APPENDICES

ลิขสิทธิ์มหาวิทยาลัยเชียงใหม่
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Appendix A

Numerical Simulation and Experimental Results

ลิขสิทธิ์มหาวิทยาลัยเชียงใหม่
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Table A.1 Numerical simulation results for organic Rankine cycle (low pressure turbine)

Numerical results of various heat source temperature																		
V_f		m_f		T_{so}	T_{si}	$T_{vg,i}$	$T_{T,i}$	P_2	Pr	P_3	$T_{T,o}$	$T_{c,i}$	$T_{c,o}$	Q_{vg}	Q_{cond}	W_p	W_T	W_{net}	$\eta_{th,system}$	$\eta_{th,carnot}$
l/h	l/min	kg/h	kg/s	°C	°C	°C	°C	kPa	-	kPa	°C	°C	°C	kW	kW	kW	kW	kW	%	%
90	1.50	112	0.031	70	10.0	30.31	60	246.0	1.5	164.0	46.5	35.51	30.0	4.04	2.25	0.004	0.64	0.63	15.66	11.57
			0.031	80	10.0	30.31	70	324.8	1.5	216.5	55.7	44.66	30.0	5.41	3.50	0.006	0.83	0.82	15.25	14.07
			0.031	90	10.0	30.31	80	421.2	1.5	280.8	64.7	53.65	30.0	6.77	4.72	0.008	1.02	1.01	14.87	16.44
			0.031	100	10.0	30.31	90	537.7	1.5	358.4	73.7	62.69	30.0	8.13	5.96	0.011	1.17	1.16	14.25	18.68
180	3.00	223	0.062	70	10.0	30.31	60	246.0	1.5	164.0	46.5	41.02	30.0	8.09	4.50	0.008	1.27	1.27	15.66	11.57
			0.062	80	10.0	30.31	70	324.8	1.5	216.5	55.7	50.17	30.0	10.81	7.00	0.012	1.66	1.65	15.25	14.07
			0.062	90	10.0	30.31	80	421.2	1.5	280.8	64.7	59.16	30.0	13.54	9.45	0.017	2.03	2.01	14.87	16.44
			0.062	100	10.0	30.31	90	537.7	1.5	358.4	73.7	68.20	30.0	16.26	11.91	0.022	2.34	2.32	14.25	18.68
240	4.00	298	0.083	70	10.0	30.31	60	246.0	1.5	164.0	46.5	42.39	30.0	10.79	6.00	0.010	1.70	1.69	15.66	11.57
			0.083	80	10.0	30.31	70	324.8	1.5	216.5	55.7	51.54	30.0	14.42	9.33	0.016	2.21	2.20	15.25	14.07
			0.083	90	10.0	30.31	80	421.2	1.5	280.8	64.7	60.53	30.0	18.05	12.60	0.022	2.71	2.68	14.87	16.44
			0.083	100	10.0	30.31	90	537.7	1.5	358.4	73.7	69.58	30.0	21.68	15.88	0.030	3.12	3.09	14.25	18.68
300	5.00	372	0.103	70	10.0	30.31	60	246.0	1.5	164.0	46.5	43.23	30.0	13.48	7.51	0.013	2.12	2.11	15.66	11.57
			0.103	80	10.0	30.31	70	324.8	1.5	216.5	55.7	52.38	30.0	18.02	11.66	0.020	2.77	2.75	15.25	14.07
			0.103	90	10.0	30.31	80	421.2	1.5	280.8	64.7	61.37	30.0	22.56	15.74	0.028	3.38	3.36	14.87	16.44
			0.103	100	10.0	30.31	90	537.7	1.5	358.4	73.7	70.42	30.0	27.10	19.85	0.037	3.90	3.86	14.25	18.68

$T_{v,i}$ = Vapor generator inlet temperature (°C

$T_{T,i}$ = Turbine inlet temperature (°C)

$T_{T,o}$ = Turbine outlet temperature (°C)

$T_{c,i}$ = Condenser inlet temperature (°C)

$T_{c,o}$ = Condenser outlet temperature (°C)

T_{so} = Temperature heat source (°C)

T_{si} = Temperature heat sink (°C)

P_2 = Turbine inlet Pressure (kPa)

P_3 = Turbine outlet Pressure (kPa)

Pr = Pressure ratio (P_2/P_3)

$\mathbf{Q_{vapor}}$ = Heat input at vapor generator

$\mathbf{Q_{cond}}$ = Heat sink at water cool condenser

Table A.2 Experimental results of heat source temperature 72.4^{o}C and mass flow rate 0.0334 kg/s

Date : 15 June 2013

Location : Propulsion and Aerodynamics Research and Applications Laboratory (PARA LAB), Department of Mechanical Engineering, Chiang Mai University

Average heat source temperature :	72.4	^{o}C
Average working fluid mass flow rate :	120.3	kg/h
Water circulation mass flow rate :	961.2	kg/h
Electric heater :	6.0	kW

Experiment 1-1 Heat Source Temperature 72.4^{o}C at m = 0.0334 kg/s

Test No.	m_{wf}	Heat source	$T_{source, 6}$	$T_{sink, 7}$	T_1	T_2	P_2	P_3	T_3	Pr	T_4	T_5	Q_{vapor}	Q_{cond}	Speed	W	Torq	Power	η_{sys}	η_{cnt}
	kg/s	kW	^{o}C	^{o}C	^{o}C	^{o}C	kPa	kPa	^{o}C	-	^{o}C	^{o}C	kW	kW	RPM	g	N.m	W	-	-
A-150613-1	0.0346	4.17	71.9	11.0	30.5	60.6	251.0	225.0	56.9	1.12	49.2	30.9	4.57	3.95	37	13	0.032	0.12	0.003	9.02
A-150613-2	0.0350	4.21	72.4	11.0	30.3	61.3	256.0	227.1	57.2	1.13	50.3	31.3	4.76	3.98	139	12	0.029	0.43	0.009	9.27
A-150613-3	0.0345	4.20	72.3	10.9	29.1	61.4	256.7	231.1	57.8	1.11	50.9	30.8	4.89	4.09	231	11	0.026	0.63	0.013	9.65
A-150613-4	0.0343	4.18	72.0	11.0	28.7	61.2	255.3	231.1	57.8	1.10	49.4	31.3	4.89	3.99	314	9	0.023	0.76	0.016	9.72
A-150613-5(opt)	**0.0341**	**4.19**	**72.1**	**10.9**	**28.0**	**61.5**	**257.5**	**234.5**	**58.3**	**1.10**	**52.6**	**31.4**	**5.01**	**4.02**	**387**	**8**	**0.020**	**0.81**	**0.016**	**10.01**
A-150613-6	0.0337	4.21	72.4	10.9	29.1	61.4	256.7	236.5	58.6	1.09	53.6	31.0	4.78	4.08	451	7	0.017	0.80	0.017	9.65
A-150613-7	0.0329	4.22	72.6	10.8	28.3	61.1	254.6	239.9	59.1	1.06	52.0	31.3	4.74	4.02	505	6	0.014	0.74	0.016	9.81
A-150613-8	0.0328	4.22	72.6	10.9	29.9	61.2	255.3	241.3	59.3	1.06	52.4	31.3	4.51	4.04	550	5	0.011	0.65	0.014	9.36
A-150613-9	0.0327	4.21	72.5	10.8	27.2	61.2	255.3	241.9	59.4	1.06	52.7	31.6	4.89	4.00	585	3	0.008	0.52	0.011	10.17
A-150613-10	0.0325	4.21	72.5	10.8	28.3	61.1	254.6	243.3	59.6	1.05	53.1	30.8	4.68	4.11	610	2	0.006	0.37	0.008	9.81
A-150613-11	0.0322	4.22	72.6	10.8	26.8	60.8	252.4	243.3	59.6	1.04	51.4	31.6	4.80	3.96	627	1	0.003	0.19	0.004	10.18
A-150613-12	0.0319	4.21	72.5	10.9	28.7	60.4	249.5	242.6	59.5	1.03	50.6	31.2	4.44	3.96	634	0	0.000	0.01	0.000	9.50
Minimum	**0.0319**	**4.17**	**71.9**	**10.8**	**26.8**	**60.4**	**249.5**	**225.0**	**56.9**	**1.03**	**49.2**	**30.8**	**4.44**	**3.95**	**37**	**0**	**0.000**	**0.01**	**0.000**	**9.02**
Maximum	**0.0350**	**4.22**	**72.6**	**11.0**	**30.5**	**61.5**	**257.5**	**243.3**	**59.6**	**1.13**	**53.6**	**31.6**	**5.01**	**4.11**	**634**	**13**	**0.032**	**0.81**	**0.017**	**10.18**
Average	**0.0334**	**4.20**	**72.4**	**10.9**	**28.7**	**61.1**	**254.6**	**236.5**	**58.6**	**1.08**	**51.5**	**31.2**	**4.75**	**4.02**	**423**	**6**	**0.016**	**0.50**	**0.010**	**9.68**

T_1 = Vapor generator inlet temperature (^{o}C) (M)

T_2 = Turbine inlet temperature (^{o}C) (M)

T_3 = Turbine outlet temperature (^{o}C) (M)

T_4 = Water cool condenser inlet temperature (^{o}C) (M)

T_5 = Water cool condenser outlet temperature (^{o}C) (M)

T_6 = Temperature heat source (^{o}C) (M)

T_7 = Temperature heat sink (^{o}C) (M)

P_2 = Turbine inlet pressure (kPa)

P_3 = Turbine outlet pressure (kPa)

Pr = Pressure ratio (P_2/P_3)

Q_{vapor} = Heat input at vapor generator

Q_{cond} = Heat sink at water cooling condenser

Table A.3 Experimental results of heat source temperature 82.3^{o}C and mass flow rate 0.0340 kg/s

Date : 16 June 2013

Location : Propulsion and Aerodynamics Research and Applications Laboratory (PARA LAB), Department of Mechanical Engineering, Chiang Mai University

Average heat source temperature : 82.3 ^{o}C

Average working fluid mass flow rate : 124.6 kg/h

Water circulation mass flow rate : 961.2 kg/h

Electric heater : 6.0 kW

Experiment 1 - 2 Heat Source Temperature 82.3^{o}C at m = 0.0340 kg/s																				
Test No.	**m_f**	**Heat source**	**$T_{source,6}$**	**$T_{sink,7}$**	**$T_{v,i}$**	**$T_{T,i}$**	**P_2**	**P_3**	**$T_{T,o}$**	**Pr**	**T_4**	**T_5**	**Q_{vapor}**	**Q_{cond}**	**Speed**	**W**	**Torq**	**Power**	**η_{sys}**	**η_{cnt}**
	kg/s	**kW**	**^{o}C**	**^{o}C**	**^{o}C**	**^{o}C**	**kPa**	**kPa**	**^{o}C**	**-**	**^{o}C**	**^{o}C**	**kW**	**kW**	**RPM**	**g**	**N.m**	**W**	**-**	**-**
B-160613-1	0.0369	4.88	82.4	10.9	31.1	69.1	283.2	237.9	64.8	1.19	52.1	31.3	6.16	5.43	54	15	0.038	0.21	0.003	11.1
B-160613-2	0.0368	4.86	82.1	10.8	31.6	69.1	283.2	238.7	64.9	1.19	52.8	31.4	6.06	5.42	165	14	0.034	0.59	0.010	11.0
B-160613-3	0.0354	4.89	82.5	10.9	31.4	69.3	284.7	249.5	66.4	1.14	54.0	31.6	5.89	5.41	265	12	0.030	0.83	0.014	11.1
B-160613-4	0.0347	4.85	81.9	10.9	30.5	69.3	284.7	254.6	67.1	1.12	54.0	30.9	5.91	5.52	355	11	0.026	0.97	0.016	11.3
B-160613-5	0.0345	4.85	82.0	10.8	31.3	69.2	284.0	255.3	67.2	1.11	52.8	30.8	5.74	5.52	431	9	0.023	1.02	0.018	11.1
B-160613-6(opt)	**0.0345**	**4.86**	**82.1**	**10.9**	**31.2**	**69.3**	**284.7**	**256.0**	**67.3**	**1.11**	**54.6**	**31.0**	**5.77**	**5.50**	**504**	**8**	**0.020**	**1.03**	**0.018**	**11.1**
B-160613-7	0.0341	4.89	82.6	11.0	31.9	68.8	281.0	255.3	67.2	1.10	53.1	31.2	5.53	5.40	562	7	0.016	0.97	0.018	10.8
B-160613-8	0.0341	4.87	82.3	10.9	31.5	69.0	282.5	256.7	67.4	1.10	53.2	30.8	5.62	5.49	609	5	0.013	0.84	0.015	11.0
B-160613-9	0.0343	4.89	82.6	11.0	31.0	69.5	286.2	258.9	67.7	1.11	56.0	31.2	5.80	5.50	647	4	0.010	0.68	0.012	11.2
B-160613-10	0.0339	4.89	82.6	11.0	31.6	68.8	281.0	256.7	67.4	1.09	52.1	31.3	5.55	5.38	674	3	0.007	0.49	0.009	10.9
B-160613-11	0.0335	4.88	82.4	11.0	31.2	69.4	285.5	264.0	68.4	1.08	57.0	31.3	5.63	5.47	691	2	0.004	0.27	0.005	11.2
B-160613-12	0.0326	4.89	82.5	11.0	31.4	68.6	279.5	266.1	68.5	1.05	53.0	31.6	5.32	5.28	700	0	0.000	0.03	0.000	10.9
Minimum	**0.0326**	**4.85**	**81.9**	**10.8**	**30.5**	**68.6**	**279.5**	**237.9**	**64.8**	**1.05**	**52.1**	**30.8**	**5.32**	**5.28**	**54**	**0**	**0.000**	**0.03**	**0.000**	**10.8**
Maximum	**0.0369**	**4.89**	**82.6**	**11.0**	**31.9**	**69.5**	**286.2**	**266.1**	**68.5**	**1.19**	**57.0**	**31.6**	**6.16**	**5.52**	**700**	**15**	**0.038**	**1.03**	**0.018**	**11.3**
Average	**0.0346**	**4.88**	**82.3**	**10.9**	**31.3**	**69.1**	**283.3**	**254.1**	**67.0**	**1.12**	**53.7**	**31.2**	**5.75**	**5.44**	**471**	**8**	**0.018**	**0.66**	**0.011**	**11.0**

T_1 = Vapor generator inlet temperature (^{o}C) (M)

T_2 = Turbine inlet temperature (^{o}C) (M)

T_3 = Turbine outlet temperature (^{o}C) (M)

T_4 = Water cool condenser inlet temperature (^{o}C) (M)

T_5 = Water cool condenser outlet temperature (^{o}C) (M)

T_6 = Temperature heat source (^{o}C) (M)

T_7 = Temperature heat sink (^{o}C) (M)

P_2 = Turbine inlet pressure (kPa)

P_3 = Turbine outlet pressure (kPa)

Pr = Pressure ratio (P_2/P_3)

Q_{vapor} = Heat input at vapor generator

Q_{cond} = Heat sink at water cooling condenser

Table A.4 Experimental results of heat source temperature 90.7^{o}C and mass flow rate 0.0354 kg/s

Date : 22 June 2013

Location : Propulsion and Aerodynamics Research and Applications Laboratory (PARA LAB), Department of Mechanical Engineering, Chiang Mai University

