search by author** starts directly from the research paper matrix. The paper No. codes (left-hand column) can be used for document retrieval and the subject codes (top of each column) refer to the subjects listed on Table 1.

A search for papers on Mist Flow (item (A)[2] ⑤),for example, would indicateone paper (D131, by Paniev) on Table 2(A), 2/3. A search by author Paniev would indicate papers on Mist Flow as well as Analytical Models for Absorption Phenomena (Theoretical and numerical model,(A)[4] ①, and heat transfer analysis,(A)[4] ②.

2.4 Recommendations for Future Research

The number of papers on **Generators** is conspicuously small, with all but two areas (heat & mass transfer in solution regeneration and heat transfer analysis) falling in the categories of limited, little or no information available. A list of items requiring research on Generators, presented below, prioritizes the subjects according to the scarcity of papers surveyed so far.

Flow patterns	
- flush	(none)
- pulsating flow	"
- bubble flow	(1 paper)
- slug flow	"
- horizontal falling film	(2 papers)
Regeneration	
- stirring and mixing effect	(none)
- electro-magnetic effect	"
- marangoni effect and enhancement tube	(1 paper)
- utilization of vibration effect	"
- regeneration enhancement tube	(2 papers)
Analytical models for boiling or evaporation phenomena	
- thermodynamic model	(none)
- laminar and turbulent flow model	(1 paper)
- vertical and horizontal flow model	"

Although a substantially larger number of papers was obtained on Absorbers, little or no information was found on the following items:

Flow patterns	
- mist flow	(1 paper)
- bubble flow	(2 papers)
- pulsating flow	"
Absorption enhancement techniques	
- electro-magnetic effect	(1 paper)
- utilization of vibration effect	(2 papers)
Analytical models for absorption phenomena	
- thermodynamic model	(1 paper)

The key item and research paper matrices represent an initial frame work whose completion calls for every possible effort in the way of gathering more detailed information. Topics on which little or no information has been found are the ones requiring most attention, followed by those on which limited information is available at present.

Table 2.1 Key items of the surveyed papers

(A) ABSORBER	Number of papers
[1] Main Factors of the Absorption Phenomena	42
① Heat & mass transfer in falling film	*****5*****10*****15*****20*****
② The effect of wave generated at the interface	***
③ Convection & Marangoni effect (including the effect of surface tension and surfactant additives)	***** ****
④ Wettability	*****
[2] Flow Patterns	44
① Static and pooled	***** *
② Vertical falling film	***** ***** ***** *****
③ Horizontal falling film	***** ****
④ Bubble flow	**
⑤ Mist flow	*
⑥ Pulsating flow	**
⑦ Dropwise liquid flow	****
[3] Absorption Enhancement Techniques	28
① Absorption enhancement tube	***** **
② Marangoni effect and surfactant additives	***** ***** ****
③ Utilization of vibration effect	**
④ Stirring and mixing effect	****
⑤ Electro-Magnetic effect	*
[4] Analytical Models for Absorption Phenomena	88
① Theoretical and numerical model	***** ***** ***** ***
② Heat transfer analysis	***** ***** ***** ***** *****
③ Mass transfer analysis	***** ***** ***** ***** ***
④ Laminar and turbulent flow model	*****
⑤ Thermodynamic model	*
⑥ Absorption enhancement model	*****
⑦ Vertical and horizontal flow model	*****
⑧ Others (experimental model, etc.)	***** *
(B) GENERATOR	**Number of papers**
[1] Main Factors of the Regenerative Phenomena	11
① Heat & mass transfer in solution regeneration	***** ***
② Effect of wave generated at the interface	**
③ Wettability of heating surface	
④ Effect of surfactant on boiling or evaporating characteristics	*
[2] Flow Patterns	12
① Pooled	****
② Vertical falling film	****
③ Horizontal falling film	**
④ Bubble flow	*
⑤ Slug flow	*
⑥ Flush	
⑦ Pulsating flow	
[3] Regeneration Enhancement Techniques	4
① Regeneration enhancement tube	**
② Marangoni effect and enhancement tube	*
③ Utilization of vibration effect	*
④ Stirring and mixing effect	
⑤ Electro-Magnetic effect	
[4] Analytical Models for Boiling or Evaporation phenomena	18
① Enhancement mode	****
② Heat transfer analysis	***** **
③ Mass transfer analysis	****
④ Laminar and turbulent flow model	*
⑤ Thermodynamic model	
⑥ Vertical and horizontal flow model	*
⑦ Others	*

Table 2.2 (A) 1/3
Research paper MATRIX

Paper No.	First Author	Working Fluids	(A) ABSORBER [1] ①	[1] ②	[1] ③	[1] ④	[2] ①	[2] ②	[2] ③	[2] ④	[2] ⑤	[2] ⑥	[2] ⑦	[3] ①	[3] ②	[3] ③	[3] ④	[3] ⑤	[4] ①	[4] ②	[4] ③	[4] ④	[4] ⑤	[4] ⑥	[4] ⑦	[4] ⑧	Remarks
D019	Brauner,N. et al.																										
D268	Burdukov,A.P. et al.																										
B043	Burnett,J.C. et al.	NH_3/H_2O			○										○												Organic additives(19)
D021	Butz,Dieter et al.	NH_3/H_2O	○					○												○	○	?	?		?		
D223	Fujita,T	$H_2O/LiBr$, NH_3/H_2O etc.	○	○	○	○	○	○	○			○	○	○	○		○										Review paper, CH_3OH, C_2H_5OH, CFC included
D261	Gabsi,S. et al.																										
D045	Genest,Bernard																										
D051	Gottier,G.N. et al.									○			○			○											
D197	Grossman,G.		○	○	○			○							○		○		○	○	○	○		○			
D057	Grossman,G.		○																○	○	○						Inner diffusion effect
D056	Grossman,G. et al.		○	○														○	○	○	○				○		Eddy diffusivity
D063	Guha,D.K. et al.	Air/CO_2-H_2O										○										○					Pulsive & circulating flow
D071	Iedema,P.D.																										
D199	Iedema,P.D. et al.													○													Corrugated heat & mass exchanger
D276	Infante Ferreira,C.A																										
D274	Infante Ferreira,C.A et al.																										
D072	Infante Ferreira,C.A et al.																										
D203	Inoue,N.	$H_2O/LiBr$	○					○												○	○				○	○	Concentration coefficient NTU
D211	Inoue,N.	$H_2O/LiBr$	○		○			○												○	○				○	○	Non-condensable gas effect
D213	Inoue,N.	$H_2O/LiBr$	○					○												○	○				○	○	Absorption heat considered
D209	Inoue,N. et al.	$H_2O/LiBr$	○					○							○												
D210	Inoue,N. et al.	$H_2O/LiBr$	○				○																				
D208	Inoue,N. et al.	$H_2O/LiBr$			○				○					○													Pin-fin tube, Knurl tube, Marangoni
B088	Iyoki,S. et al.	$H_2O/LiBr$																									

Table 2.2 (A) 2/3
Research paper MATRIX

Paper No.	First Author	Working Fluids	(A) ABSORBER [1]				[2]							[3]					[4]								Remarks
			①	②	③	④	①	②	③	④	⑤	⑥	⑦	①	②	③	④	⑤	①	②	③	④	⑤	⑥	⑦	⑧	
A093	Jennings,B.H. et al.	NH_3/H_2O-LiBr																									
B097	Kashiwagi,T. et al.	H_2O/LiBr			○		○								○					○				○			Basic model for Marangoni
D228	Kashiwagi,T. et al.	H_2O/LiBr	○					○							○												Vertical falling film
D230	Kashiwagi,T. et al.	H_2O/LiBr	○					○							○									○			Visualization of Marangoni
D245	Kashiwagi,T. et al.	H_2O/LiBr													○												Isomer of additives
D241	Kashiwagi,T. et al.	H_2O/LiBr													○									○			
D243	Kashiwagi,T. et al.	NH_3H_2O					○								○												NH_3 ternary system
D206	Kiyota,M. et al.	H_2O/LiBr							○																		
D202	Kohno,K. et al.	H_2O/LiBr	○					○						○						○	○						Air-cooled absorber
D227	Kunugi,Y. et al.	H_2O/LiBr	○						○					○						○	○						
D091	Le Goff,H. et al.		○																								
D092	Le Goff,H. et al.		○																			○					
D093	Le Goff,H. et al.		○																								
D198-0	Le Goff,H. et al.	H_2O/LiBr	○																○			○					
D098	Luk,S. et al.																										Gas absorption.Theoretical
D102	Mashelkar,R.A.et al.																										
B123	Matsuda,A. et al.	H_2O/LiBr	○					○											○								One-dimensional diffusion model
D103	McCready,M.J. et al.																										Gas absorption
D104	McCready,M.J. et al.																										Gas absorption
D108	Michel,J.W.														○												
D207	Morioka,I. et al.	H_2O/LiBr					○												○								
D258	Morioka,I. et al.	H_2O/LiBr	○					○																		○	Experimental

Table 2.2 (A) 3/3
Research paper MATRIX

Paper No.	First Author	Working Fluids	(A) ABSORBER [1] ①	[1] ②	[1] ③	[1] ④	[2] ①	[2] ②	[2] ③	[2] ④	[2] ⑤	[2] ⑥	[2] ⑦	[3] ①	[3] ②	[3] ③	[3] ④	[3] ⑤	[4] ①	[4] ②	[4] ③	[4] ④	[4] ⑤	[4] ⑥	[4] ⑦	[4] ⑧	Remarks
D204	Nakao,K. et al.	H_2O/LiBr	○					○											○	○							Vertical heat exchanger
D212	Ogawa,K. et al.	H_2O/LiBr	○						○																		
D218	Ozono,T. et al.	H_2O/LiBr	○						○																		
D232	Ohuchi,T. et al.	H_2O/LiBr	○					○						○													Air-cooled double effect
D234	Ohuchi,T. et al.	H_2O/LiBr						○																			Inner tube absorption
D200	Nagaoka,Y. et al.	H_2O/LiBr			○				○					○	○												Evaluation analysis
D201	Nagaoka,Y. et al.	H_2O/LiBr																		○							High performance tube
D131	Paniev,G.A.	H_2O/LiBr									○								○	○							
D139	Prevost,M. et al.	H_2O/LiBr																	○	○							3 types of new absorbers
D194	Ramadane,A. et al.	H_2O/LiBr	○					○									○				○						Turbulent promoters
D145	Reimann,R.C.	H_2O/LiBr CH_3NH_2/LiBr																	○								New absorption cycle
D146	Renker,M. et al.	NH_3/H_2O																									300-3000 kW class AHP
D152	Schlerkmann,H.et al.																										Inhibitors
D156	Schulze,G. et al.									○						○											Gas-absorption
D214	Sekoguchi,K. et al.	H_2O/LiBr				○			○											○	○						Evaluation method
D161	Sotelo,J.L. et al.	Glycerol/CO_2						○									○				○						Vertical absorption tower
D162	Soumerai,H.																										Thermodynamic generalization
D163	Spedding,P.L. et al.	NH_3/H_2O																									Packed tower absorber
E027	Uddholm,H. et al.																										Calculation procedure
D205	Urakawa,K. et al.	H_2O/LiBr																									Vertical falling film
D259	Urakawa,K. et al.	H_2O/LiBr																									Vertical falling film
D173	Wassenaar,R.H.																										Falling droplets thin film
D174	Wassenaar,R.H.et al.																										Falling droplets thin film
D177	Wilkinson,William H.																										Countercurrent flow Abs.
D178	Witte,I. et al.	SO_2/Na_2CO_3 Aq.																									
D179	Yeung,P.O. et al.																										Gas-liquid reactor
A238	Zawacki,T.S. et al.	H_2O/LiBr																									Static absorber
A237	Zawacki,T.S. et al.	H_2O/LiBr																									
D265	van der Wekken,B.J.C																										

Table 2.2 (B)
Research paper MATRIX

Paper No.	First Author	Working Fluids	(B) GENERATOR [1] ①	②	③	④	[2] ①	②	③	④	⑤	⑥	⑦	[3] ①	②	③	④	⑤	[4] ①	②	③	④	⑤	⑥	⑦	⑧	Remarks
D196	Dorokhov, A.R. et al.	H_2O/LiBr																	○								Polymer coating surface
D223	Fujita, T.	H_2O/LiBr, NH_3/H_2O etc.	○					○							○				○	○							Review paper
D251	Kimura, T. et al.	H_2O/LiBr					○													○							Pool boiling heat transfer
D237	Kohno, K. et al.	H_2O/LiBr	○							○														○			Inside a horizontal tube
D263	Kouremenos, D.A. et al.	NH_3/H_2O																									
D090	Kumar, P. et al.	H_2O/LiCl		○																○	○						Solar, Open cycle
D226	Kunugi, Y. et al.	H_2O	○						○					○													Evaporator
D260	Kunugi, Y. et al.	H_2O/LiBr	○						○					○						○							Heated by hot water
D091	Le Goff, H. et al.		○					○												○	○						Modeling applicable to AHP
D198 -01	Le Goff, H. et al.	H_2O/LiBr	○					○											○	○	○						Modeling applicable to AHP
D224	Matsuda, A. et al.	H_2O/LiBr	○					○											○	○	○	○					Evaporation rate
D109 -01	Michel, J.W. et al.	H_2O/LiBr				○	○								○											○	Experimental boiling enhancement by additives
D113	Moellenbruck, W.																										Two-component mathematical model
D239	Nishiguchi, A. et al.	H_2O/LiBr		○																							
B144	Ohuchi, T.	R22/E181	○								○																Air heat source AHP
D236	Watanabe, O. et al.	H_2O/LiBr-Ethylene Glycol					○																				Low pressure boiling
D252	Yoshitomi, H. et al.	H_2O/LiBr					○																				

Table 2.3 Main properties of screened refrigerants

◎ Main properties of screened refrigerants

	Water	Ammonia	Methanol	Methyl amine	R22	R133a	R123a	R134a	TFE	HFIP
Chemical Formula	H_2O	NH_3	CH_3OH	CH_3NH_2	CHF_2Cl	$CHF_2CH-ClF$	$CHClFC-ClF_2$	CF_3CH_2F	CF_3CH_2OH	$C_3H_2F_6O$
Structural Formula	H O H	H N H H	H H C H OH	H H C H NH_2	F H C Cl F	F H H C C Cl F F	Cl F H C C Cl F F	F H F C C F F H	F H F C C OH F H	F H F F C C C F FOH F
Molecular Weight	18.0	17.0	32.0	31.1	86.5	118.5	152.9	102.0	100.0	168.0
Specific Gravity (25·C)	0.997	0.681 (b.p.)	0.787	0.694 (b.p.)	1.409 (b.p.)	1.365 (20·C)	1.498 (27.4·C)	1.223 (b.p.)	1.391 (20·C)	1.617 (20·C)
Melting Temp. (·C)	0	-77.9	-98.0	-93.4	-160	—	—	—	-45.0	-4
Boiling Temp. (·C)	100.0	-33.3	65.0	-6.1	-40.8	8.0	29.4	-26.3	73.6	58.0
Critical Temp. (·C)	374.15	132.4	239.43	156.9	96.0	—	—	106.0	249.3	~195
Viscosity (cP)(25·C)	0.9	0.13	0.58	0.24 (0·C)	0.013	—	—	—	1.75	1.95 (20·C)
Thermal Conductivity (mW/m·K) 7·C	576	524	207.8	16.3	9.4	—	—	—	—	—
Latent Heat of Vaporization (KJ/Kg) (0·C)	2502	1263	1248	859	205	208	183	204	441	428
Enthalpy of evaporation per mole relative to that water	1	0.477	0.887	0.593	0.394	0.552	0.621	0.462	0.979	1.597
Thermal stability	○	○	○	○	△	△	△	△	○	○
Toxicity	no	yes	yes	yes	no	yes	no	unknown	unknown	unknown
Corrosion	no	yes	yes	yes	unknown	unknown	unknown	unknown	unknown	unknown
Flammability	no	yes	yes	yes	unknown	unknown	less	less	less	no
How to obtain	easy to obtain	easy to obtain	easy to obtain	less than 500 yen/kg	less than 800 yen/kg	difficult to obtain	less than 830 yen/kg	less than 1320 yen/kg	expensive	
Enviromental destruction ODP* GHP**					0.05 0.07	≦0.05 <0.1		0 <0.3		
Remarks ○ : Promising refrigerant in this paper	impossible to refrigerate ○	lethal dose 10000ppm (3hr) ○	high viscosity	○	large pumping losses ○	Toxicity problem for afetus ×	○	large pumping losses △	○	○

* Ozone Depression Potential.(R11=1.0) ** Green House Potential.(R12=1.0) 1$ 140yen

Table 2.4 Refrigerant-absorbent system

◎ Refrigerant—Absorbent Systems

Refrigerant	Absorbent		Boiling Temperature(℃)	Chemical Formula of Absorbent	Remarks	f	$10^3 n$	n_L	Temp. conditions (℃) T_E	T_C	T_A	T_G	Evaluation
H_2O	Lithium bromide		1265	LiBr	Commercially available		0.03	0.65	5	35	35	90	☆
		Lithium iodide	1190	LiBr/LiI	Lower crystallization temp.								○
		Lithium thiocyanate	-----	LiBr/LiSCN	Instability in high temp.								△
		Lithium acetate	Decomposition	$LiBr/LiCH_3CO_2$	High viscosity								×
		Lithium perchlorate	100 Decomposition	$LiBr/LiClO_4$	Ineffective								△
		Lithium nitrate	600 Decomposition	$LiBr/LiNO_3$	Lower crystallization temp. Industrial high temp.boostin								○
		Lithium chlorate	300 Decomposition	$LiBr/LiClO_3$	High corrosive								×
		Lithium chloride	1357	LiBr/LiCl 2:1	Improves the C.O.P. Reduction of working limits								△
		Ethylene glycol	197.6	$LiBr/C_2H_6O_2$	Improves the C.O.P. Lower crystallization temp.								○
		Zinc chloride	732	$LiBr/ZnCl_2$ 1:1	Improves the C.O.P. Lower crystallization temp.								○
		Zinc bromide	650	$LiBr/ZnBr_2$ 0.4:1	Increase of circulation ratio of solution								△
		Lithium chloride & Lithium thiocynate		LiBr/LiCl/LiSCN	Lower crystallization temprature								○
	Sodium hydroxide		1390	NaOH	Corrosion Industrial heat pump								△
$H_2O/C_7H_{16}O$ *	Lithium bromide		1265	LiBr	Auxiliary fluid High C.O.P.								○
NH_3	Water		100	H_2O	Necessity for rectification High temperature boosting	4.28	6.56	1.15	0	50	50	150	☆
		Lithium bromide		$H_2O/LiBr$	Lower mass diffusion coefficient								△
		Lithium nitrate		$H_2O/LiNO_3$		5.25	6.49	0.98	0	50	50	150	
	1,4-Butanediol		235	HOC_4H_8OH	High C.O.P. and Low n_L								○
	Lithium thiocyanate		----	LiSCN	High C.O.P.,No rectification								○

* 2,4-Dimetyl-3-Pentanol

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Refrigerant	Absorbent	Boiling Temperature(℃)	Chemical Formula of Absorbent	Remarks	f	$10^3 n$	n_L	Temp. conditions (℃)				Evaluation
								T_E	T_C	T_A	T_G	
CH_3OH	Lithium bromide	1265	LiBr	High C.O.P., High viscosity		0.16	0.58	-5	45	40	100	☆
	Lithium bromide / Zinc bromide	650	$LiBr/ZnBr_2$ 1:1, 2:1	Lower crystallization temp. High viscosity		0.43	1.28	15	45	40	100	△ △
	Lithium iodide	1190	LiBr/LiI									
CH_3NH_2	Lithium thiocynate / Sodium thiocynate		LiSCN/NaSCN	Appropriate operating pressure		6.0	0.16	-15	45	40	100	○
	Ethylene glycol	197.6	$C_2H_6O_2$		6.37	5.15	1.72	0	50	50	150	○
R22	DMETEG (Dimethylether tetraethylene glycol) [E181]	275.6	$CH_3(OC_2H_4)_4OCH_3$	High thermal stability Low C.O.P.	5.89	38.76	4.58	0	50	50	150	○
	DMEDEG (Dimethylether diethylene glycol) [E141]	162.2	$CH_3(OC_2H_4)_2OCH_3$	Possibility for air-cooling								○
	DMETrEG (Dimethylether triethylene glycol)	216.1	$CH_3(OC_2H_4)_3OCH_3$		5.59	36.89	4.28	0	50	50	150	
	DMMP (Dimethyl methyl phosphonate)	79.5	$CH_3PO(OCH_3)_2$	Nontoxic but necessity for rectification								△
	DMF (N,N-Dimethyl formamide)	150.0	$CHON(CH_3)_2$	High C.O.P., Bad Heat Proof	6.0			-5	32	28	90	×
	DMA (N,N-Dimethyl acetamide)	165.0	$CH_3CON(CH_3)_2$		5.3			-5	32	28	90	
R133a	ETFE (E[illegible] tetrahydro [illegible]furyl ether)	157.8	$(C_4H_7O)CH_2OC_2H_5$	Necessity for rectification								△
	E181	275.6	$CH_3(OC_2H_4)_4OCH_3$	Toxic in refrigerant								△
R123a	ETFE	157.8	$(C_4H_7O)CH_2OC_2H_5$	Applicable to advanced cycle	4.29	4.14	3.66	0	50	50	150	○
	E181	275.6	$CH_3(OC_2H_4)_4OCH_3$		5.80	4.91	4.98	0	50	50	150	
TFE	QUN (Quinoline)	240.5	C_9H_7N	High solubility, Corrosive								△
	E181	275.6	$CH_3(OC_2H_4)_4OCH_3$	High COP, Industrial heatpump								☆
	NMP (N-Methyl-2-pyrrolidone)	201.1	C_5H_9NO	Increase of C.O.P., Toxic. High thermal stability	3.04	0.205	0.86	0	50	50	150	○
	DMEU (1,3 Dimethyl-2-imidazolidinone)	223.0	$C_5H_{10}N_2O$		3.83	0.242	1.25	0	50	50	150	△
	DMPU (1,3 Dimethyl-3,4,5,6 tetrahydro-2 (1H)-pyrimidinone)	232.0	$C_6H_{12}N_2O$		4.54	0.283	1.56	0	50	50	150	△
HFIP	E181	275.6	$CH_3(OC_2H_4)_4OCH_3$		2.45	0.44	0.92	0	50	50	150	
	DMPU	232.0	$C_6H_{12}N_2O$									

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Task 3 : Absorption Cycles Survey

3. STUDIES ON CYCLES OF ADVANCED ABSORPTION HEAT PUMP SYSTEMS

3.1 Introduction

This Working Group has been engaged in studies on cycles of absorption heat pumps. There is much literature on absorption heat pumps. So the authors have selected major literature to begin with, then determined the methods for cycle classification and evaluation, and finally reported the results of evaluation and selection of high efficiency absorption cycles suitable for cooling/heating in three steps.

3.2 Literature Survey

20 pieces of literature covering 70 cycles were surveyed. Shown below are examples of major pieces of literature.

(1) F. C. Hayes, R. J. Modahl, "Evaluation of Advanced Design Concepts for Absorption Cycles", Proceedings of the DOE/ORNL Heat Pump Conf., 1985

(2) B. A. Phillips, "High Efficiency Absorption Cycles for Residential Heating and Cooling", Int. SOC Energy Covers. Eng. Conf., Vol. 20, No. 2

(3) E. Podesser, "The Absorption Heat Pump - State of the Art and Prospect, Newsletter of the IEA Heat Pump Center", Vol. 2, No. 1/2, 1984

(4) G. Grossmann, "Multistage Absorption Heat Transformers for Industrial Applications", ASHRAE Transactions, Vol. 91, pt2B, 1985

(5) G. Alefeld, F. Ziegler, "Coefficient of Performance of Multistage Absorption Cycles", Int. J. Refrig., Vol. 10(5), 1987

In literature (1) and (2), many types of advanced absorption heat pump were proposed, while literature (3) and (4) were very useful for classification/evaluation of cycles, and literature (5) was very instructive to cycle COP calculation.

3.3 Definition of Terms concerning Cycles

For the purpose of classification and evaluation of cycles, terms concerning cycles shall be pigeonholed and defined.

3.3.1 Terms related to Classification of Cycles

(1) effect : value of theoretical efficiency of cycle in the cooling mode

(2) stage : number of evaporator(s)-absorber(s) or condenser(s) -generator(s) which do not affect the theoretical efficiency
(3) cascade : type of working fluids
(4) refrigerator : cooling cycle
(5) heat pump : type 1 heat pump
(6) heat transformer : type 2 heat pump
(7) heat pump transformer : combination of heat pump and heat transformer

3.3.2 Terms concerning cycles having Heat Exchanger
(1) AX (Absorber Heat Exchange) cycle : cycle having a heat exchanger between absorber and absorbent
(2) GX (Generator Heat Exchange) cycle : cycle having a heat exchanger between generator and absorbent
(3) GAX (Generator Absorber Heat Exchange) cycle : cycle having a heat exchanger between generator and absorber

Table 1 shows examples of cycles named according to the definition above.

3.4 Method for Classification of Cycles

By referring to Grossmann's literature, the authors adopted a method for classifying cycles by system type and cycle type, and also by temperature level, pressure level and concentration level.

(1) System type

A system type shows the manner in which main components (absorber, generator, evaporator, condenser) of an absorption cycle are combined. As shown in Table 3-2～Table 3-18, there exist 17 system types.

(2) Cycle type

A cycle type shows the manner in which working fluids in an absorption cycle are flown. Even with the same system type, there exist plural cycle types as shown in Table 3.2～Table 3.18.

(3) Temperature level

A temperature level shows the number of temperature T_i (i = 1,2, -----) given on the temperature axis (X-axis) when an absorption cycle is indicated on Dühring diagram. Fig. 3-1 shows an example of single-effect cycle whose temperature level is 3.

(4) Pressure level

A pressure level shows the number of pressure P_j (j = 1,2, -----) given on the pressure axis (Y-axis) when an absorption cycle is indicated on Dühring diagram. Fig. 3-1 shows an example of single-effect cycle whose pressure level is 2.

(5) Concentration level

A concentration level shows the number of oblique line(s) C_k (k = 1,2, -----) which shows a condition of working fluids when an absorption cycle is indicated on Dühring diagram. Fig. 3-1 shows an example of single-effect cycle whose concentration level is 2.

3.5 First Step of Cycle Evaluation

3.5.1 Evaluation Method

The first step of cycle evaluation is such that various types of cycle classified by system type, cycle type, temperature level, pressure level and concentration level are evaluated in terms of five evaluation items as explained below:

(1) NM (Number of Main Components)

Shows the number of component evaporator(s), condenser(s), absorber(s) and generator(s). The smaller the NM, the better. It is 4 in the case of single-effect cycles.

(2) NA (Number of Auxiliary Components)

Shows the number of component solution heat exchanger(s) and pump(s). The smaller the NA, the better. It is 2 in the case of single-effect cycles.

(3) COP (Coefficient of Performance)

Shows the theoretical efficiency in the cooling/heating modes. Assuming that the COP in the cooling mode is η_R and that in the heating mode is η_R, it is defined by the following equations. The higher the COP, the better. Here, the heat quantity exchanged by each component is assumed to be equal. The COP is 1, 2 in the case of single-effect cycles.

$$\eta_R = \Sigma Q_E \ / \ \Sigma Q_G \quad \text{------------------------------------}(1)$$

$$\eta_H = \Sigma (Q_A + Q_C) \ / \ \Sigma Q_G \quad \text{------------------------------}(2)$$

where Q_A : heat quantity of absorber
Q_C : heat quantity of condenser
Q_E : heat quantity of evaporator
Q_G : heat quantity of generator

(4) TSC (Transfer Surface Coefficient)

Shows the ratio of heat quantity effectively utilized for cooling/heating, to total heat quantity exchanged by the main components in the cooling/heating modes. Assuming that the COP in the cooling mode is η_R and that in the heating mode is η_H it is defined by the following equations. The larger the TSC, the better. It is 1/4, 2/4 in the case of single-effect cycles.

$$\eta_R = \Sigma Q_E \ / \ \Sigma (Q_A + Q_C + Q_E + Q_G) \quad \text{----------------------}(3)$$

$$\eta_H = \Sigma (Q_A + Q_C) \ / \ \Sigma (Q_A + Q_C + Q_E + Q_G) \quad \text{-----------}(4)$$

(5) TF (Temperature Factor)

The TF is an indicator of the heating temperature of working fluids, and defined by the following equation referring to the single-effect cycle in Fig. 3-2. Incidentally, by taking account of heat resistance of working fluids, it is desirable that the TF be smaller than 3. It is 1 in the case of single-effect cycles.

$$TF = (T_3 - T_2) / (T_2 - T_1) \quad \text{------------------------} \quad (5)$$

3.5.2 Evaluation Criteria

Evaluation criteria for the five evaluation coefficients are shown in Table 3-19. Cycles with smaller NM, NA and TF and larger COP and TSC are highly evaluated in the first step of evaluation.

3.5.3 Evaluation Results

72 cycles selected through literature survey were evaluated in terms of five evaluation coefficients, with the result that best four cycles shown in Fig. 3-1 were selected. Usually, No. 1 cycle is called a single-effect cycle, and No. 2 cycle a double-effect cycle. No. 3 cycle is a transformed double-effect cycle, and No. 4 cycle is an advanced cycle called a resorption cycle.

3.5.4 Problems

Although the four cycles were selected through the first step of evaluation, the following problems have been identified in the process of evaluation.

(1) There are four types of cycles hard to classify/evaluate.
   ① Cycles as a combination of absorption type and compression type.
   ② Cycles, such as GAX, that have heat exchangers in their absorber/generator.
   ③ Heat pump transformers.
   ④ Cycles having more than 2 types of chilled/hot water temperature level.

(2) Since the concentration is expressed by a straight line, there is no concept of concentration difference. Since, in actual cycles, working fluids circulate, the concetration difference occurs in absorbent.

3.6 Second Step of Cycle Evaluation

3.6.1 Evaluation Method

Concerning the four cycles selected through the first step of evaluation, their cycle working range (temperature, pressure, concentration) is examined under temperature conditions shown in Table 3-22, in order to evaluate the possibility of each cycle to be commercialized. In this case, the concentration difference of absorbent is assumed to be 0. The types of working fluids to be examined are shown below. 1 to 3 types of working fluids have been selected for each of the four representative refrigerant groups. All these working fluids are already expressed on Dühring chart.

(1) Water group
- ① WA + LB

(2) Ammonia group
- ① AM + WA
- ② AM + LNT/WA
- ③ MA + EG

(3) Alcohol group
- ① MA1 + LB/WA
- ② MA1 + LB/WA
- ③ TFE + NMP

(4) (H)CFC group
- ① R22 + DMETrEG
- ② R22 + DMETEG
- ③ R123a + DMETEG

3.6.2 Evaluation Criteria

Thermodynamic properties of working fluids, which serve as evaluation criteria, are shown in Table 3-22. If, under the temperature conditions shown in Table 3-22, maximum temperature, maximum pressure and maximum concentration of working fluids are below the criterional values, it is judged that the cycle commercialization is possible.