Average heat source temperature : 90.6 ^{o}C

Average working fluid mass flow rate : 127.9 kg/h

Water circulation mass flow rate : 961.2 kg/h

Electric heater : 6.0 kW

Experiment 1 - 3 Heat Source Temperature 90.7^{o}C at m = 0.0354 kg/s																				
Test No.	**m_{wf}**	**Heat source**	**$T_{source, 6}$**	**$T_{sink, 7}$**	**T_1**	**T_2**	**P_2**	**P_3**	**T_3**	**Pr**	**T_4**	**T_5**	**Q_{vapor}**	**Q_{cond}**	**Speed**	**W**	**Torq**	**Power**	**η_R**	**η_C**
	kg/s	**kW**	**^{o}C**	**^{o}C**	**^{o}C**	**^{o}C**	**kPa**	**kPa**	**^{o}C**	**-**	**^{o}C**	**^{o}C**	**kW**	**kW**	**RPM**	**g**	**N.m**	**W**	**-**	**-**
C-220613-1	0.0365	5.40	90.1	11.0	31.4	75.3	346	294	70.3	1.18	57.7	29.8	7.04	6.50	73	17	0.041	0.31	0.004	12.6
C-220613-2	0.0363	5.34	89.2	11.2	33.6	75.2	345	295	70.4	1.17	56.2	30.5	6.63	6.36	192	15	0.037	0.75	0.011	11.9
C-220613-3	0.0361	5.37	89.6	11.1	30.5	75.3	346	297	70.7	1.16	56.8	30.1	7.11	6.44	301	14	0.034	1.06	0.015	12.9
C-220613-4	0.0360	5.48	91.3	11.1	33.6	75.3	346	298	70.8	1.16	57.7	30.8	6.60	6.33	397	12	0.030	1.25	0.019	12.0
C-220613-5(opt)	**0.0359**	**5.48**	**91.3**	**11.0**	**31.6**	**75.5**	**348**	**300**	**71.1**	**1.16**	**58.1**	**29.0**	**6.93**	**6.64**	**482**	**11**	**0.026**	**1.32**	**0.019**	**12.6**
C-220613-6	0.0353	5.49	91.5	11.0	30.9	75.4	347	305	71.6	1.14	56.4	31.6	6.90	6.20	557	9	0.022	1.30	0.019	12.8
C-220613-7	0.0353	5.46	91.0	11.2	30.5	75.5	348	305	71.7	1.14	57.8	30.8	6.98	6.34	619	8	0.019	1.23	0.018	12.9
C-220613-8	0.0353	5.43	90.5	10.8	32.1	75.5	348	305	71.7	1.14	59.2	31.2	6.73	6.28	670	6	0.015	1.07	0.016	12.4
C-220613-9	0.0350	5.37	89.6	10.9	29.4	75.4	347	307	71.9	1.13	58.7	31.2	7.08	6.26	709	5	0.012	0.86	0.012	13.2
C-220613-10	0.0349	5.45	90.9	10.9	31.2	75.5	348	309	72.1	1.13	58.4	31.3	6.79	6.26	738	3	0.008	0.63	0.009	12.7
C-220613-11	0.0348	5.49	91.4	11.0	31.6	75.5	348	310	72.2	1.12	58.1	31.3	6.71	6.26	755	2	0.005	0.36	0.005	12.6
C-220613-12	0.0346	5.47	91.1	11.1	31.4	75.5	348	311	72.4	1.12	57.2	31.4	6.71	6.24	764	0	0.001	0.08	0.001	12.6
Minimum	**0.0346**	**5.34**	**89.2**	**10.8**	**29.4**	**75.2**	**345**	**294**	**70.3**	**1.12**	**56.2**	**29.0**	**6.60**	**6.20**	**73**	**0**	**0.001**	**0.08**	**0.001**	**11.9**
Maximum	**0.0365**	**5.49**	**91.5**	**11.2**	**33.6**	**75.5**	**348**	**311**	**72.4**	**1.18**	**59.2**	**31.6**	**7.11**	**6.64**	**764**	**17**	**0.041**	**1.32**	**0.019**	**13.2**
Average	**0.0355**	**5.43**	**90.6**	**11.0**	**31.5**	**75.4**	**347**	**303**	**71.4**	**1.15**	**57.7**	**30.8**	**6.85**	**6.34**	**522**	**8**	**0.021**	**0.85**	**0.012**	**12.6**

T_1 = Vapor generator inlet temperature (^{o}C) (M)

T_2 = Turbine inlet temperature (^{o}C) (M)

T_3 = Turbine outlet temperature (^{o}C) (M)

T_4 = Water cool condenser inlet temperature (^{o}C) (M)

T_5 = Water cool condenser outlet temperature (^{o}C) (M)

T_6 = Temperature heat source (^{o}C) (M)

T_7 = Temperature heat sink (^{o}C) (M)

P_2 = Turbine inlet pressure (kPa)

P_3 = Turbine outlet pressure (kPa)

Pr = Pressure ratio (P_2/P_3)

Q_{vapor} = Heat input at vapor generator

Q_{cond} = Heat sink at water cooling condenser

Table A.5 Experimental results of heat source temperature 96.1^{o}C and mass flow rate 0.0359 kg/s

Date : 23 June 2013

Location : Propulsion and Aerodynamics Research and Applications Laboratory (PARA LAB), Department of Mechanical Engineering, Chiang Mai University

Average heat source temperature :	96.1	^{o}C
Average working fluid mass flow rate :	129.3	kg/h
Water circulation mass flow rate :	961.2	kg/h
Electric heater :	6.0	kW

Experiment 1 - 4 Heat Source Temperature 96.1^{o}C at m = 0.0359 kg/s

Test No.	m_{wf}	Heat source	$T_{source,6}$	$T_{sink,7}$	T_1	T_2	P_2	P_3	T_3	Pr	T_4	T_5	Q_{vapor}	Q_{cond}	Speed	W	Torq	Power	η_R	η_C
	kg/s	kW	^{o}C	^{o}C	^{o}C	^{o}C	kPa	kPa	^{o}C	-	^{o}C	^{o}C	kW	kW	RPM	g	N.m	W	-	-
D-230613-1	0.0378	5.63	93.5	10.6	31.5	85.2	479	394	78.3	1.22	63.9	31.9	8.91	7.70	94	19	0.047	0.46	0.005	15.0
D-230613-2	0.0371	5.72	94.9	10.5	31.4	85.3	480	402	79.1	1.20	64.5	31.6	8.78	7.74	222	17	0.042	0.97	0.011	15.0
D-230613-3	0.0361	5.82	96.3	10.7	31.2	84.9	476	409	79.8	1.16	64.6	31.8	8.51	7.61	338	15	0.037	1.31	0.015	15.0
D-230613-4	0.0351	5.78	95.8	10.8	31.3	84.5	471	416	80.5	1.13	64.6	31.3	8.20	7.59	442	13	0.032	1.49	0.018	14.9
D-230613-5(opt)	**0.0358**	**5.86**	**96.9**	**9.9**	**32.2**	**85.1**	**478**	**414**	**79.3**	**1.15**	**64.5**	**32.3**	**8.32**	**7.39**	**533**	**12**	**0.029**	**1.60**	**0.019**	**14.8**
D-230613-6	0.0358	5.77	95.6	10.2	31.4	85.4	480	416	79.5	1.15	65.0	31.4	8.49	7.56	611	10	0.025	1.58	0.019	15.1
D-230613-7	0.0359	5.84	96.7	11.0	32.7	85.3	482	416	79.5	1.16	65.4	31.4	8.29	7.58	677	9	0.021	1.50	0.018	14.7
D-230613-8	0.0356	5.82	96.4	10.9	32.5	85.3	480	418	79.7	1.15	64.9	30.9	8.25	7.63	732	7	0.017	1.31	0.016	14.7
D-230613-9	0.0356	5.83	96.5	10.3	32.3	85.3	480	418	79.7	1.15	65.3	31.9	8.29	7.48	772	5	0.013	1.06	0.013	14.8
D-230613-10	0.0355	5.85	96.8	11.0	32.1	85.3	480	419	79.8	1.15	64.9	31.6	8.31	7.52	802	4	0.009	0.79	0.009	14.8
D-230613-11	0.0355	5.90	97.5	10.5	31.9	85.2	479	419	79.8	1.14	65.3	31.8	8.30	7.48	819	2	0.005	0.46	0.006	14.9
D-230613-12	0.0351	5.78	95.8	10.8	31.3	84.5	471	416	79.5	1.13	64.8	32.4	8.20	7.26	832	1	0.001	0.13	0.002	14.9
Minimum	**0.0351**	**5.63**	**93.5**	**9.9**	**31.2**	**84.5**	**471**	**394**	**78.3**	**1.13**	**63.9**	**30.9**	**8.2**	**7.26**	**94**	**1**	**0.001**	**0.13**	**0.002**	**14.7**
Maximum	**0.0378**	**5.90**	**97.5**	**11.0**	**32.7**	**85.4**	**482**	**419**	**80.5**	**1.22**	**65.4**	**32.4**	**8.9**	**7.74**	**832**	**19**	**0.047**	**1.60**	**0.019**	**15.1**
Average	**0.0359**	**5.80**	**96.1**	**10.6**	**31.8**	**85.1**	**478**	**413**	**79.5**	**1.16**	**64.8**	**31.7**	**8.4**	**7.54**	**573**	**9**	**0.023**	**1.05**	**0.013**	**14.9**

T_1 = Vapor generator inlet temperature (^{o}C) (M)

T_2 = Turbine inlet temperature (^{o}C) (M)

T_3 = Turbine outlet temperature (^{o}C) (M)

T_4 = Water cool condenser inlet temperature (^{o}C) (M)

T_5 = Water cool condenser outlet temperature (^{o}C) (M)

T_6 = Temperature heat source (^{o}C) (M)

T_7 = Temperature heat sink (^{o}C) (M)

P_2 = Turbine inlet pressure (kPa)

P_3 = Turbine outlet pressure (kPa)

Pr = Pressure ratio (P_2/P_3)

Q_{vapor} = Heat input at vapor generator

Q_{cond} = Heat sink at water cooling condenser

Table A.6 Experiment results of heat source temperature 71.1°C and mass flow rate 0.0636 kg/s

Date : 30 June 2013

Location : Propulsion and Aerodynamics Research and Applications Laboratory (PARA LAB), Department of Mechanical Engineering, Chiang Mai University, Thailand

Average heat source temperature : 71.1 °C

Average working fluid mass flow rate : 228.8 kg/h

Water circulation mass flow rate : 961.2 kg/h

Electric heater : 6.0 kW

Experiment 2-1 Heat Source Temperature 71.1°C at m = 0.0636 kg/s																				
Test No.	**m_{wf}**	**Heat source**	**$T_{source,6}$**	**$T_{sink,7}$**	**T_1**	**T_2**	**P_2**	**P_3**	**T_3**	**Pr**	**T_4**	**T_5**	**Q_{vapor}**	**Q_{cond}**	**Speed**	**W**	**Torq**	**Power**	**η_R**	**η_C**
	kg/s	**kW**	**°C**	**°C**	**°C**	**°C**	**kPa**	**kPa**	**°C**	**-**	**°C**	**°C**	**kW**	**kW**	**RPM**	**g**	**N.m**	**W**	**-**	**-**
E-300613-1	0.0657	4.15	71.5	11.6	31.6	60.3	248	213	55.1	1.17	52.5	31.6	8.29	6.79	95	20	0.0495	0.49	0.006	8.61
E-300613-2	0.0656	4.16	71.7	11.7	31.7	61.0	253	218	55.8	1.16	52.2	31.3	8.45	7.06	268	18	0.0452	1.27	0.015	8.77
E-300613-3	0.0659	4.13	71.3	11.5	31.6	61.5	257	220	56.1	1.17	53.0	31.2	8.66	7.21	425	17	0.0410	1.83	0.021	8.93
E-300613-4	0.0652	4.04	70.0	11.8	31.9	61.2	255	220	56.2	1.16	52.0	30.8	8.39	7.27	566	15	0.0362	2.15	0.026	8.76
E-300613-5(opt)	**0.0659**	**4.19**	**72.1**	**11.5**	**31.5**	**61.9**	**260**	**222**	**56.5**	**1.17**	**53.2**	**31.3**	**8.80**	**7.29**	**691**	**13**	**0.0321**	**2.32**	**0.026**	**9.07**
E-300613-6	0.0655	4.15	71.5	11.3	31.6	62.4	264	227	57.2	1.16	54.2	31.0	8.86	7.54	799	11	0.0274	2.29	0.026	9.18
E-300613-7	0.0638	4.17	71.8	11.4	31.6	61.7	258	228	57.4	1.13	53.7	31.6	8.43	7.23	891	9	0.0224	2.09	0.025	8.99
E-300613-8	0.0633	4.02	69.7	11.1	31.6	62.6	265	236	58.5	1.12	54.5	31.3	8.62	7.56	967	7	0.0180	1.82	0.021	9.23
E-300613-9	0.0605	4.08	70.6	11.0	31.6	60.8	252	234	58.3	1.07	54.6	30.9	7.76	7.29	1027	5	0.0129	1.39	0.018	8.74
E-300613-10	0.0604	4.10	70.8	11.2	31.7	61.6	258	241	59.2	1.07	53.4	30.8	7.93	7.53	1071	4	0.0088	0.99	0.012	8.93
E-300613-11	0.0599	4.12	71.1	11.3	31.7	61.6	258	243	59.5	1.06	54.7	31.3	7.86	7.41	1099	2	0.0045	0.51	0.007	8.93
E-300613-12	0.0610	4.08	70.6	11.2	31.7	61.7	258	238	58.9	1.08	54.3	31.1	8.04	7.45	1112	0	0.0003	0.04	0.000	8.96
Minimum	**0.0599**	**4.02**	**69.7**	**11.0**	**31.5**	**60.3**	**248**	**213**	**55.1**	**1.06**	**52.0**	**30.8**	**7.76**	**6.79**	**95**	**0**	**0.0003**	**0.04**	**0.000**	**8.607**
Maximum	**0.0659**	**4.19**	**72.1**	**11.8**	**31.9**	**62.6**	**265**	**243**	**59.5**	**1.17**	**54.7**	**31.6**	**8.86**	**7.56**	**1112**	**20**	**0.0495**	**2.32**	**0.026**	**9.233**
Average	**0.0636**	**4.12**	**71.1**	**11.4**	**31.6**	**61.5**	**257**	**228**	**57.4**	**1.13**	**53.5**	**31.2**	**8.34**	**7.30**	**751**	**10**	**0.0249**	**1.43**	**0.017**	**8.926**

T_1 = Vapor generator inlet temperature (°C) (M)

T_2 = Turbine inlet temperature (°C) (M)

T_3 = Turbine outlet temperature (°C) (M)

T_4 = Water cool condenser inlet temperature (°C) (M)

T_5 = Water cool condenser outlet temperature (°C) (M)

T_6 = Temperature heat source (°C) (M)

T_7 = Temperature heat sink (°C) (M)

P_2 = Turbine inlet pressure (kPa)

P_3 = Turbine outlet pressure (kPa)

Pr = Pressure ratio (P_2/P_3)

Q_{vapor} = Heat input at vapor generator

Q_{cond} = Heat sink at water cooling condenser

Table A.7 Experimental results for heat source temperature 83.6^{o}C and mass flow rate 0.0667 kg/s

Date :	6 July 2013
Location :	Propulsion and Aerodynamics Research and Applications Laboratory (PARA LAB), Department of Mechanical Engineering, Chiang Mai University, Thailand

Average heat source temperature :	83.6	^{o}C
Average working fluid mass flow rate :	240.3	kg/h
Water circulation mass flow rate :	961.2	kg/h
Electric heater :	6.0	kW

Experiment 2-2 Heat Source Temperature 83.6^{o}C at m = 0.0667 kg/s																			
Test No.	**m_{wf}**	**Heat source**	**$T_{source,6}$**	**$T_{sink,7}$**	**T_1**	**T_2**	**P_2**	**P_3**	**T_3**	**Pr**	**T_4**	**T_5**	**Q_{vapor}**	**Q_{cond}**	**Speed**	**W**	**Torq**	**Power**	**η_R**	**η_C**
	kg/s	**kW**	**^{o}C**	**^{o}C**	**^{o}C**	**^{o}C**	**kPa**	**kPa**	**^{o}C**	**-**	**^{o}C**	**^{o}C**	**kW**	**kW**	**RPM**	**g**	**N.m**	**W**	**-**	**-**
F-060713-1	0.0685	5.02	84.4	10.5	31.9	70.2	335	276	64.1	1.21	58.5	31.2	11.52	9.89	127	23	0.057	0.76	0.007	11.15
F-060713-2	0.0683	4.97	83.7	10.0	30.5	70.3	336	278	64.3	1.21	59.8	31.2	11.93	9.92	316	21	0.053	1.74	0.015	11.59
F-060713-3	0.0679	4.91	82.9	11.2	32.5	70.4	337	280	64.6	1.20	59.2	30.8	11.30	10.07	486	19	0.047	2.40	0.021	11.03
F-060713-4	0.0672	5.06	85.0	10.0	31.9	69.8	332	279	64.4	1.19	59.1	31.6	11.18	9.68	639	17	0.042	2.79	0.025	11.05
F-060713-5(opt)	**0.0671**	**4.93**	**83.2**	**11.7**	**30.8**	**70.0**	**334**	**280**	**64.6**	**1.19**	**59.9**	**31.0**	**11.56**	**9.91**	**773**	**15**	**0.036**	**2.94**	**0.025**	**11.42**
F-060713-6	0.0661	4.89	82.5	11.3	32.6	69.1	326	278	64.3	1.17	59.0	30.8	10.59	9.72	891	13	0.031	2.89	0.027	10.66
F-060713-7	0.0666	5.05	84.9	10.1	30.7	70.2	335	284	65.1	1.18	59.7	31.3	11.55	9.88	990	11	0.026	2.75	0.024	11.50
F-060713-8	0.0662	4.85	81.9	11.9	31.0	70.0	334	284	65.1	1.17	59.6	30.9	11.34	9.95	1073	9	0.021	2.37	0.021	11.37
F-060713-9	0.0665	4.97	83.7	11.3	31.0	70.5	338	287	65.4	1.18	58.8	31.6	11.54	9.88	1136	7	0.016	1.92	0.017	11.49
F-060713-10	0.0658	4.99	84.0	11.4	30.2	70.0	334	286	65.3	1.17	58.5	31.3	11.51	9.83	1183	5	0.011	1.38	0.012	11.60
F-060713-11	0.0662	4.93	83.2	11.4	32.3	70.4	337	287	65.5	1.17	59.7	31.3	11.08	9.94	1211	2	0.006	0.76	0.007	11.09
F-060713-12	0.0646	4.94	83.3	11.3	30.3	69.9	325	283	65.0	1.15	58.6	31.4	11.24	9.54	1224	0	0.001	0.07	0.001	11.54
Minimum	**0.0646**	**4.85**	**81.9**	**10.0**	**30.2**	**69.1**	**325**	**276**	**64.1**	**1.15**	**58.5**	**30.8**	**10.59**	**9.54**	**127**	**0**	**0.001**	**0.07**	**0.001**	**10.66**
Maximum	**0.0685**	**5.06**	**85.0**	**11.9**	**32.6**	**70.5**	**338**	**287**	**65.5**	**1.21**	**59.9**	**31.6**	**11.93**	**10.07**	**1224**	**23**	**0.057**	**2.94**	**0.027**	**11.60**
Average	**0.0667**	**4.96**	**83.6**	**11.0**	**31.3**	**70.1**	**334**	**282**	**64.8**	**1.18**	**59.2**	**31.2**	**11.36**	**9.85**	**837**	**12**	**0.029**	**1.90**	**0.017**	**11.29**