(1) Maximum temperature T_{MAX}

Taking account of heat resistance of working fluids, maximum temperature shall be below 160 [℃].

(2) Maximum pressure P_{MAX}

Taking account of auxiliary power of pump, maximum pressure shall be below 2000 [kPa].

(3) Maximum concentration C_{MAX}

In the case of working fluids of solid-liquid system, the concentration shall be smaller than the concentration of crystallization. In the case of working fluids of liquid-liquid system, the concentration of refrigerant shall be over 5 [%].

3.6.3 Evaluation results

The results of the second step of evaluation are shown in Table 3-23. In Table 3-23, symbols have the following meaning:

(1) ○ denotes that commercial operation of cycle is possible when temperature, pressure and concentration of working fluids are below the criterional values.

(2) △ denotes that commercial operation is difficult to realize, since maximum temperature is over 160 [℃] or maximum pressure is over 2000 [kPa].
(3) × denotes that cycle cannot be established, since maximum concentration of working fluids is higher than criterional value.

3.6.4 Problems

In the process of the second step of evaluation, the following problems have been identified.

(1) Treatment of concentration differnce remains yet to be determined. In the second step of evaluation, too, the cycle working range was examined by assuming the concentration difference of absorbent to be zero.
(2) Only single-effect cycles are capable of heat pump operation in the heating mode. Therefore, it was found that only the single-effect cycles are capable of commercial operation in both the cooling and heating modes with the same cycle. Thus, it is necessary to devise a new cycle other than the four selected cycles, and also examine the possibility of cycle change-over between cooling and heating modes.
(3) The evaluation method for cycles, such as GAX, whose heat exchange is performed internally, remains yet to be determined.

3.7 Third Step of Evaluation

3.7.1 Evaluation Method

3.7.1.1 Basic Approach

COP of cycles, which were found operative by the second step of evaluation, is calculated, and evaluated in terms of efficiency. Taking account of the problems identified through the first and second steps of evaluation, the basic approach to the third step of evaluation was determined as follows.

(1) Take account of the concentration difference.
(2) Evaluate such cycles as GAX that exchange heat internally.
(3) In addition to No. 1 to No. 4 cycles selected by the first step of evaluation, two-cascade cycles using two types of working fluids are included in cycles to be evaluated — a two-cascade triple-effect refrigeration cycle (No. 5) in the cooling mode, and a two-cascade heat pump cycle (No. 6) in the heating mode.

3.7.1.2 Cycles to be evaluated

Cycles in the cooling mode are as follows:

(1) No. 1 cycle (Single-effect refrigeration)
(2) No. 2 cycle (Double-effect refrigeration)
(3) No. 3 cycle (Double-effect refrigeration)
(4) No. 4 cycle (Double-effect refrigeration)
(5) No. 5 cycle (Two-cascade triple-effect refrigeration)

Cycles in the heating mode are as follows:

(1) No. 1 cycle (Single-effect heat pump)
(2) No. 2 cycle (Double-effect heat pump)
(3) No. 3 cycle (Double-effect heat pump)
(4) No. 4 cycle (Double-effect heat pump)
(5) No. 6 cycle (Two-cascade heat pump)

Here, cycles No. 2 to No. 6 shall be called "multistage cycle".

3.7.1.3 Working Fluids to be evaluated

(1) WA + LB
(2) AM + WA
(3) TFE + NMP
(4) R22 + DMETEG

3.7.2 Evaluation Criteria

In the third step of evaluation, cycles to be evaluated are evaluated in terms of COP values in the cooling and heating modes. Evaluation criteria in both modes are shown in Table 24. In both cases, the COP shall be higher than 1.2.

3.7.3 Method for calculating the COP of Single-effect Cycle

3.7.3.1 Assumption

The assumption when calculating the COP is shown below.

(1) A refrigerant heat exchanger shall be neglected.
(2) The temperature efficiency of heat exchangers shall be assumed to be 100%.

3.7.3.2 Definition of COP

As shown in Table 3-25, a single-effect cycle has three functions, and the COP of each function is defined as follows.

(1) Refrigerator

$$\eta_R = Q_E / Q_G \quad \text{------------------------------} \quad (6)$$

(2) Heat pump

$$\eta_R = (Q_A + Q_C)/Q_G = 1 + \eta_R \quad \text{------------------} \quad (7)$$

(3) Heat transformer

$$\eta_T = Q_A / (Q_E + Q_G) \quad \text{------------------------} \quad (8)$$

3.7.3.3 How to seek the Concentration

The method for seeking the concentration of absorbent in a single-effect cycle is explained below, referring to Fig. 3.3.

(1) Concentration of strong solution

The concentration of strong solution shall be either smaller of equilibrium concentration at 160 [℃] of absorbent temperature or concentration of absorbent crystallization, under saturated condenser vapor pressure.

(2) Concentration of weak solution

The concentration of weak solution shall be equilibrium concentration at T_C of absorber outlet temperature of absorbent, under saturated evaporator vapor pressure.

3.7.3.4 How to seek the COP

Since the method for heat exchange in the cycle differs according to the concentration difference, the method for seeking the COP in three cases is explained by using Table 3-26.

(1) Case of small concentration difference

For heat exchange in the cycle, only the solution heat exchanger is considered.

Heat quantity exchanged by the solution heat exchanger Q_{EX1} is given by the followng equation:

$$Q_{EX1} = G_{SL2} (H_{SL4} - H_{SL5}) = G_{SL1} (H_{SL7} - H_{SL6}) \text{------- (9)}$$

where G_{SL1} : Weak solution mass flow rate

G_{SL2} : Strong solution mass flow rate

H_{SL4} : Enthalpy of absorbent at the point ④

Heat quantity of the generator Q_G and heat quantity of the absorber Q_A are given by the following equations:

$$Q_G = 0.5\, G_{RV} (H_{RV3} + H_{RV4}) + G_{SL2} H_{SL4} - G_{SL1} H_{SL7} \text{ ------------ (10)}$$

$$Q_A = G_{RV} H_{RV1} + G_{SL2} H_{SL5} - G_{SL1} H_{SL6} \text{ ------------ (11)}$$

$$G_{RV} = G_{SL1} - G_{SL2} \text{ ------------ (12)}$$

where G_{RV} : Total mass flow rate of refrigerant vapor

H_{RV3} : Enthalpy of refrigerant vapor at the point ③

(2) Case of middle concentration difference

For heat exchange in the cycle, AX (heat exchange between absorber and weak solution), GX (heat exchange between generator and strong solution), and liquid heat exchanger are considered.

Heat quantity exchanged by the solution heat exchanger Q_{EX1}, heat quantity exchanged by the AX, Q_{EX2}, and heat quantity exchanged by the GX, Q_{EX3}, are given by the following equations:

$$Q_{EX1} = G_{SL2} (H_{SL8} - H_{SL5}) = G_{SL1} (H_{SL11} - H_{SL7}) \text{----- (13)}$$

$$Q_{EX2} = G_{SL1} (H_{SL7} - H_{SL6}) = G_{RV2} H_{RV1} + G_{SL2} H_{SL5} - (G_{SL2} + G_{RV2}) H_{SL9} \text{ ------------ (14)}$$

$$Q_{EX3} = G_{SL2} (H_{SL4} - H_{SL8})$$

$$= 0.5\ G_{RV3}\ (H_{RV3} + H_{RV10}) + (G_{SL1} - G_{RV3})\ H_{SL10} - G_{SL1}\ H_{SL11} \text{ --------- } (15)$$

where G_{RV2} : Mass flow rate of refrigerant in absorber whose heat is exchanged by AX

G_{RV3} : Mass flow rate of refrigerant in generator whose heat is exchanged by GX

Heat quantity of the generator Q_G and heat quantity of the absorber Q_A are given by the following equations:

$$Q_G = 0.5\ (G_{RV} - G_{RV3})\ (H_{RV10} + H_{RV4}) + G_{SL2}\ H_{SL4} - (G_{SL1} - G_{RV3})\ H_{SL10} \text{ ------------ } (16)$$

$$Q_A = (G_{RV} - G_{RV2})\ H_{RV1} + (G_{SL2} + G_{RV2})\ H_{SL9} - G_{SL1}\ H_{SL6} \text{ ------------- } (17)$$

(3) Case of large concentration difference

For heat exchange in the cycle, GAX (heat exchange between generator and absorber), AX and GX are considered.

Heat quantity exchanged by the AX, Q_{EX2}, heat quantity exchanged by the GX, Q_{EX3}, and heat quantity exchanged by the GAX, Q_{EX4}, are given by the following equations:

$$Q_{EX2} = G_{SL1}\ (H_{SL3} - H_{SL6}) = G_{RV2}\ H_{RV1} + (G_{SL2} + G_{RV4})\ H_{SL8} - (G_{SL2} + G_{RV4} + G_{RV2})\ H_{SL8} \text{ ---------------- } (18)$$

$$Q_{EX3} = G_{SL2}\ (H_{SL4} - H_{SL5}) = 0.5\ G_{RV3}\ (H_{RV7} + H_{RV10}) + (G_{SL1} - G_{RV5} - G_{RV3}) H_{SL10} - (G_{SL1} - G_{RV5})\ H_{SL7} \text{ ----------------------- } (19)$$

$$Q_{EX4} = G_{RV4}\ H_{RV1} + G_{SL2}\ H_{SL5} - (G_{SL2} + G_{RV4})\ H_{SL8} = 0.5\ G_{RV5}\ (H_{RV3} + H_{RV7}) + (G_{SL1} - G_{RV5})\ H_{SL7} - G_{SL1}\ H_{SL3} \text{ ---------------------------------- } (20)$$

where G_{RV4} : Mass flow rate of refrigerant in absorber whose heat is exchanged by GAX

G_{RV5} : Mass flow rate of refrigerant in generator whose heat is exchaged by GAX

Heat quantity of the generator Q_C and heat quantity of the absorber Q_A are given by the following equations:

$$Q_G = 0.5\ (G_{RV} - G_{RV3} - G_{RV5})\ (H_{RV10} + H_{RV4}) + G_{SL2}\ H_{SL4} - (G_{SL1} - G_{RV3} - G_{RV5})\ H_{SL10} \text{ -------------- } (21)$$

$$Q_A = (G_{RV} - G_{RV2} - G_{RV4})\ H_{RV1} + (G_{SL2} + G_{RV2} + G_{RV4})\ H_{SL9} - G_{SL1}\ H_{SL6} \text{ ------------------------------------ } (22)$$

3.7.4 How to Seek the COP of Multistage Cycle

A multistage cycle can be decomposed into two single-effect cycles. Therefore, as shown in Tables 3-27 and 3-28, its COP can be calculated from the COP of each single-effect cycle.

3.7.5 Evaluation Results

3.7.5.1 No. 1 Cycle

Dühring diagram of this cycle is shown in Fig. 4, evaluation results in the cooling mode in Table 3-29, and evaluation results in the heating mode in Table 3-30.

In the cooling mode, all working fluids were unacceptable, since the COP was below 1.

In the heating mode, favorable results were obtained for the working fluids of AM + WA, TFE + NMP and R22 + DMETEG. On the other hand, WA + LB was evaluated to be unacceptable,since the concentration is so high that it goes beyond the working range.

3.7.5.2 No. 2 Cycle

Dühring diagram of this cycle is shown in Fig. 3-5, evaluation results in the cooling mode in Table 3-31, and evaluation results in the heating mode in Table 3-32.

In the cooling mode, favorable results were obtained for the working fluids of WA + LB and TFE + NMP. On the other hand, AM + WA and R22 + DMETEG were evaluated to be unacceptable, since pressure exceeds 2,000 [kPa].

In the heating mode, all working fluids were unacceptable, since, in the case of WA + LB group, the concentration is so high that it goes beyond the working range, and in the case of other working fluids, pressure and temperature are exceedingly high.

3.7.5.3 No. 3 Cycle

Dühring diagram of this cycle is shown in Fig. 6, evaluation results in the cooling mode in Table 3-33, and evaluation results in the heating mode in Table 3-34.

In the cooling mode, favorable results were obtained only for the working fluids of TFE + NMP. On the other hand, WA + LB was evaluated to be unacceptable, since its concentration is so high that it goes beyond the working range. AM + WA and R22 + DMETEG were also evaluated to be unacceptable, since the COP is below 1.2.

In the heating mode, all working fluids were unacceptable, since, in the case of WA + LB, the concentration is so high that it goes beyond the working range, and in the case of other working fluids, pressure and temperature are exceedingly high.

3.7.5.4 No. 4 Cycle

Dühring diagram of this cycle is shown in Fig. 3-7, evaluation results in the cooling mode in Table 3-35, and evaluation results in the heating mode in Table 3-36.

In the cooling mode, all working fluids were unacceptable, since, in the case of WA + LB, the concentration is so high that it goes beyond the working range, and in the case of other working fluids, the COP is below 1.2.

In the heating mode, too, all working fluids were unacceptable, since, in the case of other working fluids, pressure and temperature are exceedingly high.

3.7.5.5. No. 5 Cycle

Dühring diagram of this cycle is shown in Fig. 3-8, and evaluation results in the cooling mode in Table 3-37.

A two-cascade cycle uses two types of working fluids which were selected by taking account of their thermodynamic properties. For the low temperature side cycle, WA + LB was selected to obtain a high COP, while for the high temperature side cycle, working fluids with a wide working range other than WA + LB were selected. Since this cycle is for cooling only, the heating mode is not considered. In the cooling mode, all working fluids were unacceptable, since, in all working fluid combinations, temperature of working fluids in the high temperature side cycle is higher than 160 [℃].

3.7.5.6 No. 6 Cycle

Dühring diagram of this cycle is shown in Fig. 3-9, and evaluation results in the cooling mode in Table 3-38.

For the low temperature side cycle, working fluids other than WA + LB were selected to pump up heat from heat source whose temperature is below 0℃. For the high temperature side cycle, WA + LB was selected to obtain a high COP.

Since this cycle for heating only, the cooling mode is not considered. In the heating mode, favorable results were obtained for all working fluids.

3.8 Conclusion

This Working Group has conducted a literature survey of absorption heat pump cycles, and evaluated various proposed cycles to examine their suitability to cooling/heating.

In the first step of evaluation, the cycles were evaluated in terms of five evaluation coefficients, and four cycles having a high theoretical efficiency and excelling in compactness were selected.

In the second step of evaluation, by using Dühring diagrams of working fluids, the cycle working range (temperature, pressure, concentration) was examined to confirm if these cycles can be realized.

In the third step of evaluation, the COP was calculated on cycles and working pairs which are highly realizable to evaluate them in terms of efficiency.

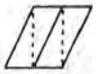
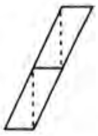
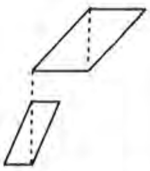
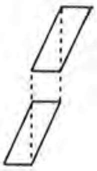
The conclusions obtained through the serial steps of evaluation are summarized below.

(1) The best two combinations of cycle and working fluids by which the COP in the cooling mode is expected to be higher than 1.2 are: ① No. 2 cycle using WA + LB or TFE + NMP as working fluids; ② No. 3 cycle using TFE + NMP as working fluids.

(2) The best two combinations of cycle and working fluids by which the COP in the heating mode is expected to be higher than 1.2 are: ① No. 1 cycle using AM + WA, TFE + NMP or R22 + DMETEG as working fluids; ② No. 6 cycle using WA + LB in the high temperature side cycle and AM + WA, TFE + NMP or R22 + DMETEG in the low temperature side cycle as working fluids.

(3) Combinations of cycle and working fluids by which the COP in both cooling and heating modes is expected to be higher than 1.2 do not exist within the scope of this work.

Table 3-1. Comparison of cycle terms

Cycles	G. Alefeld	Phillips	Trane	This work
	Single-effect	Single-effect	Single-effect	Single-effect
	Double-effect	Two-stage GAX	Double-effect generator/common condenser	Double-effect
	Double-effect	Double-effect		Double-effect
	Double-effect	Resorber augmented	Double-effect evaporation employing resorption/ desorption	Double-effect
				Two-cascade heat pump
	Double-effect			Double-effect two-cascade heat pump
	Triple-effect refrigerator			Triple-effect two-cascade refrigerator

CLASSIFICATION OF CYCLES (1)

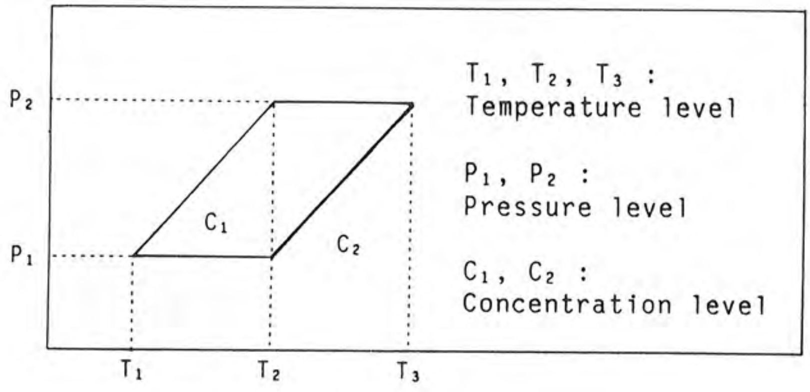
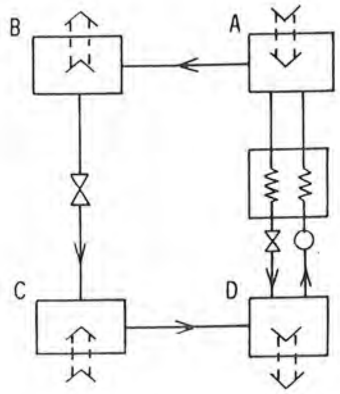


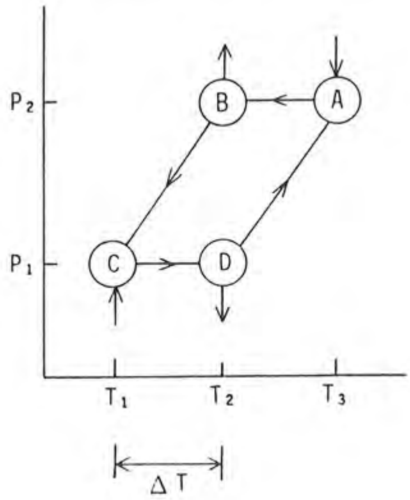
Fig. 3-1 Classification of Absorption Cycles

Table 3-2. Classification of cycles by system and cycle type

System type No. 1



Cycle type No. 1

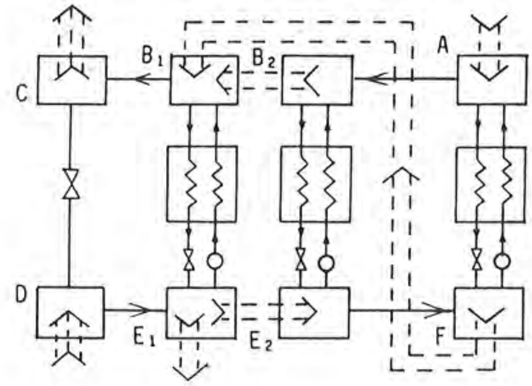


Cycle type No. 2

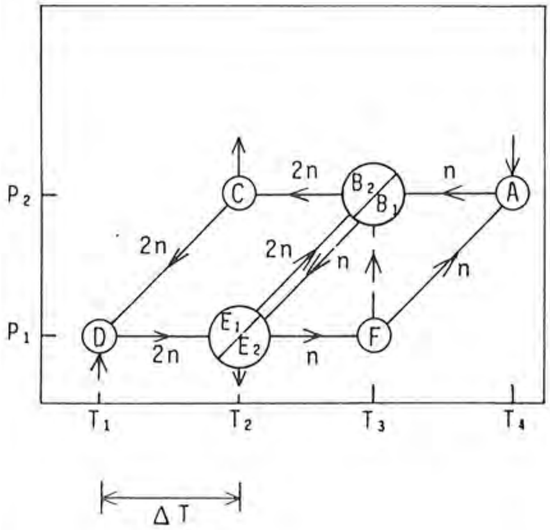
Level	Temperature	3	NA	Heat exchanger	1
	Pressure	2		Pump	1
	Concentration	1	COP	Cooling	1
NM	Evaporator	1		Heating	2
	Condenser	1	TSC	Cooling	1/4
	Absorber	1		Heating	2/4
	Generator	1	TF		1

Table 3-3. Classification of cycles by system and cycle type

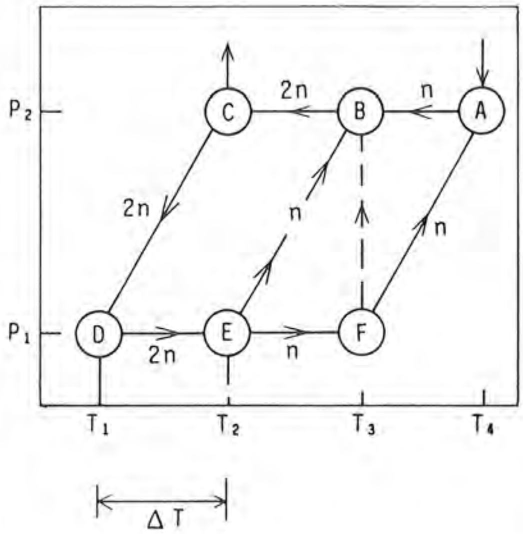
System type No. 2



Cycle type No. 1



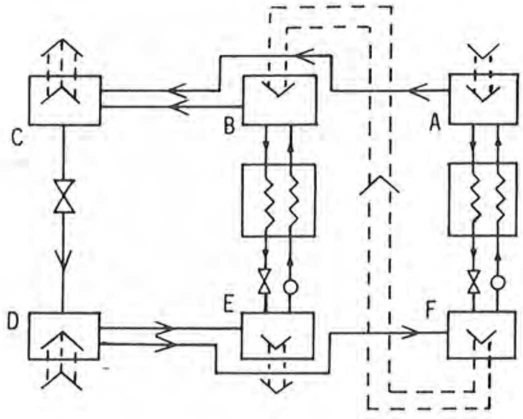
Cycle type No. 2



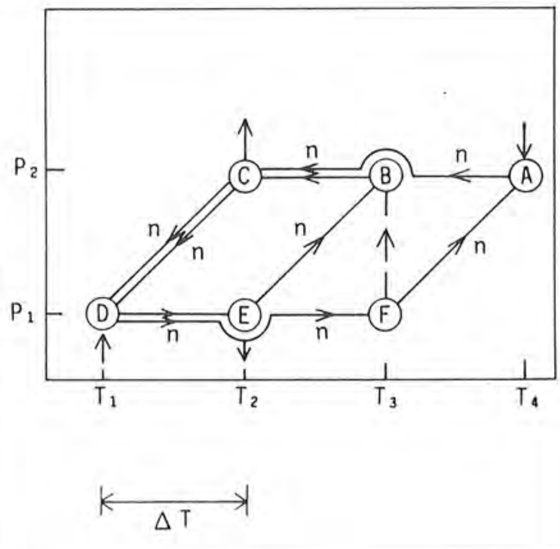
Level	Temperature	4	NA	Heat exchanger	3
	Pressure	2		Pump	3
	Concentration	3	COP	Cooling	2
NM	Evaporator	1		Heating	3
	Condenser	1	TSC	Cooling	2/12
	Absorber	3		Heating	3/12
	Generator	3	TF		2

Table 3-4. Classification of cycles by system and cycle type

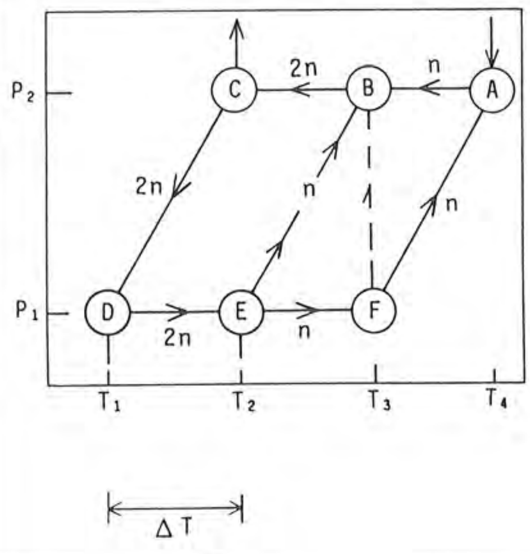
System type No. 3



Cycle type No. 1



Cycle type No. 2

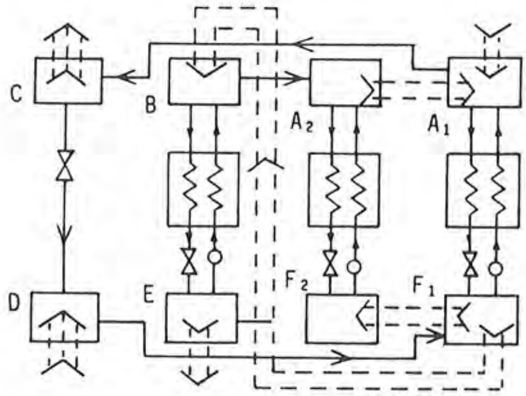


Level	Temperature	4	NA	Heat exchanger	2
	Pressure	2		Pump	2
	Concentration	3	COP	Cooling	2
NM	Evaporator	1		Heating	3
	Condenser	1	TSC	Cooling	2/8
	Absorber	2		Heating	3/8
	Generator	2	TF		2

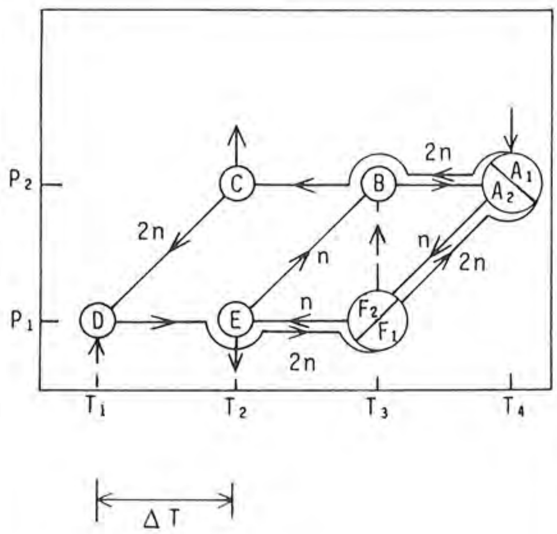
CLASSIFICATION OF CYCLES (5)

Table 3-5. Classification of cycles by system and cycle type

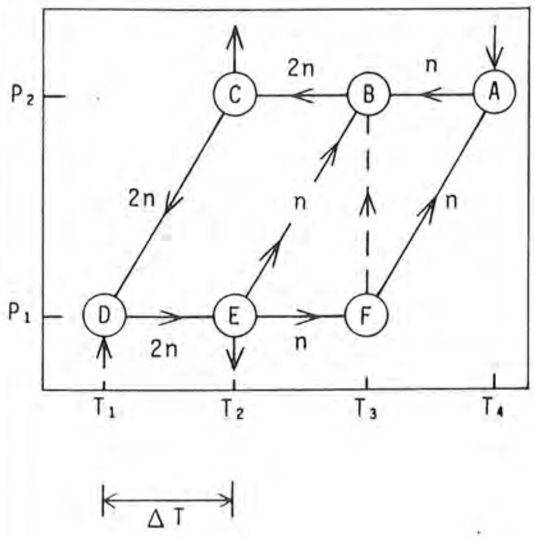
System type No. 4



Cycle type No. 1



Cycle type No. 2

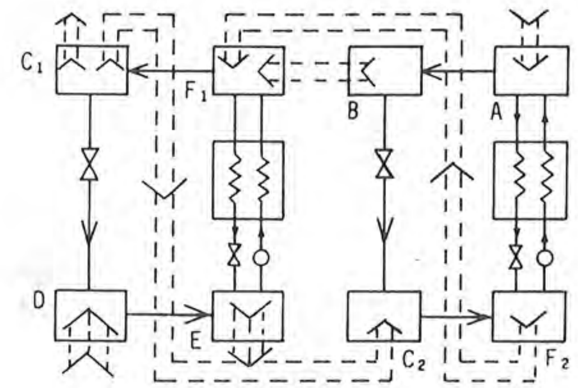


Level	Temperature	4	NA	Heat exchanger	3
	Pressure	2		Pump	3
	Concentration	3	COP	Cooling	2
NM	Evaporator	1		Heating	3
	Condenser	1	TSC	Cooling	2/12
	Absorber	3		Heating	3/12
	Generator	3	TF		2

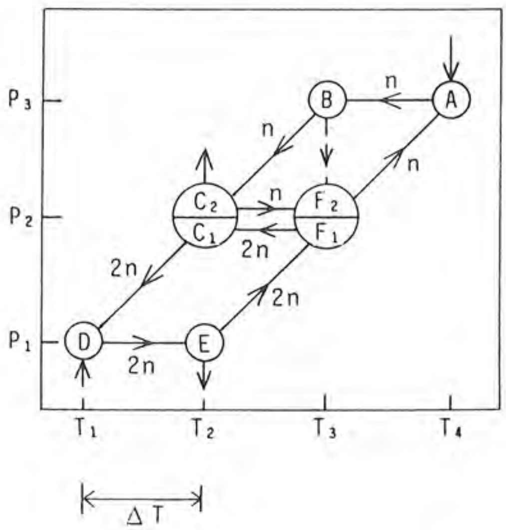
CLASSIFICATION OF CYCLES (6)

Table 3-6. Classification of cycles by system and cycle type

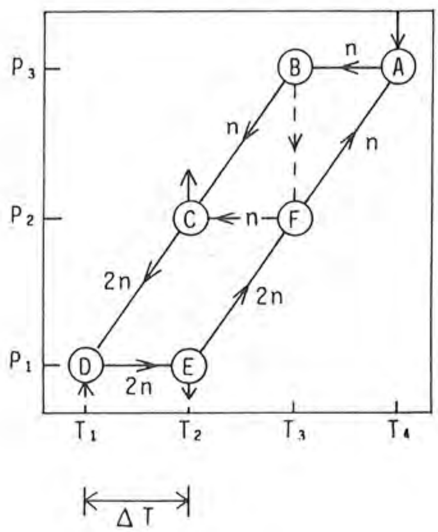
System type No. 5



Cycle type No. 1



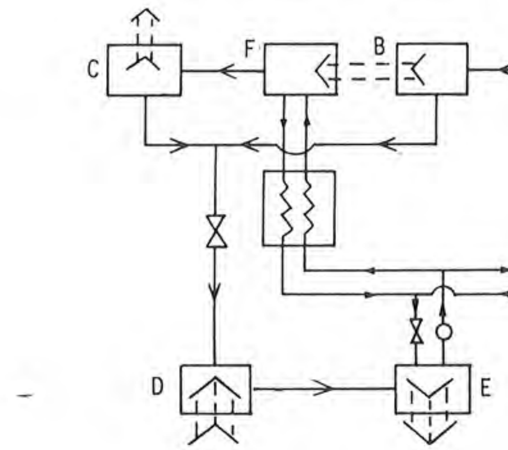
Cycle type No. 2



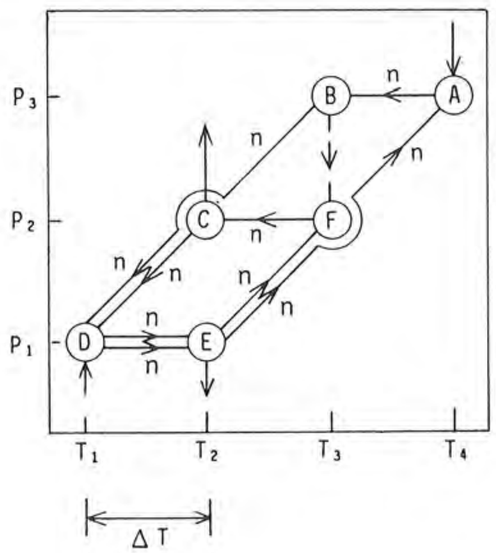
Level	Temperature	4	NA	Heat exchanger	2
	Pressure	3		Pump	2
	Concentration	2	COP	Cooling	2
NM	Evaporator	2		Heating	3
	Condenser	2	TSC	Cooling	2/12
	Absorber	2		Heating	3/12
	Generator	2	TF		2