T_1 = Vapor generator inlet temperature (^{o}C) (M)
T_2 = Turbine inlet temperature (^{o}C) (M)
T_3 = Turbine outlet temperature (^{o}C) (M)
T_4 = Water cool condenser inlet temperature (^{o}C) (M)
T_5 = Water cool condenser outlet temperature (^{o}C) (M)
T_6 = Temperature heat source (^{o}C) (M)
T_7 = Temperature heat sink (^{o}C) (M)
P_2 = Turbine inlet pressure (kPa)
P_3 = Turbine outlet pressure (kPa)
Pr = Pressure ratio (P_2/P_3)
Q_{vapor} = Heat input at vapor generator
Q_{cond} = Heat sink at water cooling condenser

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Table A.8 Seventh experiment for heat source temperature 90.6^oC and 0.0614 kg/s

Date : 7 July 2013

Location : Propulsion and Aerodynamics Research and Applications Laboratory (PARA LAB), Department of Mechanical Engineering, Chiang Mai University, Thailand

Average heat source temperature : 90.6 ^oC

Average working fluid mass flow rate : 221.2 kg/h

Water circulation mass flow rate : 961.2 kg/h

Electric heater : 6.0 kW

Experiment 2-3 Heat Source Temperature 90.6^oC at m = 0.0614 kg/s

Test No.	m_{wf}	Heat source	$T_{source,6}$	$T_{sink,7}$	T_1	T_2	P_2	P_3	T_3	Pr	T_4	T_5	Q_{vapor}	Q_{cond}	Speed	W	Torq	Power	η_R	η_C
	kg/s	kW	^oC	^oC	^oC	^oC	kPa	kPa	^oC	-	^oC	^oC	kW	kW	RPM	g	N.m	W	-	-
G-070713-1	0.0647	5.42	90.4	10.7	31.4	79.3	414	361	73.9	1.15	69.2	30.1	13.61	12.44	162	24	0.060	1.0	0.007	13.6
G-070713-2	0.0633	5.36	89.5	10.8	31.6	79.2	413	368	74.6	1.12	61.8	30.5	13.24	12.27	366	22	0.054	2.1	0.016	13.5
G-070713-3	0.0628	5.43	90.6	10.7	31.6	79.2	413	371	74.9	1.11	69.2	29.8	13.14	12.45	550	20	0.048	2.8	0.021	13.5
G-070713-4	0.0616	5.46	91.0	10.9	30.1	79.1	412	377	75.6	1.09	69.8	30.8	13.25	12.11	714	17	0.042	3.2	0.024	13.9
G-070713-5(opt)	**0.0613**	**5.45**	**90.9**	**10.8**	**31.1**	**78.8**	**409**	**376**	**75.5**	**1.09**	**69.0**	**30.8**	**12.83**	**12.03**	**859**	**15**	**0.037**	**3.31**	**0.026**	**13.6**
G-070713-6	0.0609	5.45	90.9	10.8	31.4	79.2	413	382	76.1	1.08	69.5	29.0	12.79	12.61	985	13	0.032	3.3	0.026	13.6
G-070713-7	0.0609	5.46	91.0	10.8	31.9	79.2	413	382	76.1	1.08	69.0	31.4	12.66	11.96	1092	11	0.027	3.1	0.024	13.4
G-070713-8	0.0605	5.42	90.4	10.9	31.5	78.6	407	379	75.8	1.07	69.1	31.6	12.51	11.74	1178	9	0.022	2.7	0.021	13.4
G-070713-9	0.0606	5.43	90.6	10.8	31.5	78.9	410	381	76.0	1.08	70.1	31.3	12.62	11.90	1247	7	0.016	2.1	0.017	13.5
G-070713-10	0.0605	5.43	90.6	10.8	30.0	79.1	412	384	76.3	1.07	69.6	31.3	13.04	11.95	1295	5	0.012	1.6	0.012	13.9
G-070713-11	0.0605	5.44	90.7	10.9	32.1	79.2	413	385	76.4	1.07	71.2	31.2	12.51	12.01	1324	3	0.007	0.9	0.007	13.4
G-070713-12	0.0596	5.41	90.3	10.9	32.8	79.2	413	391	77.0	1.06	69.2	31.2	12.14	11.99	1336	1	0.001	0.2	0.002	13.2
Minimum	**0.0596**	**5.36**	**89.5**	**10.7**	**30.0**	**78.6**	**407**	**361**	**73.9**	**1.06**	**61.8**	**29.0**	**12.14**	**11.74**	**162**	**1**	**0.001**	**0.2**	**0.002**	**13.2**
Maximum	**0.0647**	**5.46**	**91.0**	**10.9**	**32.8**	**79.3**	**414**	**391**	**77.0**	**1.15**	**71.2**	**31.6**	**13.61**	**12.61**	**1336**	**24**	**0.060**	**3.3**	**0.026**	**13.9**
Average	**0.0614**	**5.43**	**90.6**	**10.8**	**31.4**	**79.1**	**412**	**378**	**75.7**	**1.09**	**68.9**	**30.8**	**12.86**	**12.12**	**926**	**12**	**0.030**	**2.2**	**0.017**	**13.5**

T_1 = Vapor generator inlet temperature (^oC) (M)

T_2 = Turbine inlet temperature (^oC) (M)

T_3 = Turbine outlet temperature (^oC) (M)

T_4 = Water cool condenser inlet temperature (^oC) (M)

T_5 = Water cool condenser outlet temperature (^oC) (M)

T_6 = Temperature heat source (^oC) (M)

T_7 = Temperature heat sink (^oC) (M)

P_2 = Turbine inlet pressure (kPa)

P_3 = Turbine outlet pressure (kPa)

Pr = Pressure ratio (P_2/P_3)

Q_{vapor} = Heat input at vapor generator

Q_{cond} = Heat sink at water cooling condenser

Table A.9 Experimental results for heat source temperature 100^oC and mass flow rate 0.062 kg/s

Date : 13 July 2013

Location : Propulsion and Aerodynamics Research and Applications Laboratory (PARA LAB), Department of Mechanical Engineering, Chiang Mai University, Thailand

Average heat source temperature :	96.1	^oC
Average working fluid mass flow rate :	237.9	kg/h
Water circulation mass flow rate :	961.2	kg/h
Electric heater :	6.0	kW

Experiment 2-4 Heat Source Temperature 96.1^oC at m = 0.0661 kg/s

Test No.	m_{wf}	Heat source	$T_{source,6}$	$T_{sink,7}$	T_1	T_2	P_2	P_3	T_3	Pr	T_4	T_5	Q_{vapor}	Q_{cond}	Speed	W	Torq	Power	η_R	η_C
	kg/s	kW	^oC	^oC	^oC	^oC	kPa	kPa	^oC	-	^oC	^oC	kW	kW	RPM	g	N.m	W	-	-
H-130713-1	0.0670	5.87	97.1	11.4	32.3	85.6	484	407	79.3	1.19	75.6	31.6	15.69	14.04	202	28	0.068	1.4	0.01	14.86
H-130713-2	0.0669	5.83	96.5	11.5	32.9	85.6	484	408	79.4	1.19	72.8	31.8	15.49	13.99	419	25	0.062	2.7	0.02	14.69
H-130713-3	0.0667	5.68	94.3	11.9	30.5	85.6	484	409	79.7	1.18	73.5	32.9	16.14	13.71	616	23	0.056	3.6	0.02	15.36
H-130713-4	0.0664	5.74	95.2	11.7	30.0	85.6	484	411	80.0	1.18	74.1	31.6	16.22	14.12	792	20	0.050	4.2	0.03	15.50
H-130713-5(opt)	**0.0664**	**5.85**	**96.8**	**11.0**	**31.5**	**85.6**	**484**	**411**	**80.0**	**1.18**	**74.8**	**32.3**	**15.78**	**13.92**	**946**	**18**	**0.044**	**4.35**	**0.03**	**15.08**
H-130713-6	0.0664	5.77	95.6	11.3	30.6	85.7	485	412	80.2	1.18	73.2	31.8	16.07	14.12	1080	15	0.038	4.3	0.03	15.35
H-130713-7	0.0662	5.86	97.0	11.1	30.7	85.7	485	413	80.5	1.17	74.6	30.9	15.98	14.41	1193	13	0.032	4.0	0.03	15.33
H-130713-8	0.0656	5.85	96.8	11.4	29.9	84.9	476	409	79.7	1.16	72.7	31.4	15.84	13.91	1286	11	0.026	3.5	0.02	15.36
H-130713-9	0.0660	5.80	96.0	11.2	31.0	85.7	485	414	80.7	1.17	75.8	32.4	15.86	14.00	1357	8	0.020	2.9	0.02	15.24
H-130713-10	0.0660	5.80	96.1	11.0	32.5	85.7	485	414	80.7	1.17	74.5	31.4	15.42	14.29	1407	6	0.014	2.1	0.01	14.83
H-130713-11	0.0658	5.82	96.3	11.3	31.3	85.7	485	415	80.9	1.17	74.4	32.3	15.73	14.05	1437	3	0.008	1.2	0.01	15.16
H-130713-12	0.0654	5.82	96.4	11.4	29.2	85.4	482	415	80.9	1.16	73.1	31.9	16.13	14.07	1447	1	0.002	0.3	0.00	15.67
Minimum	**0.0654**	**5.68**	**94.3**	**11.0**	**29.2**	**84.9**	**476**	**409**	**79.7**	**1.16**	**72.7**	**30.9**	**15.42**	**13.71**	**616**	**1**	**0.002**	**0.3**	**0.00**	**14.83**
Maximum	**0.0667**	**5.86**	**97.0**	**11.9**	**32.5**	**85.7**	**485**	**415**	**80.9**	**1.18**	**75.8**	**32.9**	**16.22**	**14.41**	**1447**	**23**	**0.056**	**4.3**	**0.03**	**15.67**
Average	**0.0661**	**5.80**	**96.1**	**11.3**	**30.7**	**85.6**	**483**	**413**	**80.3**	**1.17**	**74.1**	**31.9**	**15.92**	**14.06**	**1156**	**12**	**0.029**	**3.1**	**0.02**	**15.29**

T_1 = Vapor generator inlet temperature (^oC) (M)

T_2 = Turbine inlet temperature (^oC) (M)

T_3 = Turbine outlet temperature (^oC) (M)

T_4 = Water cool condenser inlet temperature (^oC) (M)

T_5 = Water cool condenser outlet temperature (^oC) (M)

T_6 = Temperature heat source (^oC) (M)

T_7 = Temperature heat sink (^oC) (M)

P_2 = Turbine inlet pressure (kPa)

P_3 = Turbine outlet pressure (kPa)

Pr = Pressure ratio (P_2/P_3)

Q_{vapor} = Heat input at vapor generator

Q_{cond} = Heat sink at water cooling condenser

Table A.10 Experiment results of heat source temperature 70°C and mass flow rate 0.0839 kg/s

Date : 14 July 2013

Location : Propulsion and Aerodynamics Research and Applications Laboratory (PARA LAB), Department of Mechanical Engineering, Chiang Mai University, Thailand

Average heat source temperature :	73.4	°C
Average working fluid mass flow rate :	302.2	kg/h
Water circulation mass flow rate :	961.2	kg/h
Electric heater :	6.0	kW

Experiment 3-1 Heat Source Temperature 70°C at m = 0.082 kg/s																				
Test No.	**m_{wf}**	**Heat source**	**$T_{source,6}$**	**$T_{sink,7}$**	**T_1**	**T_2**	**P_2**	**P_3**	**T_3**	**Pr**	**T_4**	**T_5**	**Q_{vapor}**	**Q_{cond}**	**Speed**	**W**	**Torq**	**Power**	**η_R**	**η_C**
	kg/s	**kW**	**°C**	**°C**	**°C**	**°C**	**kPa**	**kPa**	**°C**	**-**	**°C**	**°C**	**kW**	**kW**	**RPM**	**g**	**N.m**	**W**	**-**	**-**
I-140713-1	0.0915	4.23	72.7	10.3	30.4	60.1	247	203	53.6	1.22	44.8	31.3	11.9	8.97	143	42	0.103	1.5	0.013	8.91
I-140713-2	0.0892	4.20	72.3	10.1	29.6	59.7	244	206	54.3	1.19	44.8	30.9	11.8	9.17	402	38	0.092	3.9	0.033	9.04
I-140713-3	0.0874	4.16	71.7	10.4	30.8	60.3	248	214	55.4	1.16	44.6	31.3	11.3	9.26	638	33	0.082	5.5	0.048	8.85
I-140713-4	0.0860	4.24	72.9	10.1	30.3	60.0	246	215	55.6	1.14	44.9	30.8	11.2	9.37	849	29	0.072	6.4	0.057	8.91
I-140713-5(opt)	**0.0859**	**4.20**	**72.3**	**10.1**	**30.8**	**60.7**	**251**	**220**	**56.3**	**1.14**	**44.9**	**31.0**	**11.3**	**9.54**	**1037**	**26**	**0.063**	**6.80**	**0.060**	**8.96**
I-140713-6	0.0846	4.23	72.8	10.1	31.8	60.3	248	221	56.4	1.13	44.8	31.6	10.6	9.22	1199	22	0.053	6.7	0.063	8.55
I-140713-7	0.0845	4.27	73.4	10.1	31.2	59.9	246	219	56.1	1.12	44.6	31.2	10.6	9.24	1337	18	0.044	6.2	0.058	8.62
I-140713-8	0.0842	4.31	73.9	10.1	32.1	59.8	245	219	56.1	1.12	44.8	31.3	10.2	9.17	1451	15	0.036	5.5	0.053	8.32
I-140713-9	0.0841	4.29	73.6	10.2	31.5	60.1	247	221	56.4	1.12	44.8	31.6	10.6	9.16	1541	11	0.027	4.3	0.041	8.58
I-140713-10	0.0843	4.29	73.7	10.2	31.5	60.4	249	222	56.6	1.12	44.7	31.3	10.7	9.36	1607	8	0.019	3.1	0.029	8.64
I-140713-11	0.0821	4.33	74.3	10.1	31.1	59.7	244	224	56.8	1.09	44.8	30.8	10.3	9.38	1649	4	0.009	1.6	0.015	8.59
I-140713-12	0.0798	4.27	73.4	10.5	31.9	59.9	246	231	56.9	1.06	44.6	31.3	9.8	8.97	1668	0	0.001	0.1	0.001	8.41
Minimum	**0.0798**	**4.16**	**71.7**	**10.1**	**29.6**	**59.7**	**244**	**203**	**53.6**	**1.06**	**44.6**	**30.8**	**9.8**	**8.97**	**143**	**0**	**0.001**	**0.1**	**0.001**	**8.3**
Maximum	**0.0915**	**4.33**	**74.3**	**10.5**	**32.1**	**60.7**	**251**	**231**	**56.9**	**1.22**	**44.9**	**31.6**	**11.9**	**9.54**	**1668**	**42**	**0.103**	**6.8**	**0.063**	**9.0**
Average	**0.0839**	**4.27**	**73.4**	**10.2**	**31.4**	**60.1**	**247**	**221**	**56.4**	**1.12**	**44.8**	**31.2**	**10.6**	**9.23**	**1371**	**20**	**0.036**	**4.5**	**0.042**	**8.6**

T_1 = Vapor generator inlet temperature (°C) (M)

T_2 = Turbine inlet temperature (°C) (M)

T_3 = Turbine outlet temperature (°C) (M)

T_4 = Water cool condenser inlet temperature (°C) (M)

T_5 = Water cool condenser outlet temperature (°C) (M)

T_6 = Temperature heat source (°C) (M)

T_7 = Temperature heat sink (°C) (M)

P_2 = Turbine inlet pressure (kPa)

P_3 = Turbine outlet pressure (kPa)

Pr = Pressure ratio (P_2/P_3)

Q_{vapor} = Heat input at vapor generator

Q_{cond} = Heat sink at water cooling condenser

Table A.11 Experiment results of heat source temperature 80^{o}C and mass flow rate 0.082 kg/s

Date : 20 July 2013

Location : Propulsion and Aerodynamics Research and Applications Laboratory (PARA LAB), Department of Mechanical Engineering, Chiang Mai University, Thailand

Average heat source temperature : 83.4 ^{o}C

Average working fluid mass flow rate : 292.3 kg/h

Water circulation mass flow rate : 961.2 kg/h

Electric heater : 6.0 kW

Experiment 3-2 Heat Source Temperature 80^{o}C at m = 0.082 kg/s																				
Test No.	**m_{wf}**	**Heat source**	**$T_{source, 6}$**	**$T_{sink, 7}$**	**T_1**	**T_2**	**P_2**	**P_3**	**T_3**	**Pr**	**T_4**	**T_5**	**Q_{vapor}**	**Q_{cond}**	**Speed**	**W**	**Torq**	**Power**	**η_R**	**η_C**
	kg/s	**kW**	**^{o}C**	**^{o}C**	**^{o}C**	**^{o}C**	**kPa**	**kPa**	**^{o}C**	**-**	**^{o}C**	**^{o}C**	**kW**	**kW**	**RPM**	**g**	**N.m**	**W**	**-**	**-**
J-200713-1	0.0928	4.85	82.0	11.0	28.4	72.1	344	288	65.6	1.19	63.8	31.8	17.82	13.78	190	46	0.11	2.2	0.013	12.66
J-200713-2	0.0889	4.85	82.0	11.0	28.4	71.0	334	285	65.3	1.17	63.8	32.0	16.64	13.01	474	41	0.10	5.0	0.030	12.38
J-200713-3	0.0796	5.02	84.5	11.0	33.8	72.7	349	303	67.4	1.15	63.9	31.6	13.61	12.52	729	37	0.09	6.9	0.051	11.25
J-200713-4	0.0782	5.02	84.5	11.1	33.2	71.8	341	300	67.0	1.14	63.6	31.2	13.26	12.30	959	32	0.08	8.0	0.060	11.19
J-200713-5(opt)	**0.0800**	**5.01**	**84.3**	**11.1**	**32.6**	**72.1**	**344**	**302**	**67.3**	**1.14**	**63.6**	**31.2**	**13.87**	**12.68**	**1160**	**28**	**0.07**	**8.44**	**0.061**	**11.44**
J-200713-6	0.0782	4.84	81.8	11.0	31.0	70.5	329	297	66.7	1.11	63.8	31.9	13.57	11.96	1337	24	0.06	8.2	0.060	11.49
J-200713-7	0.0804	5.02	84.5	11.1	33.1	72.7	349	305	67.7	1.14	63.8	31.3	13.98	12.85	1485	21	0.05	8.0	0.057	11.45
J-200713-8	0.0806	4.88	82.4	11.0	30.0	70.7	331	299	66.9	1.11	63.6	31.8	14.40	12.42	1609	16	0.04	6.7	0.047	11.84
J-200713-9	0.0837	4.91	82.9	11.0	29.6	71.8	341	306	67.8	1.11	63.8	31.4	15.51	13.38	1704	12	0.03	5.4	0.035	12.23
J-200713-10	0.0826	4.92	83.0	11.0	30.3	72.4	347	314	68.7	1.10	63.8	31.3	15.28	13.57	1774	9	0.02	3.9	0.026	12.18
J-200713-11	0.0849	4.99	84.0	11.1	29.3	72.7	349	317	69.1	1.10	63.7	31.3	16.18	14.09	1817	5	0.01	2.1	0.013	12.55
J-200713-12	0.0821	4.94	83.3	11.0	30.4	72.6	348	318	69.2	1.10	63.9	31.6	15.22	13.56	1836	0	0.00	0.2	0.001	12.21
Minimum	**0.0782**	**4.84**	**81.8**	**11.0**	**28.4**	**70.5**	**329**	**285**	**65.3**	**1.10**	**63.6**	**31.2**	**13.3**	**11.96**	**190**	**0**	**0.00**	**0.2**	**0.001**	**11.2**
Maximum	**0.0928**	**5.02**	**84.5**	**11.1**	**33.8**	**72.7**	**349**	**318**	**69.2**	**1.19**	**63.9**	**32.0**	**17.8**	**14.09**	**1836**	**46**	**0.11**	**8.4**	**0.061**	**12.7**
Average	**0.0812**	**4.95**	**83.4**	**11.0**	**31.1**	**71.9**	**342**	**307**	**67.8**	**1.12**	**63.7**	**31.4**	**14.59**	**13.01**	**1520**	**23**	**0.04**	**5.7**	**0.040**	**11.8**

T_1 = Vapor generator inlet temperature (^{o}C) (M)

T_2 = Turbine inlet temperature (^{o}C) (M)

T_3 = Turbine outlet temperature (^{o}C) (M)

T_4 = Water cool condenser inlet temperature (^{o}C) (M)

T_5 = Water cool condenser outlet temperature (^{o}C) (M)

T_6 = Temperature heat source (^{o}C) (M)

T_7 = Temperature heat sink (^{o}C) (M)

P_2 = Turbine inlet pressure (kPa)

P_3 = Turbine outlet pressure (kPa)

Pr = Pressure ratio (P_2/P_3)

Q_{vapor} = Heat input at vapor generator

Q_{cond} = Heat sink at water cooling condenser

Table A.12 Experiment results of heat source temperature 90°C and mass flow rate 0.0823 kg/s

Date :	21 July 2013
Location :	Propulsion and Aerodynamics Research and Applications Laboratory (PARA LAB), Department of Mechanical Engineering, Chiang Mai University, Thailand

Average heat source temperature :	91.4	°C
Average working fluid mass flow rate :	296.2	kg/h
Water circulation mass flow rate :	961.2	kg/h
Electric heater :	6.0	kW

Experiment 3-3 Heat Source Temperature 90°C at mass flow rate 0.0823 kg/s																			
Test No.	m_{wf}	Heat source	$T_{source,6}$	$T_{sink,7}$	T_1	T_2	P_2	P_3	T_3	Pr	T_4	T_5	Q_{vapor}	Q_{cond}	Speed	W	Torq	Power	η_R	η_C
	kg/s	kW	°C	°C	°C	°C	kPa	kPa	°C	-	°C	°C	kW	kW	RPM	g	N.m	W	-	-
K-210713-1	0.0850	5.51	91.8	12.0	30.4	76.9	389	339	71.6	1.15	57.8	31.8	17.36	14.86	243	49	0.12	3.0	0.018	13.28
K-210713-2	0.0852	5.49	91.5	11.9	30.4	77.7	397	346	72.3	1.15	57.8	32.0	17.69	15.07	549	45	0.11	6.3	0.036	13.48
K-210713-3	0.0843	5.50	91.6	12.3	32.4	78.2	403	354	73.2	1.14	57.9	31.6	16.96	15.41	824	40	0.10	8.5	0.050	13.04
K-210713-4	0.0830	5.47	91.2	11.5	33.0	77.1	391	349	72.7	1.12	57.8	31.9	16.07	14.87	1071	35	0.09	9.7	0.061	12.59
K-210713-5(opt)	**0.0836**	**5.47**	**91.1**	**12.5**	**31.3**	**77.8**	**398**	**353**	**73.1**	**1.13**	**57.7**	**31.3**	**17.07**	**15.35**	**1289**	**31**	**0.076**	**10.31**	**0.060**	**13.25**
K-210713-6	0.0828	5.52	91.9	12.2	31.6	77.1	391	350	72.8	1.12	57.8	31.4	16.54	15.05	1478	27	0.07	10.1	0.061	12.99
K-210713-7	0.0828	5.47	91.2	12.1	32.0	77.2	392	351	72.9	1.12	57.6	31.8	16.43	14.94	1638	23	0.06	9.6	0.058	12.90
K-210713-8	0.0826	5.49	91.4	12.6	34.6	77.5	395	355	73.3	1.11	57.6	31.2	15.55	15.26	1768	18	0.04	8.3	0.053	12.23
K-210713-9	0.0819	5.51	91.8	12.8	35.2	76.9	389	352	73.0	1.11	57.6	31.2	15.01	15.04	1870	14	0.03	6.6	0.044	11.91
K-210713-10	0.0821	5.49	91.5	12.5	35.8	77.4	394	356	73.4	1.11	57.9	31.6	14.99	15.08	1942	10	0.02	4.9	0.033	11.85
K-210713-11	0.0809	5.48	91.3	12.4	32.3	77.1	391	358	73.7	1.09	57.8	31.3	15.92	15.06	1985	5	0.01	2.8	0.017	12.79
K-210713-12	0.0809	5.49	91.5	12.6	35.1	77.1	391	358	73.7	1.09	57.8	31.3	14.92	15.06	2003	1	0.00	0.6	0.004	11.99
Minimum	**0.0809**	**5.47**	**91.1**	**11.5**	**30.4**	**76.9**	**389**	**339**	**71.6**	**1.09**	**57.6**	**31.2**	**14.9**	**14.86**	**243**	**1**	**0.00**	**0.6**	**0.004**	**11.9**
Maximum	**0.0852**	**5.52**	**91.9**	**12.8**	**35.8**	**78.2**	**403**	**358**	**73.7**	**1.15**	**57.9**	**32.0**	**17.7**	**15.41**	**2003**	**49**	**0.12**	**10.3**	**0.061**	**13.5**
Average	**0.0823**	**5.49**	**91.4**	**12.4**	**33.4**	**77.2**	**393**	**354**	**73.2**	**1.11**	**57.7**	**31.4**	**15.83**	**15.09**	**1672**	**25**	**0.04**	**7.0**	**0.044**	**12.5**

T_1 = Vapor generator inlet temperature (°C) (M)

T_2 = Turbine inlet temperature (°C) (M)

T_3 = Turbine outlet temperature (°C) (M)

T_4 = Water cool condenser inlet temperature (°C) (M)

T_5 = Water cool condenser outlet temperature (°C) (M)

T_6 = Temperature heat source (°C) (M)

T_7 = Temperature heat sink (°C) (M)

P_2 = Turbine inlet pressure (kPa)

P_3 = Turbine outlet pressure (kPa)

Pr = Pressure ratio (P_2/P_3)

Q_{vapor} = Heat input at vapor generator

Q_{cond} = Heat sink at water cooling condenser

Table A.13 Experimental results of heat source temperature 90^{o}C and mass flow rate 0.0835 kg/s

Date :	26 July 2013
Location :	Propulsion and Aerodynamics Research and Applications Laboratory (PARA LAB), Department of Mechanical Engineering, Chiang Mai University, Thailand

Average heat source temperature :	96.5	^{o}C
Average working fluid mass flow rate :	313.4	kg/h
Water circulation mass flow rate :	961.2	kg/h
Electric heater :	6.0	kW

Experiment 2-1 Heat Source Temperature 70^{o}C at m = 0.062 kg/s																			
Test No.	**m_{wf}**	**Heat source**	**$T_{source,6}$**	**$T_{sink,7}$**	**T_1**	**T_2**	**P_2**	**P_3**	**T_3**	**Pr**	**T_4**	**T_5**	**Q_{vapor}**	**Q_{cond}**	**Speed**	**W**	**Torq**	**Power**	**η_R**	**η_C**
	kg/s	**kW**	**^{o}C**	**^{o}C**	**^{o}C**	**^{o}C**	**kPa**	**kPa**	**^{o}C**	**-**	**^{o}C**	**^{o}C**	**kW**	**kW**	**RPM**	**g**	**N.m**	**W**	**-**	**-**
L-260713-1	0.0834	5.72	94.9	11.8	31.6	77.4	395	356	73.4	1.11	67.7	31.8	16.8	15.24	302	52	0.127	4.0	0.024	13.1
L-260713-2	0.0856	5.73	95.0	11.8	31.1	77.8	399	350	72.8	1.14	68.5	31.6	17.6	15.49	628	49	0.119	7.8	0.045	13.3
L-260713-3	0.0849	5.70	94.6	12.0	31.3	78.7	408	361	74.0	1.13	68.3	31.4	17.7	15.89	924	44	0.108	10.4	0.059	13.5
L-260713-4	0.0858	5.74	95.1	11.8	30.6	78.9	410	359	73.8	1.14	63.2	32.9	18.2	15.41	1188	40	0.097	12.1	0.066	13.7
L-260713-5(opt)	**0.0876**	**5.77**	**95.6**	**12.1**	**31.4**	**78.8**	**409**	**351**	**72.9**	**1.16**	**68.9**	**31.6**	**18.2**	**15.89**	**1420**	**35**	**0.087**	**12.90**	**0.071**	**13.5**
L-260713-6	0.0845	5.80	96.0	11.9	31.6	78.1	402	357	73.6	1.12	67.0	32.3	17.3	15.33	1620	29	0.072	12.3	0.071	13.2
L-260713-7	0.0872	5.82	96.4	11.9	31.4	78.1	402	347	72.4	1.16	68.5	32.4	17.9	15.32	1790	26	0.064	12.0	0.067	13.3
L-260713-8	0.0867	5.85	96.8	12.2	31.0	78.3	404	350	72.8	1.15	68.8	31.8	18.0	15.61	1929	21	0.052	10.4	0.058	13.5
L-260713-9	0.0914	5.87	97.1	12.3	31.5	78.5	406	334	71.0	1.22	70.0	31.3	18.9	15.94	2036	17	0.042	8.9	0.047	13.4
L-260713-10	0.0854	5.90	97.5	12.3	31.4	78.8	409	360	73.9	1.14	67.2	31.4	17.8	15.94	2110	11	0.028	6.2	0.035	13.5
L-260713-11	0.0856	5.86	96.9	12.0	31.6	78.8	409	359	73.8	1.14	68.1	30.9	17.7	16.13	2155	7	0.016	3.6	0.020	13.4
L-260713-12	0.0893	5.88	97.2	12.3	31.0	78.3	404	340	71.7	1.19	66.1	30.9	18.5	15.99	2170	2	0.005	1.1	0.006	13.5
Minimum	**0.0834**	**5.70**	**94.6**	**11.8**	**30.6**	**77.4**	**395**	**334**	**71.0**	**1.11**	**63.2**	**30.9**	**16.8**	**15.24**	**302**	**2**	**0.005**	**1.1**	**0.006**	**13.1**
Maximum	**0.0914**	**5.90**	**97.5**	**12.3**	**31.6**	**78.9**	**410**	**361**	**74.0**	**1.22**	**70.0**	**32.9**	**18.9**	**16.13**	**2170**	**52**	**0.127**	**12.9**	**0.071**	**13.7**
Average	**0.0870**	**5.83**	**96.5**	**12.1**	**31.3**	**78.5**	**406**	**351**	**72.9**	**1.16**	**67.5**	**31.7**	**18.06**	**15.68**	**1824**	**28**	**0.051**	**8.8**	**0.049**	**13.4**

T_1 = Vapor generator inlet temperature (^{o}C) (M)

T_2 = Turbine inlet temperature (^{o}C) (M)

T_3 = Turbine outlet temperature (^{o}C) (M)

T_4 = Water cool condenser inlet temperature (^{o}C) (M)

T_5 = Water cool condenser outlet temperature (^{o}C) (M)

T_6 = Temperature heat source (^{o}C) (M)

T_7 = Temperature heat sink (^{o}C) (M)

P_2 = Turbine inlet pressure (kPa)

P_3 = Turbine outlet pressure (kPa)

Pr = Pressure ratio (P_2/P_3)

Q_{vapor} = Heat input at vapor generator

Q_{cond} = Heat sink at water cooling condenser

Table A.14 Experimental results of average heat source temperature 72.6^{o}C and average mass flow rate 0.1077 kg/s

Date : 27 July 2013

Location : Propulsion and Aerodynamics Research and Applications Laboratory (PARA LAB), Department of Mechanical Engineering, Chiang Mai University