Table 3-7. Classification of cycles by system and cycle type

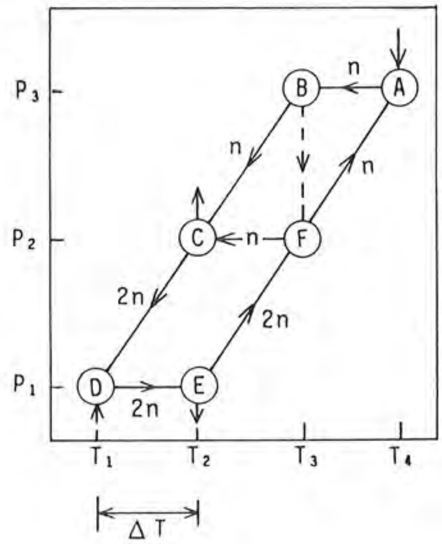
System type No. 6



Cycle type No. 1



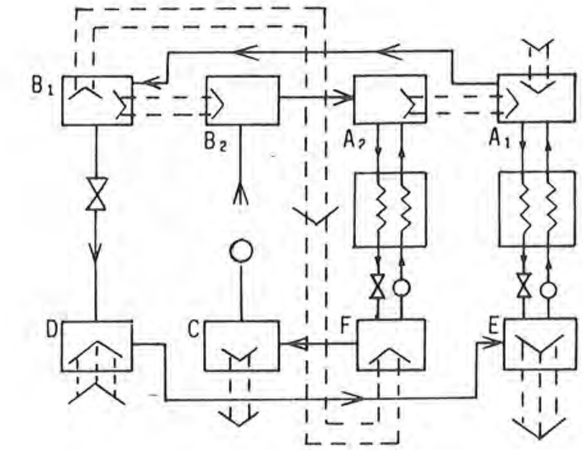
Cycle type No. 2



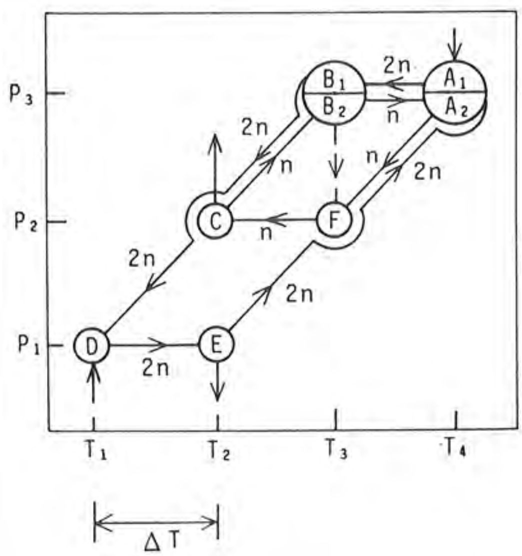
Level	Temperature	4	NA	Heat exchanger	2
	Pressure	3		Pump	1
	Concentration	2	COP	Cooling	2
NM	Evaporator	1		Heating	3
	Condenser	2	TSC	Cooling	2/8
	Absorber	1		Heating	3/8
	Generator	2	TF		2

Table 3-8. Classification of cycles by system and cycle type

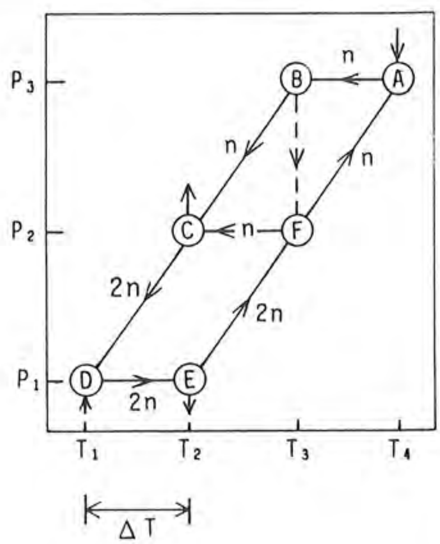
System type No. 7



Cycle type No. 1



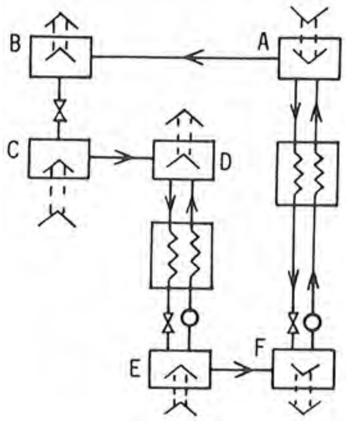
Cycle type No. 2



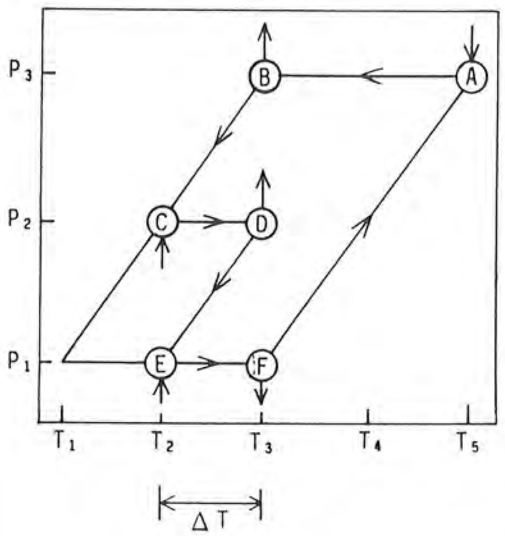
Level	Temperature	4	NA	Heat exchanger	2
	Pressure	3		Pump	3
	Concentration	2	COP	Cooling	2
NM	Evaporator	2		Heating	3
	Condenser	2	TSC	Cooling	2/12
	Absorber	2		Heating	3/12
	Generator	2	TF		2

Table 3-9. Classification of cycles by system and cycle type

System type No. 8



Cycle type No. 1



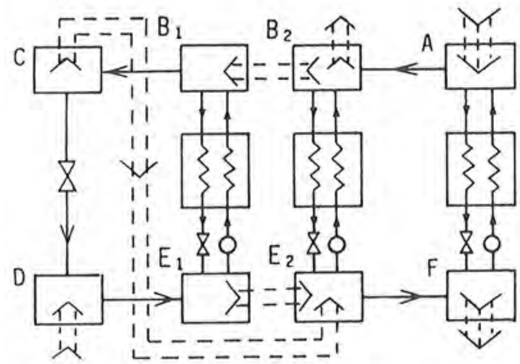
Cycle type No. 2

Level	Temperature	4	NA	Heat exchanger	2
	Pressure	3		Pump	2
	Concentration	3	COP	Cooling	2
NM	Evaporator	2		Heating	3
	Condenser	1	TSC	Cooling	2/6
	Absorber	2		Heating	3/6
	Generator	1	TF		2

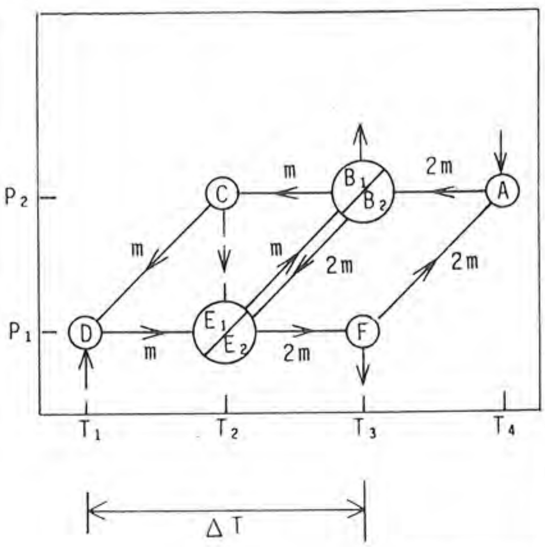
CLASSIFICATION OF CYCLES (10)

Table 3-10. Classification of cycles by system and cycle type

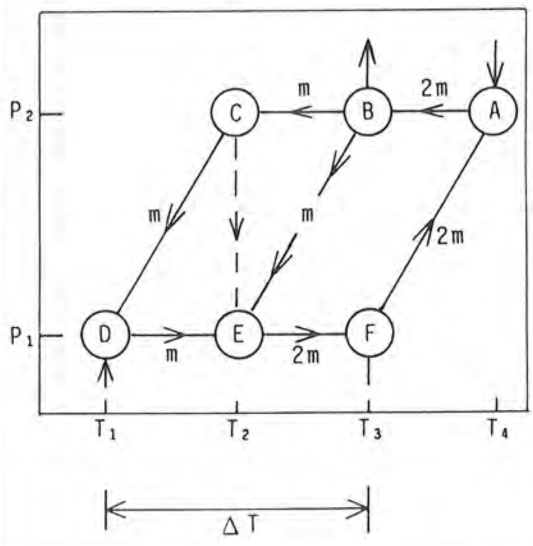
System type No. 9



Cycle type No. 1



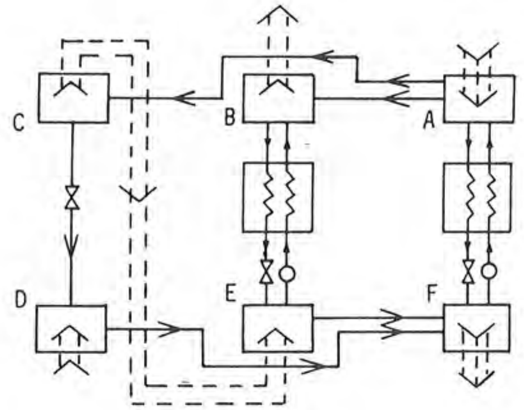
Cycle type No. 2

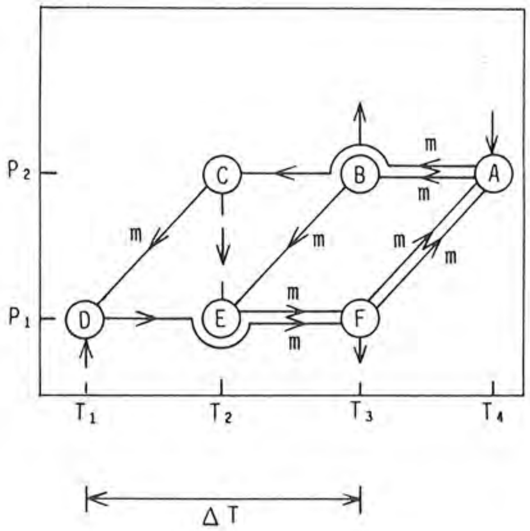
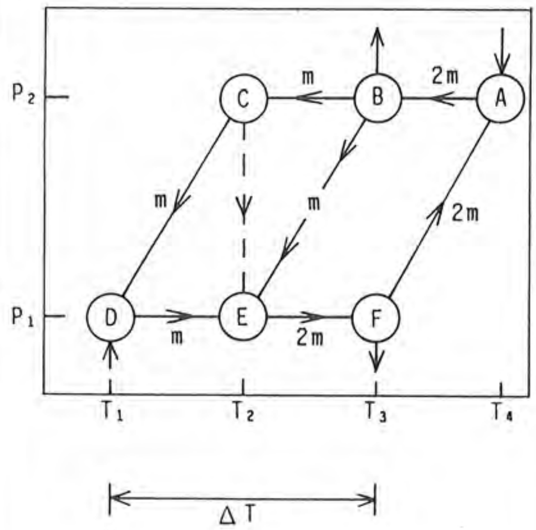


Level	Temperature	4	NA	Heat exchanger	3
	Pressure	2		Pump	3
	Concentration	3	COP	Cooling	0.5
NM	Evaporator	1		Heating	1.5
	Condenser	1	TSC	Cooling	0.5/12
	Absorber	3		Heating	1.5/12
	Generator	3	TF		0.5

Table 3-11. Classification of cycles by system and cycle type

System type No. 10



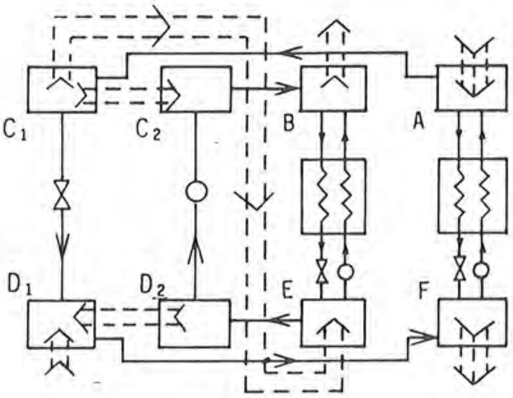
Cycle type No. 1	Cycle type No. 2
	

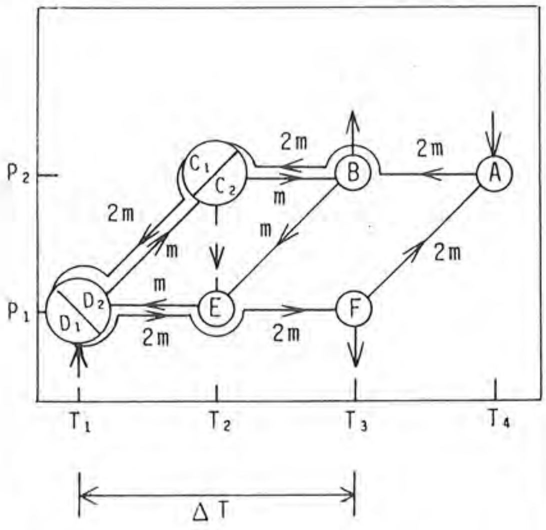
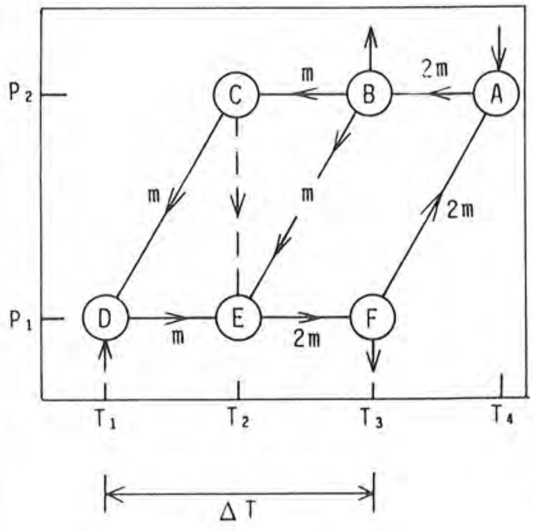
Level	Temperature	4	NA	Heat exchanger	2
	Pressure	2		Pump	2
	Concentration	3	COP	Cooling	0.5
NM	Evaporator	1		Heating	1.5
	Condenser	1	TSC	Cooling	0.5/8
	Absorber	2		Heating	1.5/8
	Generator	2	TF		0.5