Average heat source temperature : 72.6 ^{o}C

Average working fluid mass flow rate : 387.7 kg/h

Water circulation mass flow rate : 961.2 kg/h

Electric heater : 6.0 kW

Experiment 4-1 Heat Source Temperature 72.6^{o}C at m = 0.1077 kg/s

Test No.	m_{wf}	Heat source	$T_{source,6}$	$T_{sink,7}$	T_1	T_2	P_2	P_3	T_3	Pr	T_4	T_5	Q_{vg}	Q_{cond}	Speed	W	Torq	Power	η_R	η_C
	kg/s	kW	^{o}C	^{o}C	^{o}C	^{o}C	kPa	kPa	^{o}C	-	^{o}C	^{o}C	kW	kW	RPM	g	N.m	W	-	-
M-270713-1	0.1124	4.26	73.2	11.4	31.6	59.6	243	205	53.8	1.18	46.3	31.6	13.82	10.96	208	41	0.101	2.21	0.016	8.4
M-270713-2	0.1107	4.34	74.4	11.4	32.5	59.3	241	207	54.0	1.17	46.4	31.3	13.04	11.04	426	37	0.091	4.04	0.031	8.1
M-270713-3	0.1098	4.02	69.7	11.3	31.8	58.8	238	205	53.8	1.16	46.1	30.9	13.02	11.05	625	33	0.081	5.33	0.041	8.1
M-270713-4	0.1088	4.39	75.1	11.4	32.8	59.4	242	211	54.7	1.15	47.0	31.2	12.71	11.23	805	30	0.072	6.11	0.048	8.0
M-270713-5(opt)	**0.1085**	**4.11**	**71.0**	**11.4**	**32.1**	**59.3**	**241**	**211**	**54.7**	**1.14**	**45.7**	**31.4**	**12.96**	**11.10**	**965**	**26**	**0.063**	**6.38**	**0.049**	**8.2**
M-270713-6	0.1078	4.04	70.0	11.2	32.4	59.3	241	212	54.9	1.14	44.3	31.3	12.74	11.18	1107	22	0.055	6.33	0.050	8.1
M-270713-7	0.1081	4.31	73.9	11.4	32.3	59.6	243	213	55.1	1.14	46.3	31.3	12.97	11.30	1229	19	0.046	5.87	0.045	8.2
M-270713-8	0.1072	4.15	71.6	11.2	31.8	59.4	242	214	55.2	1.13	45.0	30.8	13.00	11.49	1331	15	0.037	5.17	0.040	8.3
M-270713-9	0.1063	4.04	70.0	11.3	32.4	58.9	238	213	55.0	1.12	45.6	31.3	12.37	11.06	1415	11	0.028	4.12	0.033	8.0
M-270713-10	0.1063	4.22	72.6	11.5	31.8	59.4	242	216	55.5	1.12	45.7	31.0	12.89	11.44	1489	8	0.020	3.07	0.024	8.3
M-270713-11	0.1057	4.41	75.4	11.4	32.5	59.3	241	216	55.6	1.11	45.8	31.6	12.44	11.14	1523	4	0.011	1.71	0.014	8.1
M-270713-12	0.1054	4.39	75.1	11.3	32.0	59.1	240	216	55.5	1.11	46.7	30.8	12.54	11.43	1549	1	0.003	0.43	0.003	8.2
Minimum	**0.1054**	**4.04**	**70.0**	**11.2**	**31.8**	**58.9**	**238**	**211**	**54.7**	**1.11**	**44.3**	**30.8**	**12.37**	**10.96**	**805**	**1**	**0.003**	**0.43**	**0.003**	**8.0**
Maximum	**0.1088**	**4.41**	**75.4**	**11.5**	**32.8**	**59.6**	**243**	**216**	**55.6**	**1.15**	**47.0**	**31.6**	**13.00**	**11.49**	**1549**	**41**	**0.072**	**6.38**	**0.050**	**8.3**
Average	**0.1077**	**4.22**	**72.6**	**11.3**	**32.2**	**59.3**	**241**	**212**	**54.9**	**1.14**	**45.9**	**31.2**	**12.79**	**11.20**	**1133**	**21**	**0.046**	**4.41**	**0.034**	**8.1**

T_1 = Vapor generator inlet temperature (^{o}C) (M)

T_2 = Turbine inlet temperature (^{o}C) (M)

T_3 = Turbine outlet temperature (^{o}C) (M)

T_4 = Water cool condenser inlet temperature (^{o}C) (M)

T_5 = Water cool condenser outlet temperature (^{o}C) (M)

T_6 = Temperature heat source (^{o}C) (M)

T_7 = Temperature heat sink (^{o}C) (M)

P_2 = Turbine inlet pressure (kPa)

P_3 = Turbine outlet pressure (kPa)

Pr = Pressure ratio (P_2/P_3)

Q_{vapor} = Heat input at vapor generator

Q_{cond} = Heat sink at water cooling condenser

Table A.15 experiment results of heat source temperature 80^oC and mass flow rate 0.1083 kg/s

Date : 03 August 2013

Location : Propulsion and Aerodynamics Research and Applications Laboratory (PARA LAB), Department of Mechanical Engineering, Chiang Mai University

Average heat source temperature : 83.4 ^oC

Average working fluid mass flow rate : 382.3 kg/h

Water circulation mass flow rate : 961.2 kg/h

Electric heater : 6.0 kW

Experiment 4-2 Heat Source Temperature 83.6^oC at m = 0.1083 kg/s																				
Test No.	m_{wf}	Heat source	$T_{source,6}$	$T_{sink,7}$	T_1	T_2	P_2	P_3	T_3	Pr	T_4	T_5	Q_{vapor}	Q_{cond}	Speed	W	Torq	Power	η_R	η_C
	kg/s	kW	^oC	^oC	^oC	^oC	kPa	kPa	^oC	-	^oC	^oC	kW	kW	RPM	g	N.m	W	-	-
N-030813-1	0.1129	4.95	83.5	11.2	30.0	66.7	297	250	60.5	1.19	43.3	31.4	18.20	14.43	278	58	0.143	4.16	0.023	10.8
N-030813-2	0.1113	4.96	83.6	11.3	31.1	66.7	297	253	61.0	1.17	45.2	31.6	17.40	14.37	514	52	0.128	6.87	0.039	10.5
N-030813-3	0.1102	4.93	83.2	11.1	30.1	65.5	288	247	60.2	1.16	41.4	30.8	17.14	14.24	729	47	0.115	8.79	0.051	10.5
N-030813-4	0.1079	4.98	83.9	11.3	30.3	66.1	292	257	61.5	1.14	44.7	31.2	16.97	14.36	923	41	0.100	9.67	0.057	10.6
N-030813-5(opt)	**0.1079**	**4.99**	**84.1**	**11.4**	**29.6**	**66.1**	**292**	**257**	**61.5**	**1.14**	**44.7**	**31.2**	**17.30**	**14.36**	**1095**	**36**	**0.089**	**10.18**	**0.059**	**10.8**
N-030813-6	0.1080	4.91	82.9	11.1	31.6	65.4	287	252	60.8	1.14	41.3	30.8	16.03	14.23	1246	32	0.078	10.13	0.063	10.0
N-030813-7	0.1075	4.95	83.4	11.2	30.1	64.6	280	247	60.2	1.13	41.7	31.3	16.29	13.64	1376	26	0.065	9.34	0.057	10.2
N-030813-8	0.1073	4.89	82.6	11.1	29.6	65.9	291	257	61.5	1.13	42.1	31.0	17.11	14.38	1484	22	0.054	8.31	0.049	10.7
N-030813-9	0.1070	5.01	84.3	11.3	28.8	66.2	293	260	61.9	1.13	44.5	31.3	17.57	14.38	1572	17	0.041	6.74	0.038	11.0
N-030813-10	0.1052	4.86	82.1	11.2	30.3	66.2	293	264	62.5	1.11	43.3	30.9	16.59	14.60	1638	12	0.029	5.02	0.030	10.6
N-030813-11	0.1058	4.97	83.8	11.3	30.3	66.5	296	265	62.6	1.11	43.3	31.3	16.81	14.54	1683	7	0.017	3.03	0.018	10.7
N-030813-12	0.1057	5.02	84.4	11.2	28.7	66.7	297	267	62.8	1.11	44.0	31.6	17.65	14.49	1707	2	0.006	1.10	0.006	11.2
Minimum	**0.1052**	**4.86**	**82.1**	**11.1**	**28.7**	**64.6**	**280**	**247**	**60.2**	**1.11**	**41.3**	**30.8**	**16.03**	**13.64**	**729**	**2**	**0.006**	**1.10**	**0.006**	**10.0**
Maximum	**0.1102**	**5.02**	**84.4**	**11.4**	**31.6**	**66.7**	**297**	**267**	**62.8**	**1.16**	**44.7**	**31.6**	**17.65**	**14.60**	**1707**	**58**	**0.115**	**10.18**	**0.063**	**11.2**
Average	**0.1062**	**4.95**	**83.4**	**11.2**	**29.5**	**66.3**	**294**	**263**	**62.3**	**1.12**	**43.4**	**31.2**	**17.15**	**14.33**	**1617**	**29**	**0.029**	**4.84**	**0.028**	**10.8**

T_1 = Vapor generator inlet temperature (^oC) (M)

T_2 = Turbine inlet temperature (^oC) (M)

T_3 = Turbine outlet temperature (^oC) (M)

T_4 = Water cool condenser inlet temperature (^oC) (M)

T_5 = Water cool condenser outlet temperature (^oC) (M)

T_6 = Temperature heat source (^oC) (M)

T_7 = Temperature heat sink (^oC) (M)

P_2 = Turbine inlet pressure (kPa)

P_3 = Turbine outlet pressure (kPa)

Pr = Pressure ratio (P_2/P_3)

Q_{vapor} = Heat input at vapor generator

Q_{cond} = Heat sink at water cooling condenser

Table A.16 Experimental results of heat source temperature 91.6^{o}C and mass flow rate 0.1033 kg/s

Date : 04 August 2013

Location : Propulsion and Aerodynamics Research and Applications Laboratory (PARA LAB), Department of Mechanical Engineering, Chiang Mai University

Average heat source temperature : 91.6 ^{o}C

Average working fluid mass flow rate : 389.4 kg/h

Water circulation mass flow rate : 961.2 kg/h

Electric heater : 6.0 kW

Experiment 4-3 Heat Source Temperature 91.6^{o}C at m = 0.1054 kg/s																				
Test No.	**m_{wf}**	**Heat source**	**$T_{source,6}$**	**$T_{sink,7}$**	**T_1**	**T_2**	**P_2**	**P_3**	**T_3**	**Pr**	**T_4**	**T_5**	**Q_{vapor}**	**Q_{cond}**	**Speed**	**W**	**Torq**	**Power**	**η_R**	**η_C**
	kg/s	**kW**	**^{o}C**	**^{o}C**	**^{o}C**	**^{o}C**	**kPa**	**kPa**	**^{o}C**	**-**	**^{o}C**	**^{o}C**	**kW**	**kW**	**RPM**	**g**	**N.m**	**W**	**-**	**-**
O-040813-1	0.1105	5.51	91.8	11.3	31.1	74.3	364	313	68.6	1.16	54.8	31.3	21.0	18.10	356	63	0.155	5.79	0.028	12.4
O-040813-2	0.1099	5.53	92.0	11.2	31.6	74.4	365	315	68.9	1.16	56.1	30.8	20.7	18.39	610	57	0.140	8.96	0.043	12.3
O-040813-3	0.1105	5.45	90.9	11.3	31.0	74.5	366	314	68.8	1.16	54.8	31.4	21.1	18.14	839	52	0.129	11.29	0.054	12.5
O-040813-4	0.1105	5.50	91.6	11.2	31.1	74.4	365	314	68.7	1.16	56.1	31.3	21.0	18.15	1045	47	0.115	12.54	0.060	12.5
O-040813-5(opt)	**0.1094**	**5.51**	**91.8**	**11.3**	**31.7**	**73.7**	**359**	**311**	**68.4**	**1.15**	**55.3**	**30.8**	**20.2**	**18.06**	**1229**	**41**	**0.101**	**13.00**	**0.064**	**12.1**
O-040813-6	0.1084	5.50	91.6	11.2	28.3	74.3	364	319	69.3	1.14	55.3	31.2	21.9	18.14	1390	35	0.086	12.57	0.057	13.2
O-040813-7	0.1084	5.47	91.2	11.3	31.1	74.3	364	319	69.3	1.14	55.2	31.3	20.6	18.09	1526	30	0.074	11.84	0.058	12.4
O-040813-8	0.1084	5.49	91.5	11.3	31.0	74.5	366	320	69.5	1.14	55.4	31.4	20.7	18.14	1640	25	0.062	10.60	0.051	12.5
O-040813-9	0.1073	5.49	91.4	11.2	31.6	74.4	365	323	69.8	1.13	55.9	30.8	20.2	18.37	1732	19	0.047	8.61	0.043	12.3
O-040813-10	0.1070	5.51	91.8	11.3	31.7	73.7	359	318	69.2	1.13	57.0	30.8	19.7	18.05	1799	14	0.035	6.63	0.034	12.1
O-040813-11	0.1072	5.53	92.0	11.3	31.0	74.2	364	322	69.7	1.13	54.5	31.6	20.3	17.93	1843	9	0.022	4.19	0.021	12.4
O-040813-12	0.1048	5.55	92.3	11.2	31.1	73.2	354	320	69.5	1.10	54.8	31.2	19.4	17.62	1865	4	0.009	1.81	0.009	12.2
Minimum	**0.1048**	**5.45**	**90.9**	**11.2**	**28.3**	**73.2**	**354**	**311**	**68.4**	**1.10**	**54.5**	**30.8**	**19.4**	**17.62**	**356**	**4**	**0.009**	**1.81**	**0.009**	**12.1**
Maximum	**0.1105**	**5.55**	**92.3**	**11.3**	**31.7**	**74.5**	**366**	**323**	**69.8**	**1.16**	**57.0**	**31.6**	**21.9**	**18.39**	**1865**	**63**	**0.155**	**13.00**	**0.064**	**13.2**
Average	**0.1082**	**5.50**	**91.6**	**11.3**	**31.0**	**74.1**	**363**	**318**	**69.2**	**1.14**	**55.4**	**31.2**	**20.5**	**18.10**	**1491**	**33**	**0.068**	**9.31**	**0.045**	**12.4**

T_1 = Vapor generator inlet temperature (^{o}C) (M)

T_2 = Turbine inlet temperature (^{o}C) (M)

T_3 = Turbine outlet temperature (^{o}C) (M)

T_4 = Water cool condenser inlet temperature (^{o}C) (M)

T_5 = Water cool condenser outlet temperature (^{o}C) (M)

T_6 = Temperature heat source (^{o}C) (M)

T_7 = Temperature heat sink (^{o}C) (M)

P_2 = Turbine inlet pressure (kPa)

P_3 = Turbine outlet pressure (kPa)

Pr = Pressure ratio (P_2/P_3)

Q_{vapor} = Heat input at vapor generator

Q_{cond} = Heat sink at water cooling condenser

Table A.17 Experiment results of heat source temperature 100^oC and mass flow rate 0.1085 kg/s

Date : 09 August 2013

Location : Propulsion and Aerodynamics Research and Applications Laboratory (PARA LAB), Department of Mechanical Engineering, Chiang Mai University

Average heat source temperature : 95.7 ^oC

Average working fluid mass flow rate : 378.1 kg/h

Water circulation mass flow rate : 961.2 kg/h

Electric heater : 6.0 kW

Experiment 1-3 Heat Source Temperature 90^oC at m = 0.1031 kg/s																			
Test No.	**m_{wf}**	**Heat source**	**$T_{source,6}$**	**$T_{sink,7}$**	**T_1**	**T_2**	**P_2**	**P_3**	**T_3**	**Pr**	**T_4**	**T_5**	**Q_{vapor}**	**Q_{cond}**	**Speed**	**W**	**Torq**	**Power**	**η_R**	**η_C**
	kg/s	**kW**	**^oC**	**^oC**	**^oC**	**^oC**	**kPa**	**kPa**	**^oC**	**-**	**^oC**	**^oC**	**kW**	**kW**	**RPM**	**g**	**N.m**	**W**	**-**	**-**
P-090813-1	0.1102	5.71	94.7	11.1	32.1	82.3	447	384	76.4	1.16	58.8	31.6	24.30	21.68	443	69	0.169	7.85	0.032	14.1
P-090813-2	0.1088	5.82	96.3	11.1	31.7	81.9	442	385	76.5	1.15	58.8	31.8	23.99	21.36	712	63	0.154	11.46	0.048	14.1
P-090813-3	0.1082	5.82	96.4	11.1	31.3	82.1	444	390	76.9	1.14	58.3	32.4	24.14	21.15	956	57	0.139	13.95	0.058	14.3
P-090813-4	0.1069	5.74	95.1	11.3	31.7	81.4	437	388	76.7	1.13	57.7	31.4	23.33	21.26	1175	50	0.123	15.14	0.065	14.0
P-090813-5(opt)	**0.1068**	**5.85**	**96.8**	**11.2**	**31.7**	**82.3**	**447**	**397**	**77.6**	**1.13**	**58.0**	**32.3**	**23.73**	**21.25**	**1369**	**45**	**0.110**	**15.73**	**0.066**	**14.2**
P-090813-6	0.1063	5.73	95.0	11.1	31.8	82.2	445	398	77.7	1.12	58.6	31.8	23.52	21.42	1537	39	0.095	15.23	0.065	14.2
P-090813-7	0.1060	5.74	95.1	11.1	32.1	82.1	444	398	77.7	1.12	57.9	32.3	23.28	21.13	1681	33	0.081	14.32	0.062	14.1
P-090813-8	0.1065	5.82	96.3	10.9	32.1	82.2	445	397	77.6	1.12	57.0	31.6	23.44	21.52	1799	27	0.067	12.65	0.054	14.1
P-090813-9	0.1060	5.86	96.9	11.2	30.7	82.2	445	399	77.8	1.12	57.8	30.9	23.97	21.83	1892	22	0.054	10.64	0.044	14.5
P-090813-10	0.1055	5.75	95.3	11.2	31.3	81.3	436	392	77.1	1.11	57.0	30.9	23.17	21.41	1960	17	0.040	8.31	0.036	14.1
P-090813-11	0.1036	5.80	96.1	10.9	32.2	82.2	445	408	78.7	1.09	58.9	32.9	22.75	20.84	2003	10	0.026	5.36	0.024	14.1
P-090813-12	0.1031	5.69	94.4	11.1	31.6	80.8	430	396	77.5	1.09	58.4	31.4	22.28	20.88	2022	5	0.013	2.69	0.012	13.9
Minimum	**0.1031**	**5.69**	**94.4**	**10.9**	**30.7**	**80.8**	**430**	**385**	**76.5**	**1.09**	**57.0**	**30.9**	**22.28**	**20.84**	**712**	**5**	**0.013**	**2.69**	**0.012**	**13.9**
Maximum	**0.1088**	**5.86**	**96.9**	**11.3**	**32.2**	**82.3**	**447**	**408**	**78.7**	**1.15**	**58.9**	**32.9**	**24.14**	**21.83**	**2022**	**69**	**0.154**	**15.73**	**0.066**	**14.5**
Average	**0.1050**	**5.77**	**95.7**	**11.1**	**31.5**	**81.6**	**439**	**398**	**77.7**	**1.11**	**58.0**	**31.7**	**23.10**	**21.31**	**1768**	**36**	**0.050**	**7.57**	**0.032**	**14.2**