CLASSIFICATION OF CYCLES (12)

Table 3-12. Classification of cycles by system and cycle type

System type No. 11

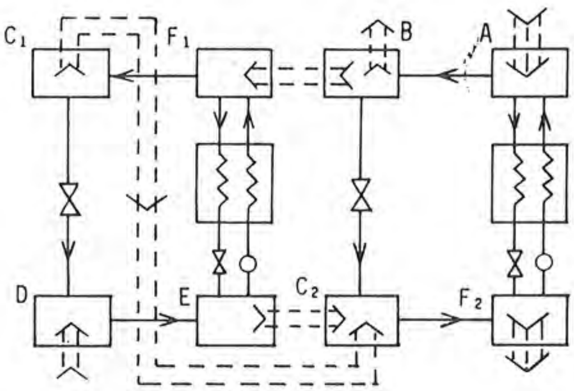


Cycle type No. 1	Cycle type No. 2
	

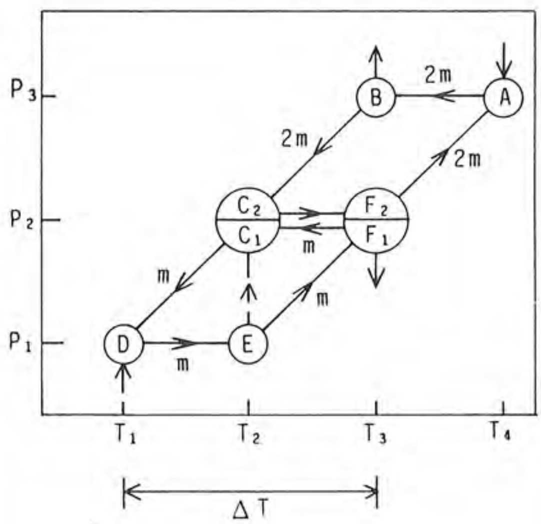
Level	Temperature	4	NA	Heat exchanger	2
	Pressure	2		Pump	3
	Concentration	3	COP	Cooling	0.5
NM	Evaporator	2		Heating	1.5
	Condenser	2	TSC	Cooling	0.5/12
	Absorber	2		Heating	1.5/12
	Generator	2	TF		0.5

Table 3-13. Classification of cycles by system and cycle type

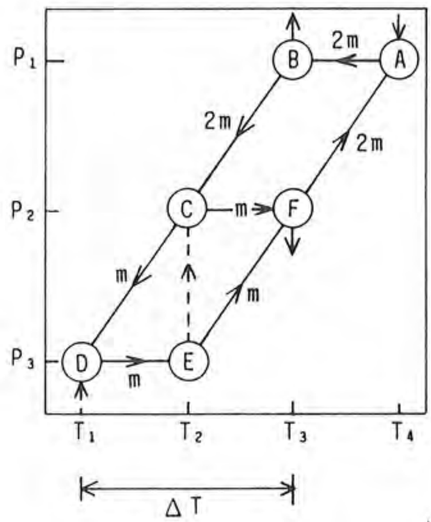
System type No. 12



Cycle type No. 1



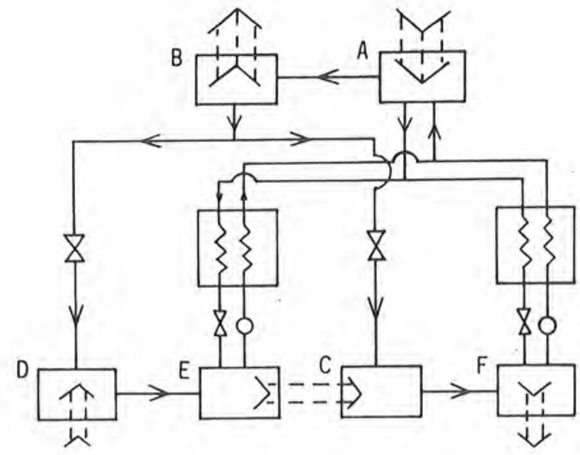
Cycle type No. 2



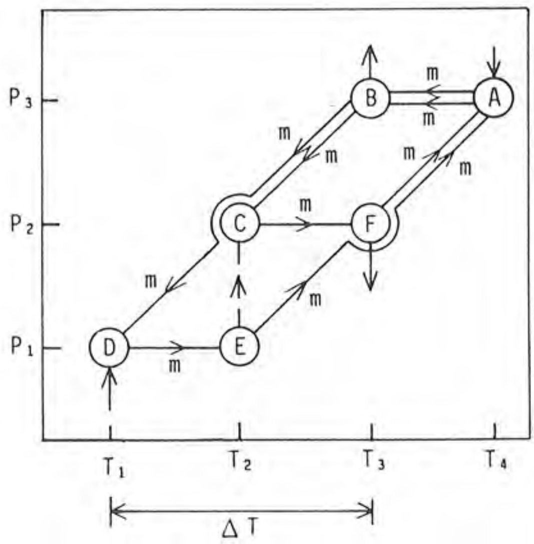
Level	Temperature	4	NA	Heat exchanger	2
	Pressure	3		Pump	2
	Concentration	2	COP	Cooling	0.5
NM	Evaporator	2		Heating	1.5
	Condenser	2	TSC	Cooling	0.5/12
	Absorber	2		Heating	1.5/12
	Generator	2	TF		0.5

Table 3-14. Classification of cycles by system and cycle type

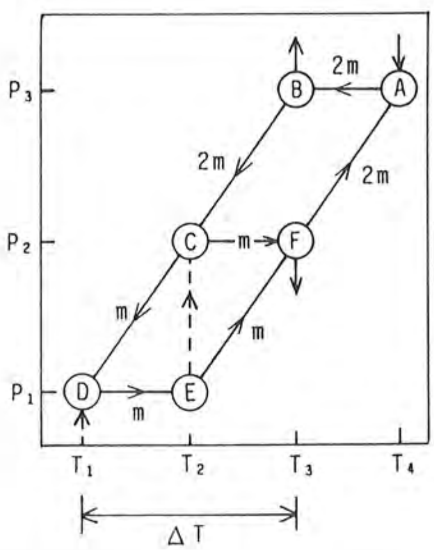
System type No. 13



Cycle type No. 1



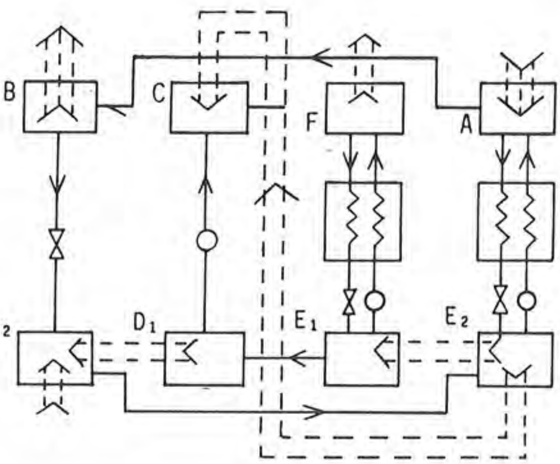
Cycle type No. 2



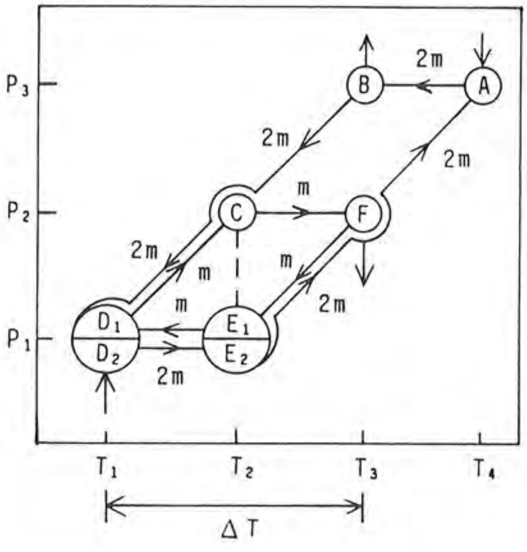
Level	Temperature	4	NA	Heat exchanger	2
	Pressure	3		Pump	2
	Concentration	2	COP	Cooling	0.5
NM	Evaporator	2		Heating	1.5
	Condenser	1	TSC	Cooling	0.5/8
	Absorber	2		Heating	1.5/8
	Generator	1	TF		0.5

Table 3-15. Classification of cycles by system and cycle type

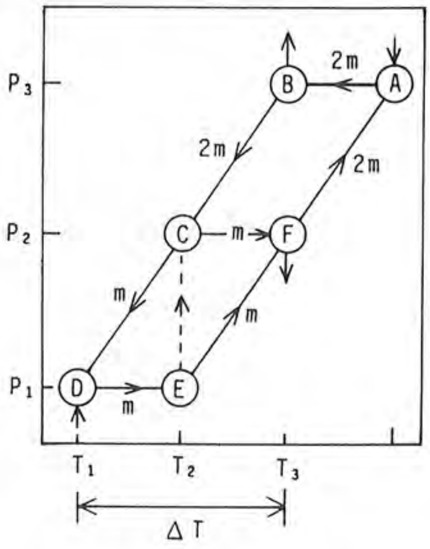
System type No. 14



Cycle type No. 1



Cycle type No. 2

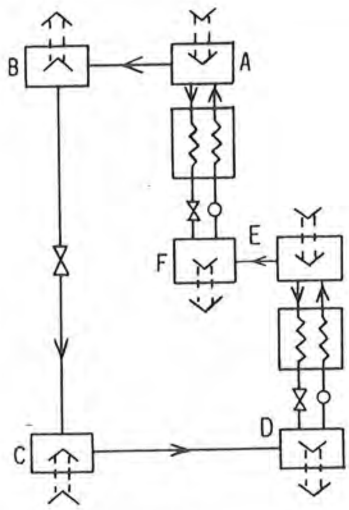


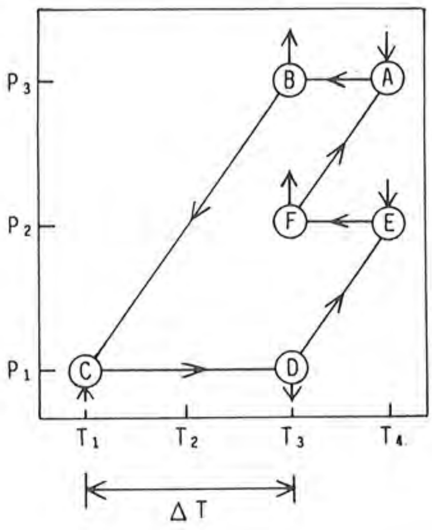
Level	Temperature	4	NA	Heat exchanger	2
	Pressure	3		Pump	3
	Concentration	2	COP	Cooling	0.5
NM	Evaporator	2		Heating	1.5
	Condenser	2	TSC	Cooling	0.5/12
	Absorber	2		Heating	1.5/12
	Generator	2	TF		0.5

CLASSIFICATION OF CYCLES (16)

Table 3-16. Classification of cycles by system and cycle type

System type No. 15



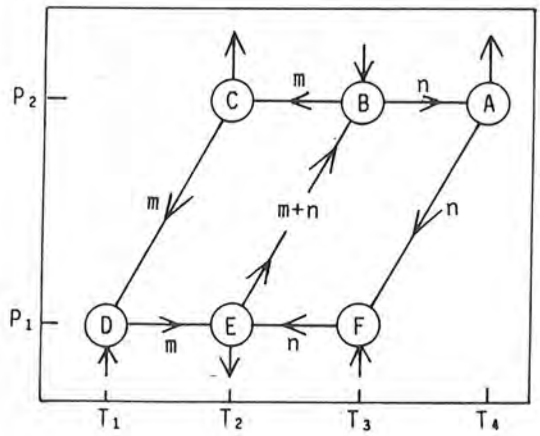
Cycle type No. 1	Cycle type No. 2
	

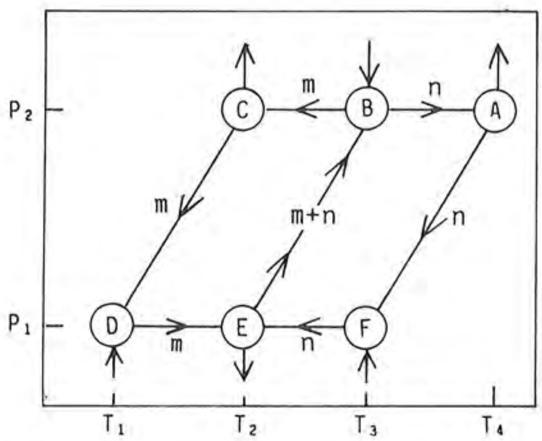
Level	Temperature	4	NA	Heat exchanger	2
	Pressure	3		Pump	2
	Concentration	3	COP	Cooling	0.5
NM	Evaporator	1		Heating	1.5
	Condenser	1	TSC	Cooling	0.5/6
	Absorber	2		Heating	1.5/6
	Generator	2	TF		0.5

CLASSIFICATION OF CYCLES (17)

Table 3-17. Classification of cycles by system and cycle type

System type No. 16



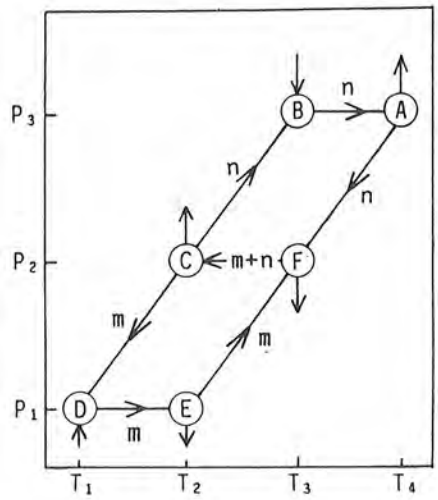
Cycle type No. 1	Cycle type No. 2
	

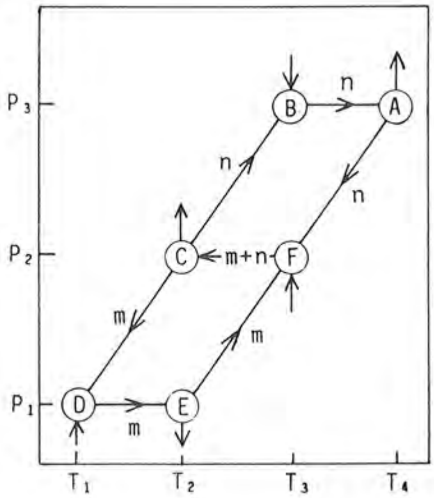
Level	Temperature	4	NA	Heat exchanger	2
	Pressure	2		Pump	2
	Concentration	3	COP	Cooling	
NM	Evaporator	1		Heating	
	Condenser	1	TSC	Cooling	
	Absorber	2		Heating	
	Generator	2	TF		

CLASSIFICATION OF CYCLES (18)

Table 3-18. Classification of cycles by system and cycle type

System type No. 17



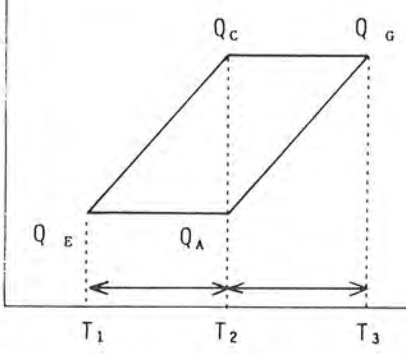
Cycle type No. 1	Cycle type No. 2
	

Level	Temperature	4	NA	Heat exchanger	2
	Pressure	3		Pump	3
	Concentration	2	COP	Cooling	
NM	Evaporator	2		Heating	
	Condenser	1	TSC	Cooling	
	Absorber	2		Heating	
	Generator	1	TF		

FIRST STEP OF EVALUATION (1)

Table 3-19. Evaluation method of absorption cycles at the first step

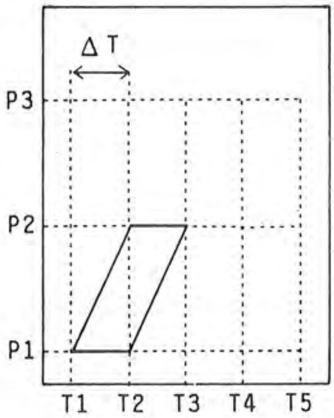
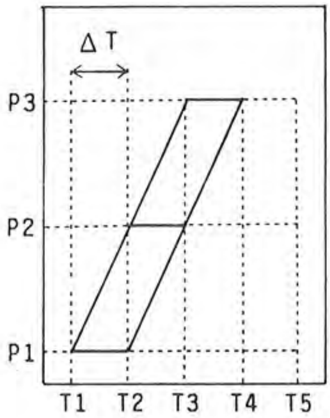
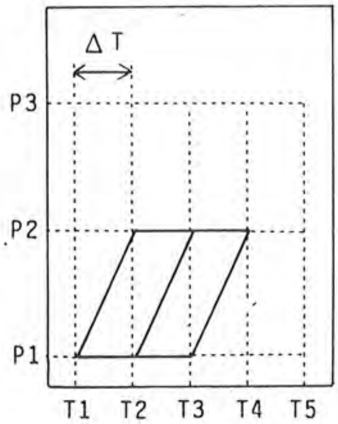
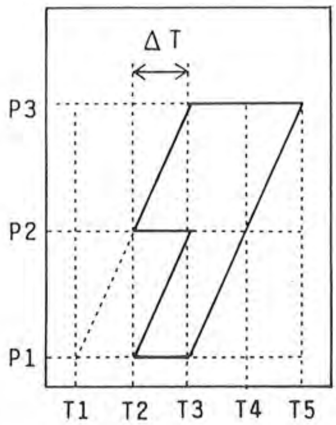
Coefficients	Criteria	
(1) NM (Number of Main Components)	NM ≤ 5	
(2) NA (Number of Auxiliary Component)	NA ≤ 2	
(3) COP (Coefficient of Performance)	$\eta_R \geq 2$ $\eta_H \geq 2$	(Cooling) (Heating)
(4) TSC (Transfer Surface Coefficient)	$a_R \geq 1/4$ $a_H \geq 2/4$	(Cooling) (Heating)
(5) TF (Temperature Factor)	TF ≤ 3	



$$TF = \frac{T_3 - T_2}{T_2 - T_1}$$

Fig. 3-2 Deffinition of Temperature Factor

Table 3-20. Selected absorption cycle at the first step of evaluation

Cycle No.	1	2
Diagram		
η_R, η_H	1, 2	2, 3
a_R, a_H	1/4, 2/4	2/8, 3/8
TF	1	2
Cycle No.	3	4
Diagram		
η_R, η_H	2, 3	2, 3
a_R, a_H	2/8, 3/8	2/6, 3/6
TF	2	2

SECOND STEP OF EVALUATION

Table 3-21. Evaluation method of absorption cycles at the second step

Thermodynamic properties	Criteria
(1) Maximum temperature T_{MAX} [°C]	$T_{MAX} \leq 160$
(2) Maximum pressure P_{MAX} [kPa]	$P_{MAX} \leq 2000$
(3) Maximum concentration C_{MAX}	$C_{MAX} \leq$ (Crystallization)

Table 3-22. Temperature condition of working fluids

Operating Mode	Evaporating Temp. T_E	Condensing Temp. T_C
Cooling	5°C	35°C
Heating	– 5°C	50°C

Table 3-23. Results of the second step of evaluation

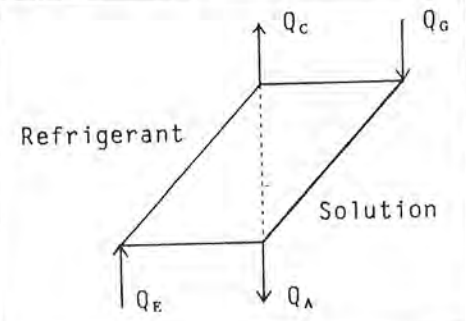
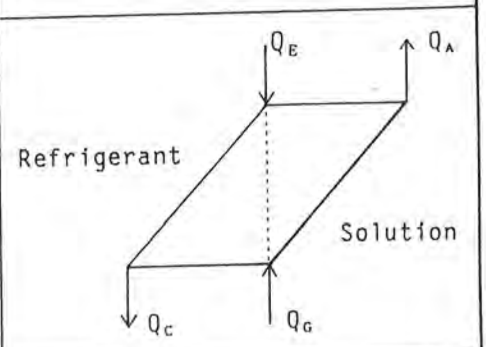
Cycles			No. 1 		No. 2 		No. 3 		No. 4 	
Operating Mode			Cool	Heat	Cool	Heat	Cool	Heat	Cool	Heat
Working Fluids	Water	WA + LB	○	×	○	×	×	×	×	×
	Ammonia	AM + WA	○	○	○	△	○	△	○	△
		AM + LNT/WA	○	○	○	△	○	△	○	△
		MA + EG	○	○	○	△	○	△	○	△
	Alcohol	MA1 + LB	○	×	○	△	△	×	×	×
		MA1 + LB/WA	○	△	○	△	△	×	△	×
		TFE + NMP	○	○	○	△	○	×	○	×
	H-CFC	R22 + DMETrEG	○	○	△	△	○	△	○	△
		DMETEG	○	○	△	△	○	△	○	△

THIRD STEP OF EVALUATION (1)

Table 3-24. Evaluation method of absorption cycles at the third step

COP	Criteria
(1) Calculated COP	$\eta_R \geq 1.2$ (Cooling) $\eta_H \geq 1.2$ (Heating)

Table 3-25. Definition of the COP of single-effect cycle

	Heat pump, Refrigerator	Heat transformer
Definition of COP	(1) Refrigerator $\eta_R = Q_E / Q_G$ (2) Heat pump $\eta_H = (Q_A + Q_C) / Q_G$ $= 1 + \eta_R$	$\eta_T = Q_A / (Q_G + Q_E)$
Diagram		

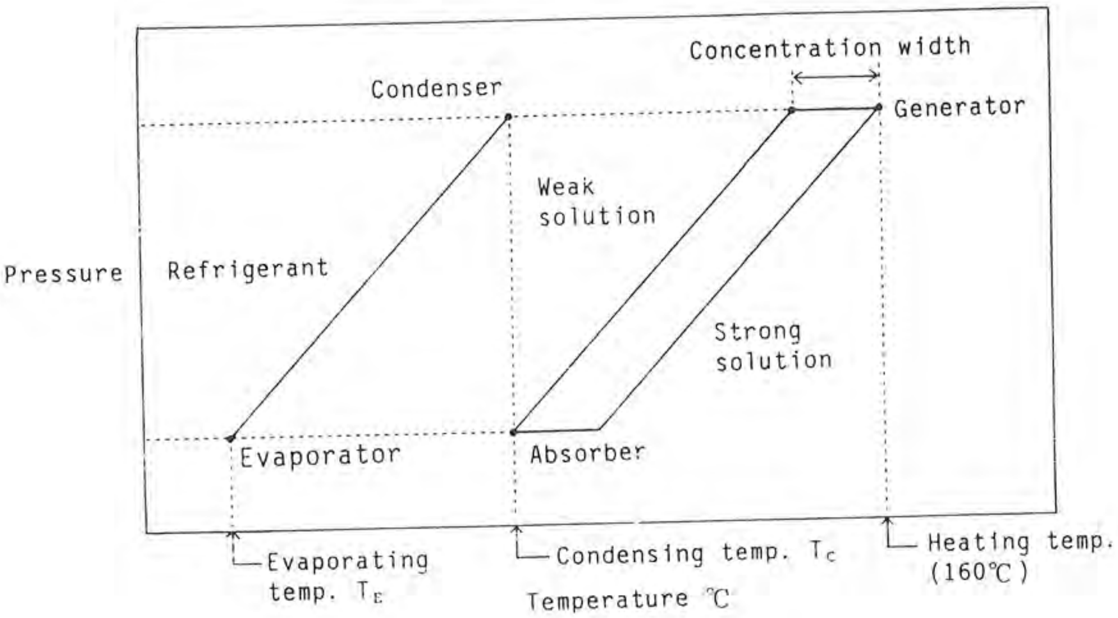
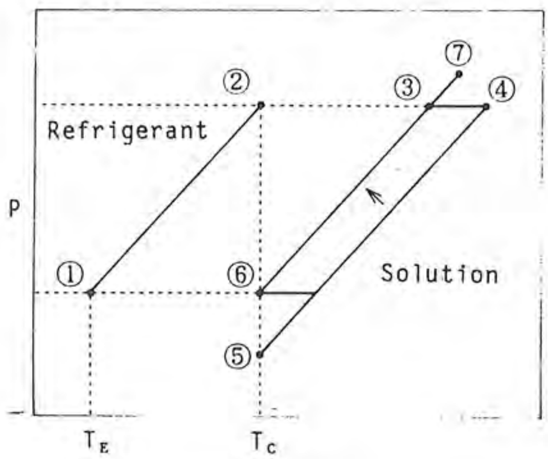
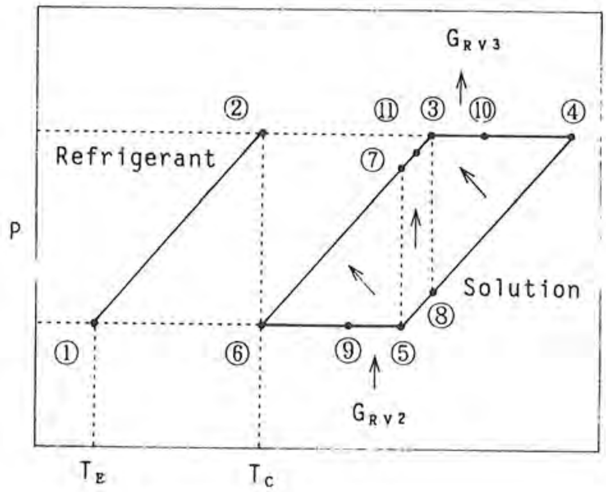
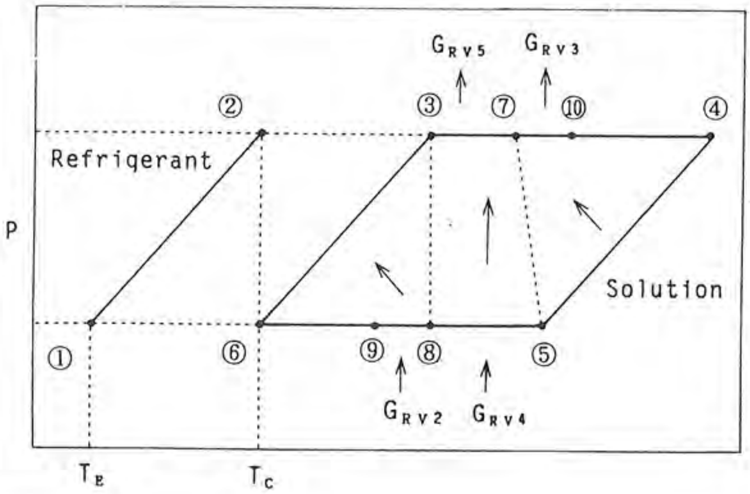
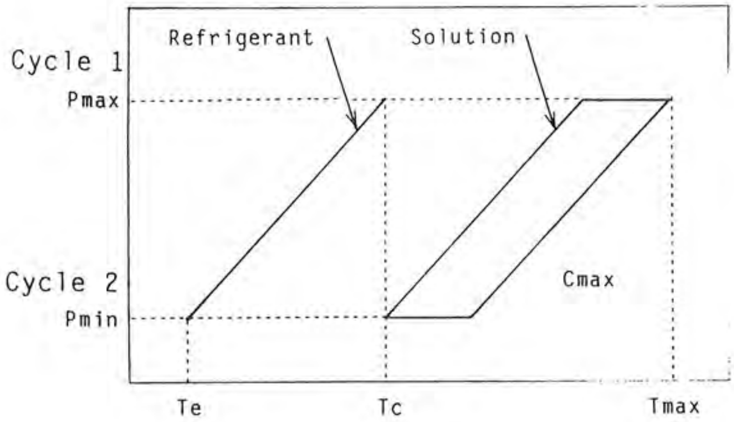


Fig. 3-3 Definition of Concentration of Single-effect Absorption Cycle

Table 3-26. Calculation method of the COP of single-effect cycle

Conc. width	Diagram	Type of heat exchanger
Small		(1) Q_{EX1} (Solution heat ex.) ④ → ⑤ → ⑥ → ⑦
Middle		(1) Q_{EX2} (AX) ⑤ → ⑨ → ⑥ → ⑦ (2) Q_{EX3} (GX) ④ → ⑧ → ③ → ⑩ (3) Q_{EX1} (Solution heat ex.) ⑧ → ⑤ → ⑦ → ⑪
Large		(1) Q_{EX4} (GAX) ⑤ → ⑧ → ③ → ⑦ (2) Q_{EX2} (AX) ⑧ → ⑨ → ⑥ → ③ (3) Q_{EX3} (GX) ④ → ⑤ → ⑦ → ⑩



Mode	Te [°C]	Tc [°C]
Cooling	5	35
Heating	− 5	50

Fig. 3-4 Diagram of No. 1 Cycle

Table 3-29. Results of evaluation of No. 1 cycle at cooling mode

Working fluids	WA + LB	AM + WA	TFE + NMP	R22 + DMETEG
Temperature Tmax [°C]	93	160	137	160
Concentration Cmax [%]	65 (LiBr)	12 (Ammonia)	5 (TFE)	16 (R22)
Pressure Pmax [kPa]	5	1400	17	1500
Second evaluation	O	O	O	O
Third evaluation (COP)	× (0.8)	× (0.8)	× (0.7)	× (0.6)

Table 3-30. Results of evaluation of No. 1 cycle at heating mode

Working fluids	WA + LB	AM + WA	TFE + NMP	R22 + DMETEG
Temperature Tmax [°C]	120	160	160	160
Concentration Cmax [%]	Out of range	18 (Ammonia)	5 (TFE)	22 (R22)
Pressure Pmax [kPa]	12	1900	36	2000
Second evaluation	×	O	O	O
Third evaluation (COP)	×	O (1.6)	O (1.5)	O (1.4)