T_1 = Vapor generator inlet temperature (^oC) (M)

T_2 = Turbine inlet temperature (^oC) (M)

T_3 = Turbine outlet temperature (^oC) (M)

T_4 = Water cool condenser inlet temperature (^oC) (M)

T_5 = Water cool condenser outlet temperature (^oC) (M)

T_6 = Temperature heat source (^oC) (M)

T_7 = Temperature heat sink (^oC) (M)

P_2 = Turbine inlet pressure (kPa)

P_3 = Turbine outlet pressure (kPa)

Pr = Pressure ratio (P_2/P_3)

Q_{vapor} = Heat input at vapor generator

Q_{cond} = Heat sink at water cooling condenser

Table A.18 Exergy analysis of the pump stage when T_0 = 298.15 K and P_0 = 101.325 kPa (h_0 = 236.01 kJ/kg, S_0 = 1.10065 kJ/kgK)

No. Exp	$T_{P,o}$	P	m	h_{in}	h_{out}	s_{in}	s_{out}	Ψ_{in}	Ψ_{out}	X_{in}	X_{out}	W_P	$W_{rev,in}$	I_p	η_{exer}
	K	kPa	kg/h	kJ/kg	kJ/kg	kJ/kgK	kJ/kgK	kJ/kg	kJ/kg	kW	kW	kW	kW	kW	%
A-150613	301.15	257.5	122.6	231.75	232.21	1.11058	1.11210	7.22	7.21	0.246	0.246	0.2888	0.00023	0.289	117.5
B-160613	304.35	284.7	124.2	235.43	235.90	1.12274	1.12426	7.17	7.15	0.247	0.247	0.2923	0.00058	0.293	118.2
C-220613	304.75	347.7	129.3	235.90	236.36	1.12426	1.12578	7.15	7.14	0.257	0.257	0.3034	0.00024	0.304	118.1
D-230613	305.35	478.1	128.9	236.59	237.05	1.12654	1.12805	7.14	7.13	0.256	0.255	0.3026	0.00035	0.303	118.3
E-300613	304.65	259.7	237.2	235.78	236.24	1.12388	1.12540	7.16	7.15	0.471	0.471	0.5208	0.00045	0.521	110.5
F-060713	303.95	333.7	241.7	234.97	235.43	1.12122	1.12274	7.17	7.17	0.482	0.481	0.5294	0.00046	0.530	109.9
G-070713	304.25	408.7	220.5	235.32	235.78	1.12236	1.12388	7.16	7.16	0.439	0.438	0.4893	0.00042	0.490	111.5
H-130713	304.65	483.9	239.1	235.78	236.24	1.12388	1.12540	7.16	7.15	0.475	0.475	0.5245	0.00045	0.525	110.3
I-140713	303.95	251.2	309.1	234.97	235.43	1.12122	1.12274	7.17	7.17	0.616	0.615	0.6516	0.00058	0.652	105.8
J-200713	305.75	343.8	287.9	237.05	237.51	1.12805	1.12955	7.13	7.12	0.570	0.569	0.6143	0.00102	0.615	107.8
K-210713	304.45	398.3	301.0	235.55	236.01	1.12312	1.12464	7.16	7.15	0.599	0.598	0.6374	0.00057	0.638	106.5
L-260713	304.55	408.9	315.3	235.67	236.13	1.12350	1.12502	7.15	7.15	0.626	0.626	0.6373	0.00060	0.638	101.7
M-270713	305.25	241.1	390.5	236.47	236.94	1.12616	1.12768	7.15	7.13	0.775	0.773	0.7881	0.00182	0.790	101.7
N-030813	302.75	292.4	388.5	233.59	234.05	1.11666	1.11818	7.19	7.19	0.776	0.776	0.7848	0.00074	0.786	101.1
O-040813	304.85	358.6	393.7	236.01	236.47	1.12464	1.12616	7.15	7.15	0.782	0.782	0.7933	0.00075	0.794	101.4
P-090813	304.85	446.5	384.4	236.01	236.47	1.12464	1.12616	7.15	7.15	0.764	0.763	0.7783	0.00073	0.779	101.9

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Table A.19 Exergy analysis of the vapor generator when T_0 = 298.15 K and P_0 = 101.325 kPa (h_0 = 236.01 kJ/kg, S_0 = 1.10065 kJ/kgK)

No. Exp	$T_{P,o}$	P	m	h_{in}	h_{out}	s_{in}	s_{out}	Ψ_{in}	Ψ_{out}	X_{in}	X_{out}	X_{heat}	I_{vg}
	K	kPa	kg/h	kJ/kg	kJ/kg	kJ/kgK	kJ/kgK	kJ/kg	kJ/kg	kW	kW	kW	kW
A-150613	345.25	257.5	122.6	232.21	479.57	1.11210	1.85705	-7.21	18.04	-0.246	0.614	-0.684	1.544
B-160613	355.25	284.7	124.2	235.90	484.77	1.12426	1.85826	-7.15	22.88	-0.247	0.789	-0.928	1.964
C-220613	364.45	347.7	129.3	236.36	488.89	1.12578	1.85830	-7.14	26.99	-0.257	0.969	-1.260	2.486
D-230613	370.05	478.1	128.9	237.05	495.20	1.12805	1.86198	-7.13	32.20	-0.255	1.153	-1.617	3.025
E-300613	345.25	259.7	237.2	236.24	479.83	1.12540	1.85709	-7.15	18.29	-0.471	1.205	-1.200	2.876
F-060713	356.35	333.7	241.7	235.43	485.24	1.12274	1.85840	-7.17	23.31	-0.481	1.565	-1.888	3.934
G-070713	364.05	408.7	220.5	235.78	491.07	1.12388	1.86030	-7.16	28.57	-0.438	1.750	-2.323	4.511
H-130713	369.95	483.9	239.1	236.24	495.52	1.12540	1.86210	-7.15	32.48	-0.475	2.158	-3.063	5.696
I-140713	345.45	251.2	309.1	235.43	479.03	1.12274	1.85697	-7.17	17.52	-0.615	1.505	-1.544	3.664
J-200713	357.45	343.8	287.9	237.51	486.64	1.12955	1.85882	-7.12	24.58	-0.569	1.966	-2.301	4.836
K-210713	364.25	398.3	301.0	236.01	490.41	1.12464	1.86006	-7.15	27.98	-0.598	2.339	-3.098	6.036
L-260713	368.75	408.9	315.3	236.13	491.07	1.12502	1.86030	-7.15	28.57	-0.626	2.502	-3.491	6.619
M-270713	344.15	241.1	390.5	236.94	478.09	1.12768	1.85680	-7.13	16.63	-0.773	1.804	-1.732	4.310
N-030813	357.25	292.4	388.5	234.05	482.65	1.11818	1.85772	-7.19	20.92	-0.776	2.257	-2.862	5.895
O-040813	364.95	358.6	393.7	236.47	487.70	1.12616	1.85914	-7.15	25.55	-0.782	2.794	-3.693	7.268
P-090813	369.95	446.5	384.4	236.47	493.37	1.12616	1.86119	-7.15	30.60	-0.763	3.268	-4.606	8.638

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Table A.20 Exergy analysis of the turbine state when T_0 = 298.15 K and P_0 = 101.325 kPa (h_0 = 236.01 kJ/kg, S_0 = 1.10065 kJ/kgK)

No. Exp	$T_{P,o}$	P	m	h_{in}	h_{out}	s_{in}	s_{out}	Ψ_{in}	Ψ_{out}	X_{in}	X_{out}	W_T	$W_{rev,out}$	I_T	η_{II}	X_{dest}	η_{exer}
	K	kPa	kg/h	kJ/kg	kJ/kg	kJ/kgK	kJ/kgK	kJ/kg	kJ/kg	kW	kW	kW	kW	kW	%	kW	%
A-150613	334.7	257.5	122.6	479.57	477.41	1.85705	1.85665	18.04	16.00	0.614	0.545	0.00081	0.069	0.069	1.17	0.069	0.1326
B-160613	342.5	284.7	124.2	484.77	483.44	1.85826	1.85790	22.88	21.66	0.789	0.747	0.00103	0.042	0.041	2.45	0.041	0.1309
C-220613	348.7	347.7	129.3	488.89	485.97	1.85830	1.85862	26.99	23.97	0.969	0.861	0.00132	0.108	0.107	1.22	0.107	0.1362
D-230613	358.3	478.1	128.9	495.20	491.40	1.86198	1.86043	32.20	28.86	1.153	1.034	0.00160	0.120	0.118	1.34	0.118	0.1388
E-300613	335.1	259.7	237.2	479.83	476.21	1.85709	1.85653	18.29	14.83	1.205	0.977	0.00232	0.227	0.225	1.02	0.225	0.1926
F-060713	343.2	333.7	241.7	485.24	481.64	1.85840	1.85749	23.31	19.98	1.565	1.341	0.00294	0.223	0.221	1.32	0.221	0.1881
G-070713	352.0	408.7	220.5	491.07	488.89	1.86030	1.85830	28.57	26.99	1.750	1.653	0.00331	0.097	0.094	3.41	0.094	0.1890
H-130713	358.8	483.9	239.1	495.52	491.86	1.86210	1.86060	32.48	29.27	2.158	1.944	0.00435	0.213	0.209	2.04	0.209	0.2015
I-140713	333.9	251.2	309.1	479.03	476.07	1.85697	1.85652	17.52	14.70	1.505	1.262	0.00680	0.243	0.236	2.80	0.236	0.4523
J-200713	345.3	343.8	287.9	486.64	483.44	1.85882	1.85790	24.58	21.66	1.966	1.732	0.00844	0.234	0.226	3.61	0.226	0.4293
K-210713	351.0	398.3	301.0	490.41	487.30	1.86006	1.85902	27.98	25.18	2.339	2.105	0.01031	0.234	0.224	4.40	0.224	0.4407
L-260713	352.0	408.9	315.3	491.07	487.17	1.86030	1.85898	28.57	25.06	2.502	2.195	0.01290	0.307	0.294	4.20	0.294	0.5155
M-270713	332.5	241.1	390.5	478.09	474.99	1.85680	1.85637	16.63	13.66	1.804	1.482	0.00638	0.322	0.316	1.98	0.316	0.3535
N-030813	339.3	292.4	388.5	482.65	479.57	1.85772	1.85705	20.92	18.04	2.257	1.947	0.01018	0.311	0.301	3.28	0.301	0.4510
O-040813	346.9	358.6	393.7	487.70	484.18	1.85914	1.85808	25.55	22.34	2.794	2.444	0.01300	0.350	0.337	3.71	0.337	0.4651
P-090813	355.5	446.5	384.4	493.37	490.28	1.86119	1.86002	30.60	27.86	3.268	2.976	0.01573	0.293	0.277	5.37	0.277	0.4814

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Table A.21 Exergy analysis of the condenser when T_0 = 298.15 K and P_0 = 101.325 kPa (h_0 = 236.01 kJ/kg, S_0 = 1.10065 kJ/kgK)

No. Exp	$T_{P,o}$	P	m	h_{in}	h_{out}	s_{in}	s_{out}	Ψ_{in}	Ψ_{out}	X_{in}	X_{out}	X_{heat}	I_{cond}
	K	kPa	kg/h	kJ/kg	kJ/kg	kJ/kgK	kJ/kgK	kJ/kg	kJ/kg	kW	kW	kW	kW
A-150613	284.05	257.5	122.6	477.41	236.13	1.85665	1.12502	16.00	-7.15	0.545	-0.243	0.249	1.037
B-160613	284.05	284.7	124.2	483.44	235.67	1.85790	1.67100	21.66	-170.39	0.747	-5.878	0.287	6.911
C-220613	284.15	347.7	129.3	485.97	233.36	1.85862	1.29840	23.97	-61.61	0.861	-2.213	0.341	3.415
D-230613	283.05	478.1	128.9	491.40	237.17	1.86043	1.12843	28.86	-7.12	1.034	-0.255	0.444	1.732
E-300613	284.65	259.7	237.2	476.21	236.01	1.85653	1.12464	14.83	-7.15	0.977	-0.471	0.417	1.866
F-060713	284.85	333.7	241.7	481.64	235.67	1.85749	1.67100	19.98	-170.39	1.341	-11.440	0.540	13.322
G-070713	283.95	408.7	220.5	488.89	235.44	1.85830	1.63374	26.99	-159.51	1.653	-9.770	0.642	12.065
H-130713	284.15	483.9	239.1	491.86	237.17	1.86060	1.12843	29.27	-7.12	1.944	-0.473	0.778	3.195
I-140713	283.25	251.2	309.1	476.07	235.67	1.85652	1.67100	14.70	-170.39	1.262	-14.629	0.593	16.485
J-200713	284.25	343.8	287.9	483.44	235.90	1.85790	1.12426	21.66	-7.15	1.732	-0.572	0.678	2.982
K-210713	285.65	398.3	301.0	487.30	236.01	1.85902	1.12464	25.18	-7.15	2.105	-0.598	0.747	3.450
L-260713	285.25	408.9	315.3	487.17	236.13	1.85898	1.12502	25.06	-7.15	2.195	-0.626	0.825	3.645
M-270713	284.55	241.1	390.5	474.99	236.13	1.85637	1.12502	13.66	-7.15	1.482	-0.775	0.619	2.877
N-030813	284.55	292.4	388.5	479.57	235.90	1.85705	1.12426	18.04	-7.15	1.947	-0.771	0.827	3.545
O-040813	284.45	358.6	393.7	484.18	235.44	1.85808	1.63374	22.34	-159.51	2.444	-3.446	0.972	6.861
P-090813	284.35	446.5	384.4	490.28	237.17	1.86002	1.12843	27.86	-7.12	2.976	-0.761	1.152	4.888

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Table 22 Total exergy analysis of the system when T_0 = 298.15 K, P_0 = 101.325 kPa, h_0 = 236.01 kJ/kg and S_0 = 1.10065 kJ/kg.K

No. exp	**T_{so} (^oC)**	**I_p (kW)**	**I_{vg} (kW)**	**I_T (kW)**	**I_C (kW)**	**I_{Total} (kW)**
A-150613	72.1	0.289	1.544	0.069	1.037	2.938
B-160613	82.1	0.293	1.964	0.041	6.911	9.209
C-220613	91.3	0.304	2.486	0.107	3.415	6.311
D-230613	96.9	0.303	3.025	0.118	1.732	5.178
E-300613	72.1	0.521	2.876	0.225	1.866	5.488
F-060713	83.2	0.530	3.934	0.221	13.322	18.006
G-070713	90.9	0.490	4.511	0.094	12.065	17.160
H-130713	96.8	0.525	5.696	0.209	3.195	9.625
I-140713	72.3	0.652	3.664	0.236	16.485	21.036
J-200713	84.3	0.615	4.836	0.226	2.982	8.659
K-210713	91.1	0.638	6.036	0.224	3.450	10.348
L-260713	95.6	0.638	6.619	0.294	3.645	11.196
M-270713	71.0	0.790	4.310	0.316	2.877	8.292
N-030813	84.1	0.786	5.895	0.301	3.545	10.526
O-040813	91.8	0.794	7.268	0.337	6.861	15.261
P-090813	96.8	0.779	8.638	0.277	4.888	14.582

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Appendix B

Numerical Simulation and Experimental Calculation

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In Figure B.1 descript the flow diagram of the ORC. The working fluid operates in the closed loop cycle. The heat source approaches the system through the vapor generator where the working fluid was heated to saturation or to its superheated point. After isobaric heat addition which occurs between stage 2 and stage 3, high pressure vapor expands in the turbine at stage 3-4. The stream of the expanded fluid is passed directly through condenser where it condenses to temperature and pressure at the point 1. After leaving condenser the working fluid enters the pump via an expansion tank. In the pump the pressure is raised to point 2 and the fluid is returned to the vapor generator.