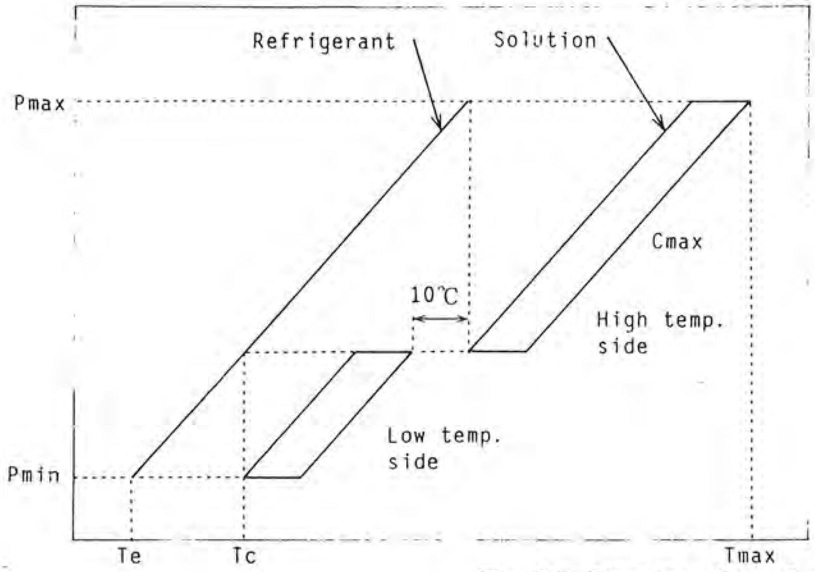


Fig. 3-5 Diagram of No. 2 Cycle

Mode	Te [°C]	Tc [°C]
Cooling	5	35
Heating	−5	50

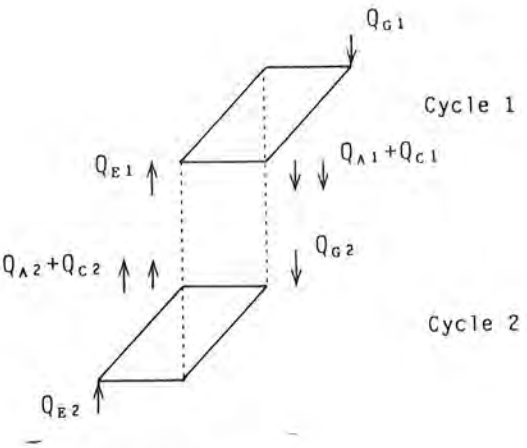
Table 3-31. Results of evaluation of No. 2 cycle at cooling mode

Working fluids	WA + LB	AM + WA	TFE + NMP	R22 + DMETEG
Temperature Tmax [°C]	160	160	160	160
Concentration Cmax [%]	67 (LiBr)	40 (Ammonia)	44 (TFE)	36 (R22)
Pressure Pmax [kPa]	63	4100	140	4100
Second evaluation	O	Δ	O	Δ
Third evaluation (COP)	O (1.4)	×	O (1.4)	×

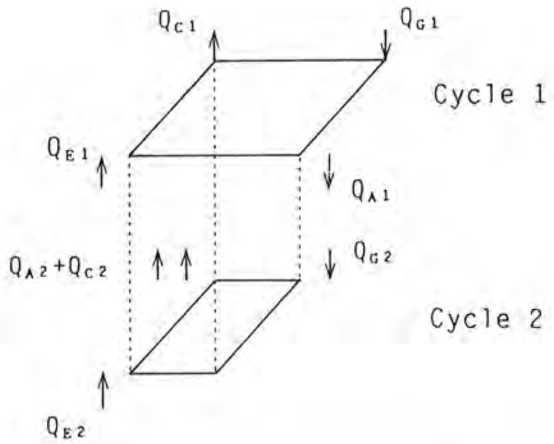
Table 3-32. Results of evaluation of No. 2 cycle at heating mode

Working fluids	WA + LB	AM + WA	TFE + NMP	R22 + DMETEG
Temperature Tmax [°C]	230	220	240	250
Concentration Cmax [%]	Out of range	32 (Ammonia)	30 (TFE)	30 (R22)
Pressure Pmax [kPa]	330	9600	840	9000
Second evaluation	×	Δ	Δ	Δ
Third evaluation (COP)	×	×	×	×

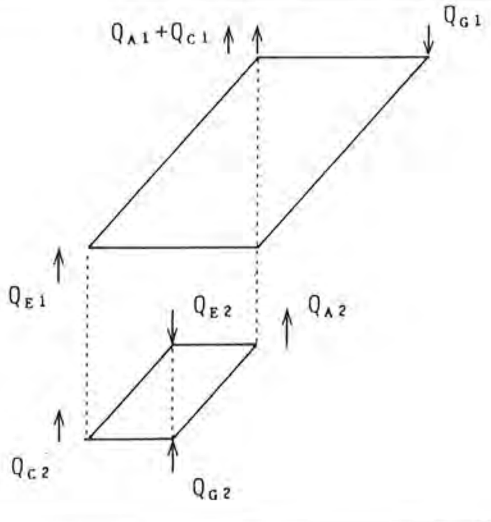
Table 3-27. Calculation method of the COP of multistage cycles

<table>
<tr><th>Cycle No.</th><th>Synthesis of multistage cycles</th><th>Equations</th></tr>
<tr><td>2</td><td>


</td><td>
(1) Heat balance
$Q_{G1} + Q_{E1} = Q_{A1} + Q_{C1}$
$Q_{G2} + Q_{E2} = Q_{A2} + Q_{C2}$
$Q_{G2} = Q_{A1} + Q_{C1}$

(2) Definition of the COP
$\eta_{R1} = Q_{E1} / Q_{G1}$
$\eta_{R2} = Q_{E2} / Q_{G2}$
$\eta_{R} = Q_{E2} / Q_{G1}$
$= \eta_{R2} (1 + \eta_{R1})$
</td></tr>
<tr><td>3</td><td>


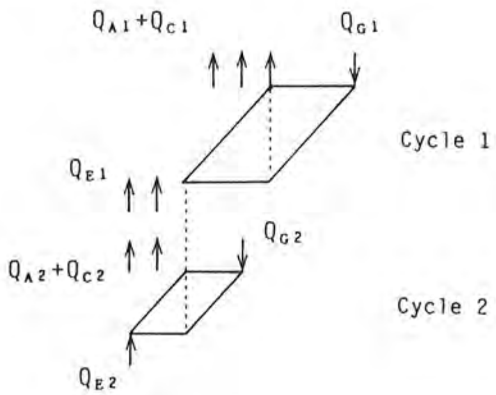
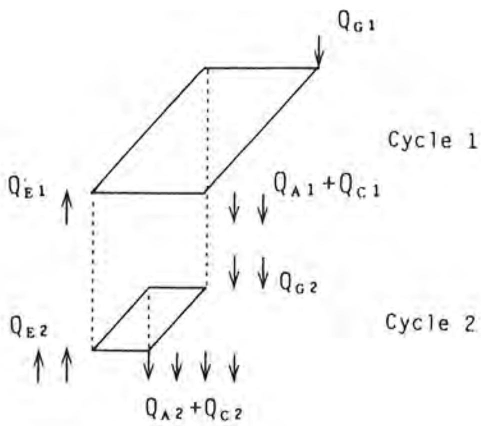
</td><td>
(1) Heat balance
$Q_{G1} + Q_{E1} = Q_{A1} + Q_{C1}$
$Q_{G2} + Q_{E2} = Q_{A2} + Q_{C2}$
$Q_{G2} = Q_{A1}$

(2) Definition of the COP
$\eta_{R1} = Q_{E1} / Q_{G1}$
$\eta_{R2} = Q_{E2} / Q_{G2}$
$\eta_{T1} = Q_{A1} / (Q_{G1} + Q_{E1})$
$\eta_{R} = (Q_{E1} + Q_{E2}) / Q_{G1}$
$= \eta_{R1} + \eta_{R2}\eta_{T1} (1 + \eta_{R1})$
</td></tr>
<tr><td>4</td><td>


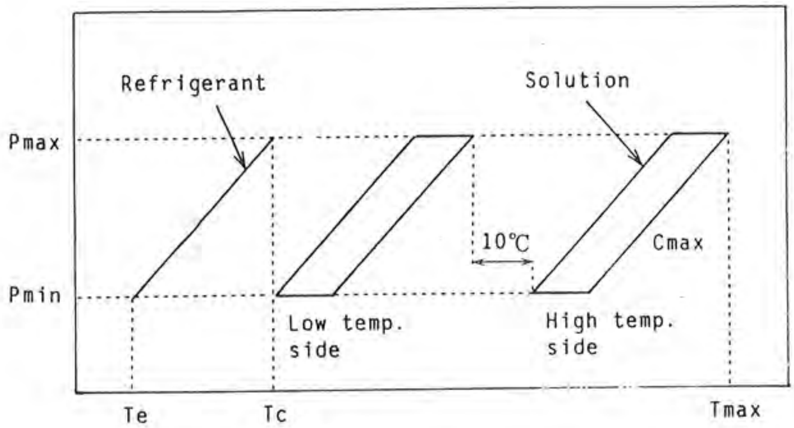
</td><td>
(1) Heat balance
$Q_{G1} + Q_{E1} = Q_{A1} + Q_{C1}$
$Q_{G2} + Q_{E2} = Q_{A2} + Q_{C2}$
$Q_{E1} = Q_{C2}$

(2) Definition of the COP
$\eta_{R1} = Q_{E1} / Q_{G1}$
$\eta_{T2} = Q_{A2} / (Q_{G2} + Q_{E2})$
$\eta_{R} = (Q_{G2} + Q_{E2}) / Q_{G1}$
$= \eta_{R1} / (1 - \eta_{T2})$
</td></tr>
</table>

Table 3-28. Calculation method of the COP of two-cascade cycles

Cycle No.	Synthesis of multistage cycles	Equations
5		(1) Heat balance $Q_{G1} + Q_{E1} = Q_{A1} + Q_{C1}$ $Q_{G2} + Q_{E2} = Q_{A2} + Q_{C2}$ $Q_{E1} = Q_{A2} + Q_{C2}$ (2) Definition of the COP $\eta_{H1} = (Q_{A1} + Q_{C1}) / Q_{G1}$ $\eta_{H2} = (Q_{A2} + Q_{C2}) / Q_{G2}$ $\eta_{H} = (Q_{A1} + Q_{C1}) / (Q_{G1} + Q_{G2})$ $= \underline{\eta_{H1}\eta_{H2} / (\eta_{H1} + \eta_{H2} - 1)}$
6		(1) Heat balance $Q_{G1} + Q_{E1} = Q_{A1} + Q_{C1}$ $Q_{G2} + Q_{E2} = Q_{A2} + Q_{C2}$ $Q_{G2} = Q_{A1} + Q_{C1}$ (2) Definition of the COP $\eta_{R1} = Q_{E1} / Q_{G1}$ $\eta_{R2} = Q_{E2} / Q_{G2}$ $\eta_{R} = (Q_{E1} + Q_{E2}) / Q_{G1}$ $= \underline{\eta_{R1} + \eta_{R2} + \eta_{R1}\eta_{R2}}$

THIRD STEP OF EVALUATION (7)



Mode	Te [°C]	Tc [°C]
Cooling	5	35
Heating	– 5	50

Fig. 3-6 Diagram of No. 3 Cycle

Table 3-33. Results of evaluation of No. 3 cycle at cooling mode

Working fluids	WA + LB	AM + WA	TFE + NMP	R22 + DMETEG
Temperature Tmax [°C]	120	160	137	160
Concentration Cmax [%]	Out of range	12 (Ammonia)	5 (TFE)	16 (R22)
Pressure Pmax [kPa]	5	1400	17	1500
Second evaluation	×	○	○	○
Third evaluation (COP)	×	× (1.1)	○ (1.2)	× (1.0)

Table 3-34. Results of evaluation of No. 3 cycle at heating mode

Working fluids	WA + LB	AM + WA	TFE + NMP	R22 + DMETEG
Temperature Tmax [°C]	200	200	240	260
Concentration Cmax [%]	Out of range	Out of range	Out of range	Out of range
Pressure Pmax [kPa]	12	1900	36	2000
Second evaluation	×	×	×	×
Third evaluation (COP)	×	×	×	×

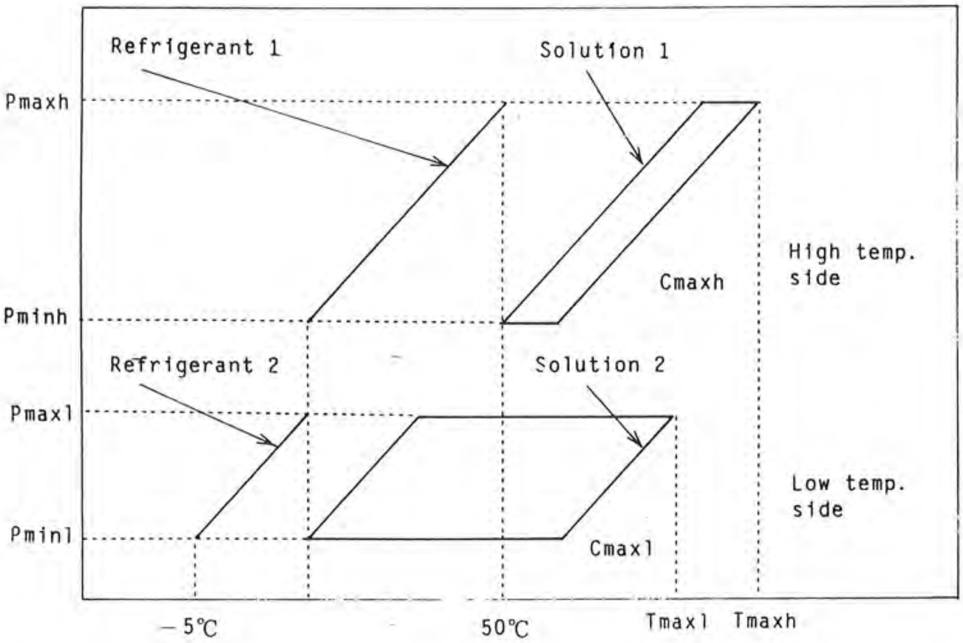


Fig. 3-9 Diagram of No. 6 Cycle

Table 3-38. Results of evaluation of No. 6 cycle at heating mode

High temp. side	Working fluids	WA + LB	WA + LB	WA + LB
	Temperature Tmaxh [°C]	114	114	114
	Concentration Cmaxh [%]	66 (LiBr)	66 (LiBr)	66 (LiBr)
	Pressure Pmaxh [kPa]	12	12	12
Low temp. side	Working fluids	AM + WA	TFE + NMP	R22 + DMETEG
	Temperature Tmaxl [°C]	155	113	160
	Concentration Cmaxl [%]	5 (Ammonia)	5 (TFE)	11 (R22)
	Pressure Pmaxl [kPa]	900	7	900
	Temperature Tm [°C]	20	20	20
Total	Second evaluation	○	○	○
	Third evaluation (COP)	○ (1.2)	○ (1.2)	○ (1.2)

Table 3-39. Results of the third step of evaluation at cooling mode

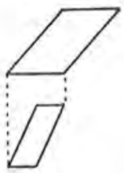
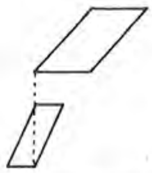
Working fluids	Absorption cycles				
	No. 1 	No. 2 	No. 3 	No. 4 	two-cascade (No. 5) 
WA/LB	× (0.8)	O (1.4)	× (----)	× (----)	
AM/WA	× (0.8)	× (----)	× (1.1)	× (1.1)	× (----)
TFE/NMP	× (0.7)	O (1.4)	O (1.2)	× (1.1)	× (----)
R22/DTG	× (0.6)	× (----)	× (1.0)	× (1.0)	× (----)

Table 3-40. Results of the third step of evaluation at heating mode

Working fluids	Absorption cycles				
	No. 1 	No. 2 	No. 3 	No. 4 	two-cascade (No. 6) 
WA/LB	× (----)	× (----)	× (----)	× (----)	
AM/WA	O (1.6)	× (----)	× (----)	× (----)	O (1.2)
TFE/NMP	O (1.5)	× (----)	× (----)	× (----)	O (1.2)
R22/DTG	O (1.4)	× (----)	× (----)	× (----)	O (1.2)

Appendix

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