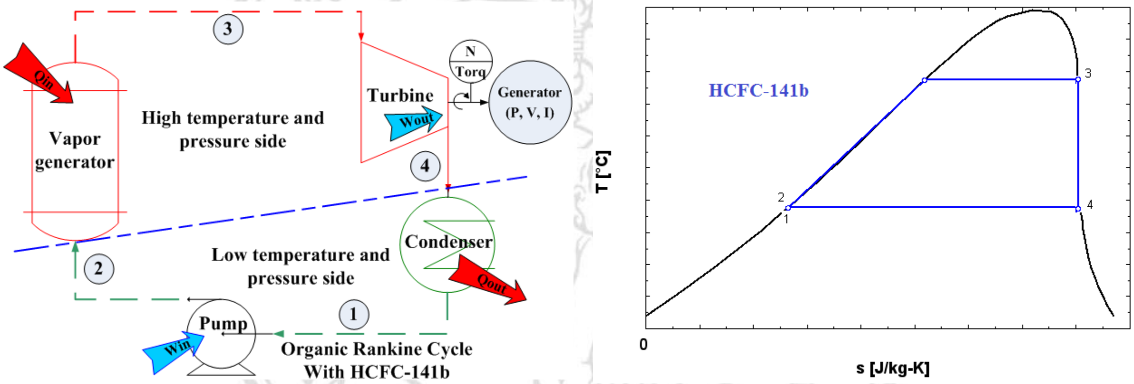

Figure B.1: Flow diagram of ORC with HCFC-141b (1,1-Dichloro-1-fluoroethane)

Assumptions of the numerical simulation

- High temperature side = 90°C and high pressure side = 537.67 kPa
- Low temperature side = 30°C and low pressure side = 94.17 kPa
- Pressure ratio at turbine (ΔP = 5) = 107.53 kPa

Thermodynamic states and ORC system performance is carried out based on the assumptions.

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Thermodynamic state and numerical results

- **State 1 - 2:** Pump: $s_2 = s_1$ = 1.1197 kJ/kg-K, (Sub-cooling)

  P_2 = 537.67 kPa $w_p = v_f (P_2 – P_1) = 0.00082\,(537.67–94.17)$ = 0.364 kJ/kg

  $h_2 = h_2 + w_p = 234.51 + 0.364$ = 234.87 kJ/kg T_2 = 30.31 °C

  ρ_2 = 1,218.59 kg/ m³ v_2 = 0.21835 m³/kg

- **State 2 - 3:** Vapor generator : $P_3 = P_2$ = 537.67 kPa, (Saturated vapor)

  T_3 = 90 °C v_3 = 0.04231 m³/kg

  h_3 = 498.38 kJ/kg s_3 = 1.8634 kJ/kg-K

- **State 3 - 4:** Turbine: $s_4 = s_3$ = 1.8634 kJ/kg-K, (Saturated vapor)

  $x_4 = (s_3 – s_f)/(s_g-s_f) = (1.8634 – 1.1197)/(1.8576 – 1.1197) = 1.009$

  $h_4 = h_f + x_4 h_{fg} = 234.51 + 1.008\,(458.22 – 234.51)$ = 460.23 kJ/kg

  T_4 = 32.95 °C P_4 = 104.55 kPa v_4 = 0.20023 m³/kg

- **State 4 – 1:** Condenser : $P_1 = P_4$ = 94.17 kPa, (Sub-cooling)

  T_1 = 30 °C h_1 = 234.51 kJ/kg s_1 = 1.1197 kJ/kg-K

  ρ_1 = 1,219.2 kg/ m³ v_1 = 0.22055 m³/kg

Results of the ORC numerical simulation

$q_i = q_{vg} = h_3 – h_2 = 498.38 – 234.87$ = 263.51 kJ/kg

$q_o = q_{co} = h_4 – h_1 = 460.23 – 234.51$ = 225.72 kJ/kg

$Q_i = Q_{vg} = \dot{m}\, q_i$ = 0.031 kg/s x 263.51 kJ/kg = 8.12 kW

$Q_o = Q_{co} = \dot{m}\, q_o$ = 0.031 kg/s x 225.72 kJ/kg = 7.00 kW

$w_P = h_2 – h_1 = 234.87 – 234.51$ = 0.364 kJ/kg

$w_T = h_3 – h_4 = 498.38 – 460.23$ = 37.720 kJ/kg

$w_{net} = w_T - w_P = 37.720 – 0.364$ = 37.356 kJ/kg

$W_{net} = \dot{m}\, w_{net}$ = 0.031 kg/s x 37.356 kJ/kg = 1.158 kW

$\eta_{th,R} = w_{net} / q_i = 37.356 / 263.51$ = 0.1415

$\eta_{th,C} = 1 – (T_L / T_H) = 1 – (30 + 273.15)/(90 + 273.15)$ = 0.1652

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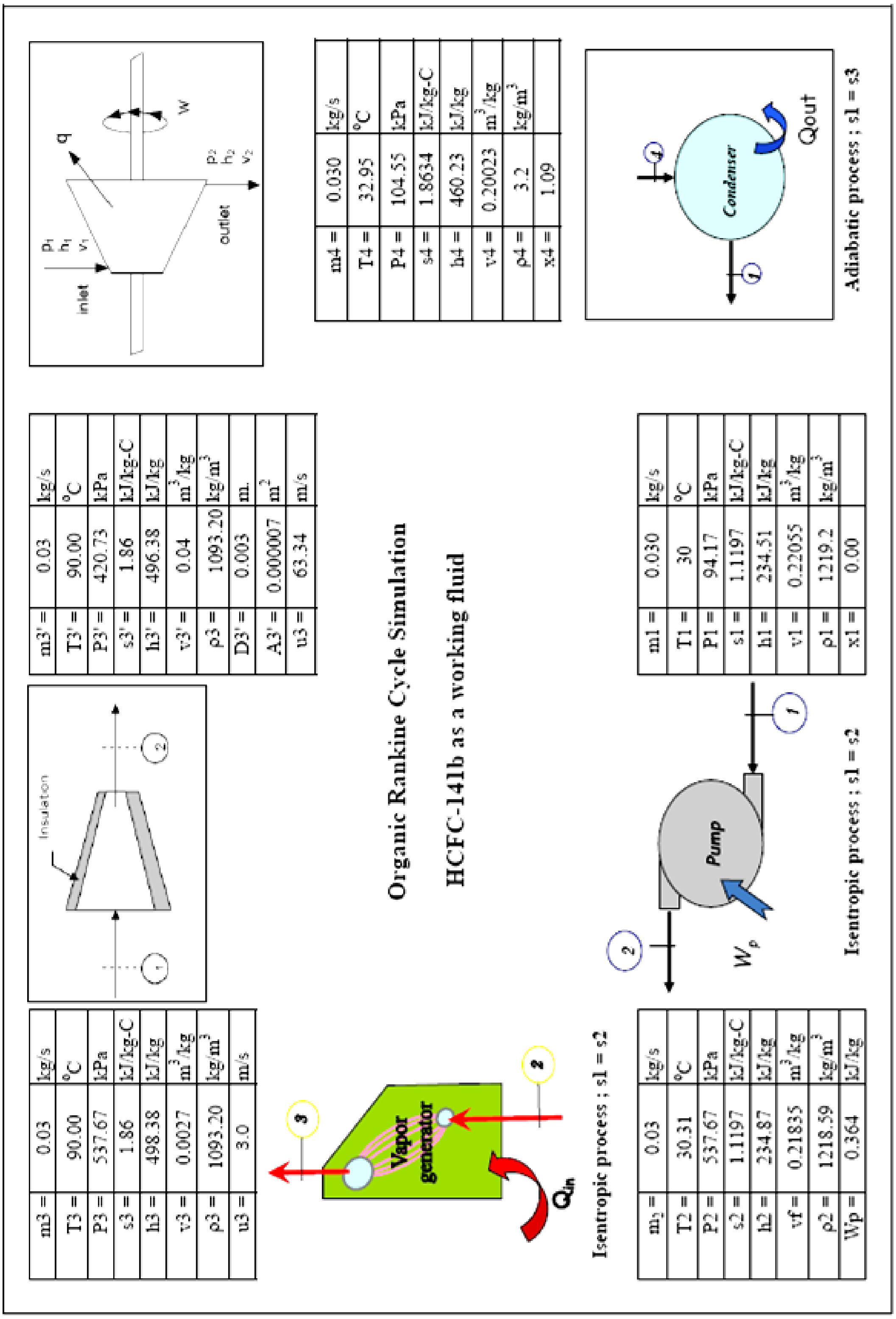

Figure B.2: Flow diagram of HCFC-141b as a working fluid on ORC cycle

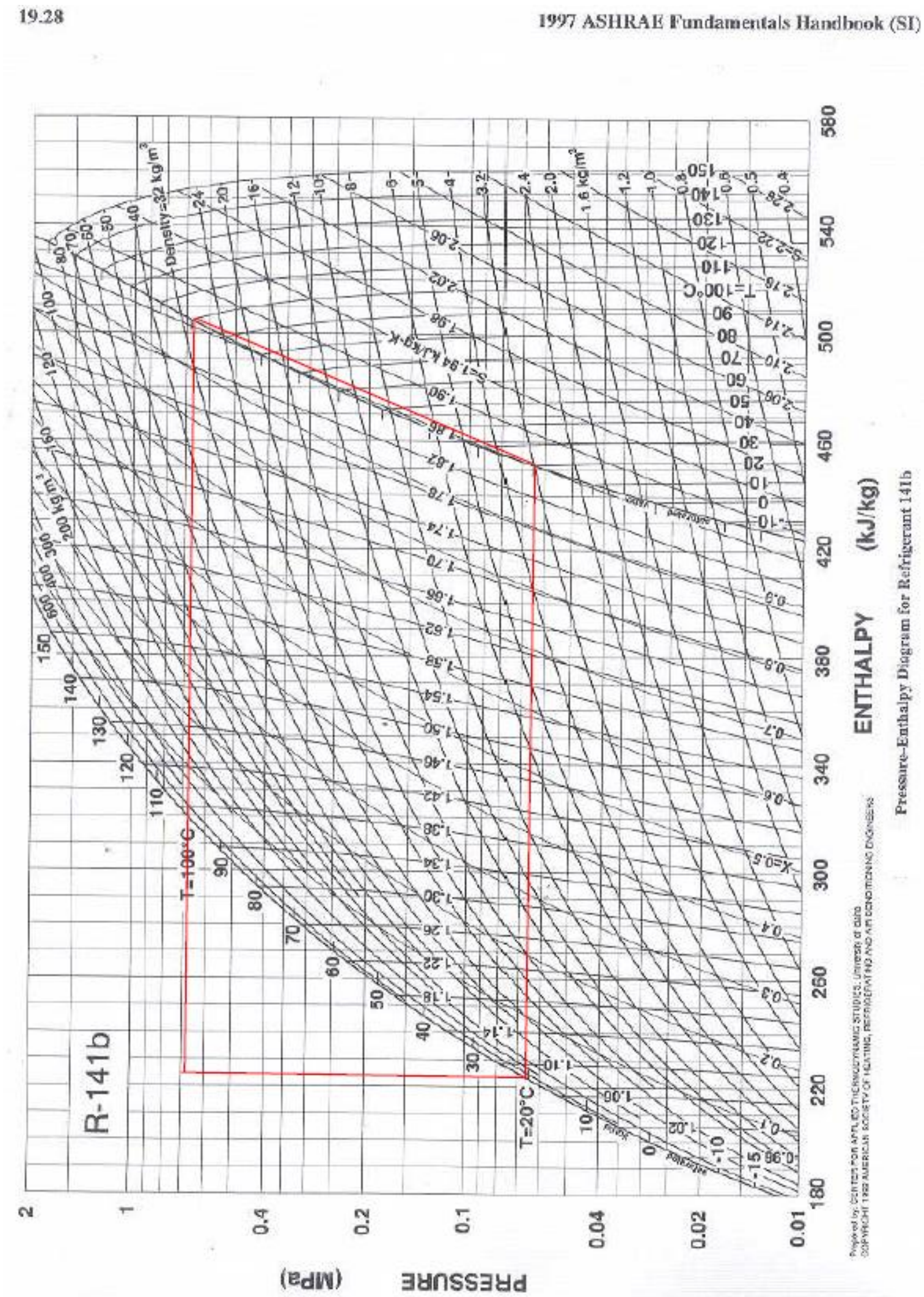

Figure B.3: P-h diagram of HCFC-141b on the ORC cycle (ASHRAE, 1996)

Table B.1: Simulation Results of ORC model

T_{so} °C	$T_{wf,i}$ °C	$T_{wf,o}$ °C	q_i kJ/kg	q_o kJ/kg	w_P kJ/kg	w_T kJ/kg	w_{net} kJ/kg	$\eta_{th,R}$ %	$\eta_{th,C}$ %
70.0	30.0	60.0	243.93	223.50	0.125	20.554	20.429	8.38	9.00
80.0	30.0	70.0	250.54	223.95	0.189	26.782	26.593	10.61	11.66
90.0	30.0	80.0	257.08	224.62	0.268	32.731	32.463	12.63	14.16
100.0	30.0	90.0	263.51	225.72	0.364	37.720	37.356	14.15	16.52

Table B.2: The working fluid mass flow rate on numerical calculation

T_{so}	$T_{wf,i}$	$T_{wf,o}$	Q_i	Q_o	W_P	W_T	W_{net}	$\eta_{th,R}$	$\eta_{th,C}$
°C	°C	°C	kW	kW	kW	kW	kW	%	%
Working fluid mass flow rate 112.0 kg/h									
70.0	30.0	60.0	7.59	6.95	0.004	0.637	0.633	8.38	9.00
80.0	30.0	70.0	7.79	6.94	0.006	0.831	0.825	10.61	11.66
90.0	30.0	80.0	8.00	6.96	0.008	1.015	1.007	12.63	14.16
100.0	30.0	90.0	8.12	7.00	0.011	1.170	1.158	14.15	16.52
Working fluid mass flow rate 223.0 kg/h									
70.0	30.0	60.0	15.12	13.86	0.008	1.275	1.267	8.38	9.00
80.0	30.0	70.0	15.53	13.88	0.012	1.661	1.649	10.61	11.66
90.0	30.0	80.0	15.94	13.93	0.017	2.030	2.014	12.63	14.16
100.0	30.0	90.0	16.34	13.99	0.022	2.340	2.318	14.15	16.52
Working fluid mass flow rate 298.0 kg/h									
70.0	30.0	60.0	20.17	18.48	0.010	1.700	1.689	8.38	9.00
80.0	30.0	70.0	20.72	18.52	0.016	2.215	2.199	10.61	11.66
90.0	30.0	80.0	21.26	18.58	0.022	2.707	2.685	12.63	14.16
100.0	30.0	90.0	21.79	18.67	0.030	3.120	3.090	14.15	16.52
Working fluid mass flow rate 372.0 kg/h									
70.0	30.0	60.0	25.21	23.09	0.013	2.125	2.112	8.38	9.00
80.0	30.0	70.0	25.89	23.14	0.020	2.769	2.749	10.61	11.66
90.0	30.0	80.0	26.56	23.21	0.028	3.384	3.356	12.63	14.16
100.0	30.0	90.0	27.23	23.32	0.037	3.900	3.863	14.15	16.52

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Thermodynamic model

Design condition:

- Vapor generator temperature and pressure are 90°C, 537.67 kPa, and Q_i = 70.36 kW respectively.
- Condenser temperature and pressure are 30°C, 94.17 kPa, and Q_o = 60.27 kW respectively.
- Isentropic Turbine and Pump efficiency are 85%.
- Vapor generator unit sizing; A_{inner} = 1.517 m^2, $T_{wf,i}$ = 30°C, $T_{wf,o}$ = 90°C, V_{inner} = 0.004058 m^3
- Condensing unit sizing; A_{inner} = 0.773 m^2, $T_{wf,i}$ = 90°C, $T_{wf,o}$ = 20°C, V_{inner} = 0.001852 m^3
- Hot side pinch and cold side pinch are 10°C and 20°C respectively.
- Working fluid mass flow rate between 112.0 – 397.0 kg/h.
- Nozzle diameter inlet and outlet = 20 mm and 10 mm respectively, and nozzle quantity = 6 holes
- Turbine blade angle = 25°, and nozzle angle = 30°

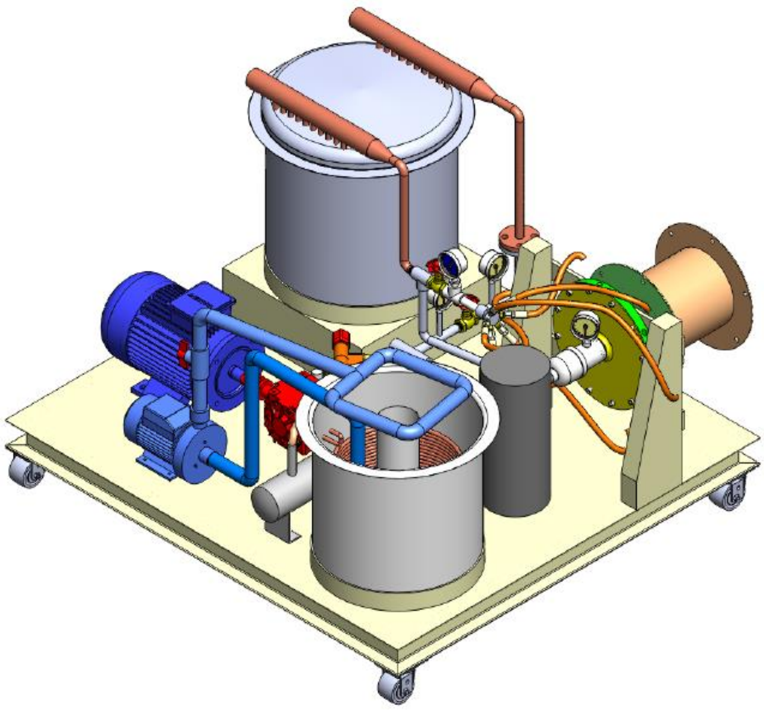

Figure B.4: Drawing configuration of ORC prototype

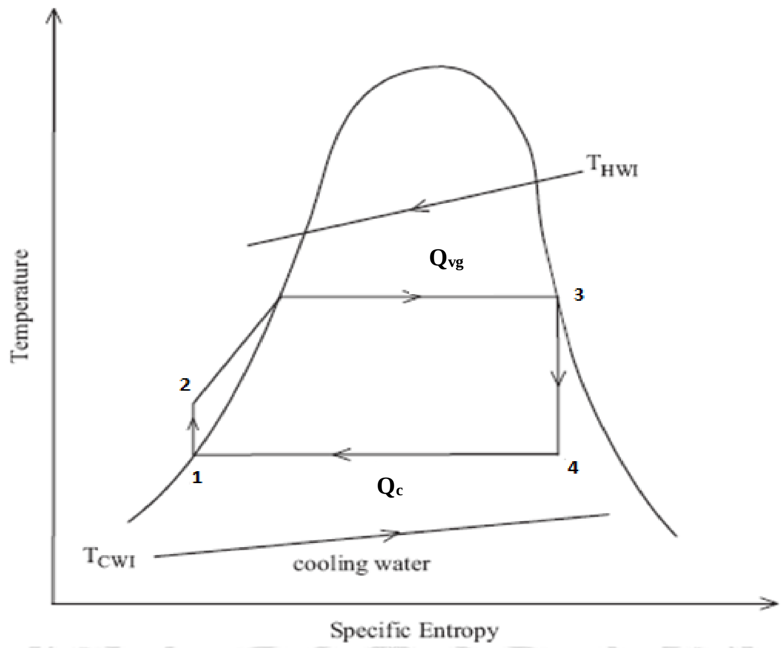

Figure B.5: T-s diagram of HCFC-141b as a working fluid on ORC cycle

Performance of ORC by calculation from experimental result

A steady flow process with a single-stream flow through the system is described by

1. Pump Phase (Stage 1-2):

The working fluid pump is the driving mechanism of the test rig system. The working fluid which leaves the condenser at reduced pressure P_1 is pumped to the vapor generator and regains pressure P_2. The pump work W_P is calculated:

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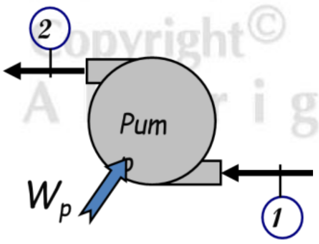

$$\dot{W}_p = \frac{\dot{W}_{p,ideal}}{\eta_p} = \frac{\dot{m}(h_1 - h_{2s})}{\eta_p}$$

Figure B.6: Flow process of working fluid pump

The specific enthalpy of the working fluid at the pump outlet is given by h_2:

$$h_2 = h_1 + \frac{W_p}{\dot{m}}$$

where

h_1 is the specific enthalpy of the working fluid at the pump inlet, kJ/kg

h_2 is the specific enthalpy of the working fluid at the pump outlet, kJ/kg

$\dot{W}_p$ is the work input of the working fluid at the pump, kW

$\dot{m}$ is the working fluid mass flow rate, kg/h

The selection of working fluid pump

In the experiment, based on its pump performance curve (Figure B.8), the reciprocating piston pump (KANTO KT-TF-22-AUTO) was able to provide the appropriate amount of head at the desired flow rates. Further, the pump housing is piston coupled which requires no seals around the shaft and reduces the possibility of leaks.

Table B.3: Specification of reciprocating piston pump (KANTO KT-TF-22-AUTO)

KANTO รุ่น KT-TF-22-AUTO		
Pressure	10 - 40	kg/cm^2
Operation	800 - 1,200	RPM
Capacity	13 - 22	L/min
Require Power	1.5 - 2.0	kW

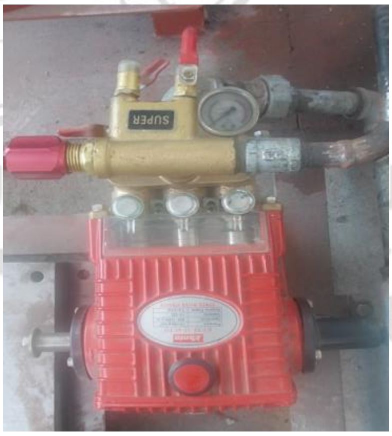

Figure B.7: Reciprocation piston pump configulation and specification

Table B.4: The optimum working fluid mass flow rate of HCFC-141b at pump

Optimum condition of experiments												
Heat source temperature setting	**70°C**			**80°C**			**90°C**			**100°C**		
Working fluid mass flow rate setting	**speed**	**flow**	**power**	**speed**	**flow**	**power**	**speed**	**flow**	**power**	**speed**	**flow**	**power**
	rpm	**kg/h**	**W**	**rpm**	**kg/h**	**W**	**rpm**	**kg/h**	**W**	**rpm**	**kg/h**	**W**
m = 112 kg/h	130	122.6	289	131	124.2	292.3	136	129.3	303.4	136	128.9	302.6
m = 223 kg/h	240	237.2	521	244	241.7	529.4	224	220.5	489.3	242	239.1	524.5
m = 298 kg/h	305	309.1	652	286	287.9	614.3	297	301.0	637.4	297	301.0	637.3
m = 372 kg/h	324	390.5	788	328	388.5	784.8	317	393.7	793.3	336	384.4	778.3

Working fluid leaving the reservoir in the sub-cooled liquid phase

T_1 = 30°C, P_1 = 94.17 kPa, h_1 = 234.51 kJ/kg,

s_1 = 1.1197 kJ/kg-K, ρ_1 = 1,219.2 kg/ m^3, v_1 = 0.22055 m^3/kg

Therefore

$s_2 = s_1$ =1.1197 kJ/kg-K, P_2 = 537.67 kPa,

$w_p = v_f (P_2 - P_1)$ = 0.00082 (537.67 – 94.17) = 0.364 kJ/kg

$h_2 = h_2 + w_p$ = 234.51 + 0.364 = 234.87 kJ/kg

ρ_2 = 1,218.59 kg/ m^3 v_2 = 0.21835 m^3/kg

2. Vaporization Phase (Stage 2-3):

The vapor generator heats the high pressure working fluid exist the pump. As the heat loss in the vapor generator is neglected, the amount of heat added to working fluid is equal to the amount of heat extracted from the heat source as is given by:

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$$\dot{Q}_{vg} = \dot{m}(h_3 - h_2)$$

Where Q_{vg} is the heat input at the vapor generator, kW

h_2 is specific enthalpy at the vapor generator inlet, kJ/kg

h_3 is specific enthalpy at the vapor generator outlet, kJ/kg

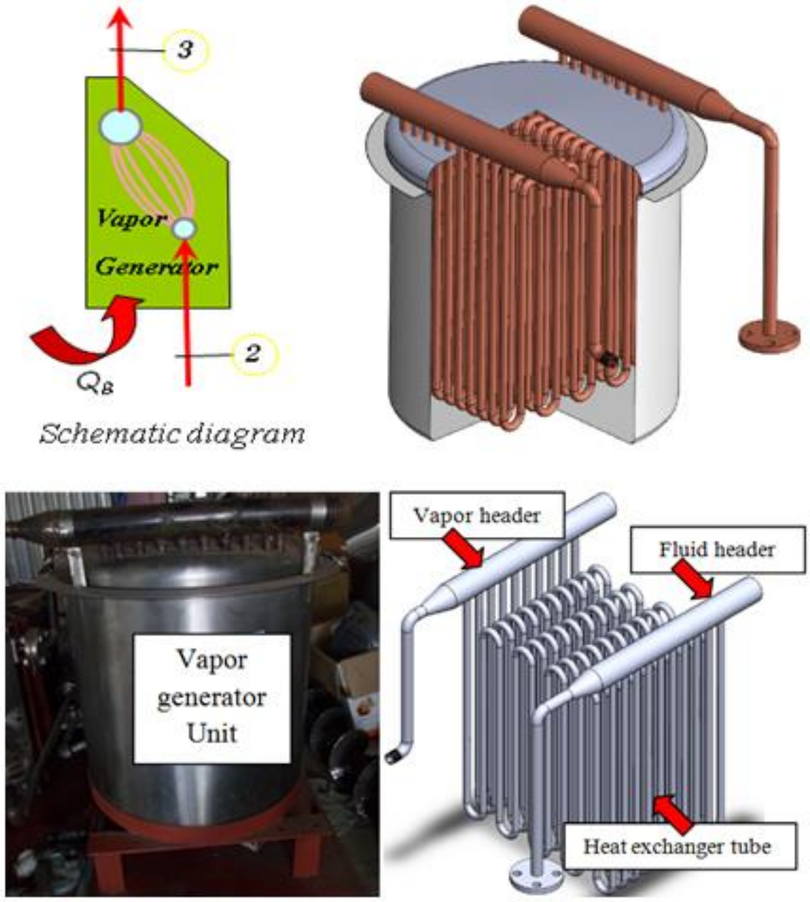

Figure B.9: Vapor generator configuration

Numerical calculation and testing of the vapor generator

The vapor generator located between of the working fluid pump and turbine is used to vapor produce transfer to the turbine. From the design calculation, can be expressed as below. Assume that the initial water 58 kg is at 10^{o}C to be supplied heat until reached 100^{o}C whereas the specific heat of water Cp 4.18 kJ/kg^{o}C with following designs condition:

- The heat storage tank diameter, high, and total volume containing are 0.45 m, 0.44 m, and 0.07 m^3 respectively.
- The water volume containing in the vapor generator is 0.0057 m^3
- Hot water tank volume = V_{ves} - V_{vg} = 0.070 - 0.0057 = 0.0643 m^3
- The tank can be hot water containing is 64.30 liter, but however containing only 90% of water, i.e. 57.9 ≈ 58 liter

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From the water 58 kg 10°C into the hot water 100°C

$$Q_w = m\ Cp\ (\Delta T) = 58\ \text{kg} \times 4.184\ \text{kJ/kg}^{o}\text{C} \times (100 - 10)^{o}\text{C} = 21{,}840\ \text{kJ}$$

The hot water within 1 h of Electric heater power consumptions required as

$$P_e = Q_w / t = 21{,}840\ \text{kJ} / (1\ \text{h} \times 3{,}600\ \text{s/h}) = 6.01\ \text{kW}$$

Heat loss calculation from hot water tank

In the hot water tank is totally thermal insulated, the heat loss will be calculated in 2 stepping as follow:

Step 1: Consider from the outside of wall insulator to the inside wall surface of the tank.

Step 2: Consider from the outside to inside surface of the tank wall.

$$Q = (T_{in} - T_{out})/(L_1/k_1A_1 + L_2/k_2A_2)$$

Design condition

Temperature:	$T_{in} = 100^{o}C$	$T_{out} = 25^{o}C$
Thickness (L):	$L_1 = 0.60$ mm	$L_2 = 25.4$ mm
Thermal conductivity:	$k_1 = 50$ W/m-K	$k_2 = 0.046$ W/m-K
Heat transfer area:	$A_{tot} = 0.622\ m^2$	$A_{up+low} = 0.318\ m^2$

Therefore

$$Q_{Loss} = (100 - 25)/(0.0006/50 \times 0.94 + 0.0254/0.046 \times 0.94)$$
$$= 144.49\ \text{W}$$

Table B.5: Heat loss calculation from heat source tank

Heat source temperature (^{o}C)	70	80	90	100
Heat loss (W)	105.96	144.49	183.03	240.82

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Design condition

- The maximum temperature in vapor generator 100°C
- Inlet and outlet temperature of working fluid 30°C and 90°C
- Mass flow rate of working fluid 112.0 kg/h
- Heat rate of heat source, Q_{in} 269.78 kJ/kg
- Thickness of copper pipe 0.001 m
- Thermal conductivity of copper pipe 401 W/m-K
- Heat exchanger was used LMTD in the outlet temperature calculation
- Constant surface temperature and non-radiation in the system

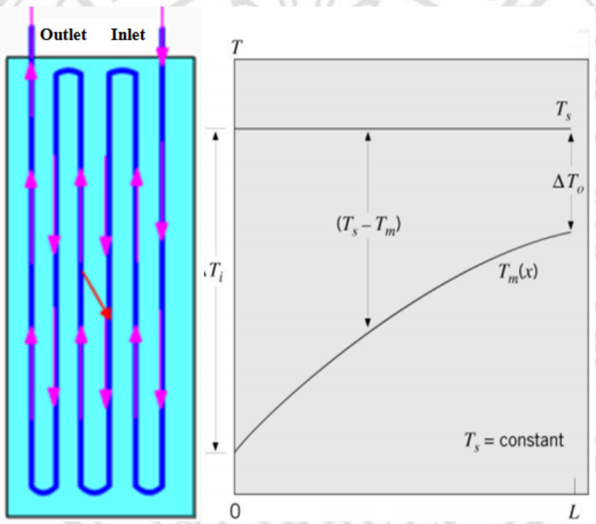

Figure B.10: Temperature profile of the vapor generator (Incropera, 2005)

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Design conditions

The working fluid temperature at inlet and outlet vapor generator $T_{wf,i}$ = 30°C and $T_{wf,o}$= 90°C respectively. The tube surface temperature (T_w) is 100°C, Therefore, average working fluid temperature is $T_{wf,avg}$ = 60°C, μ = 296.3 x 10^{-6} Pa.s, $C_{p,f}$ = 4,392 J/kg-K, and k_f = 78.7 x 10^{-3} W/m-K.

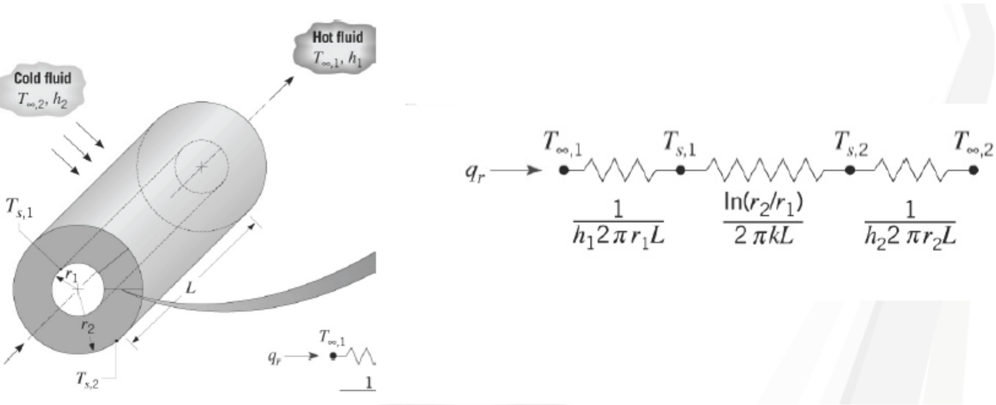

Figure B.11: Heat transfer in the vapor generator tube (Incropera, 2005).

Form equation $\quad q = UA\,\Delta T_{lm} = \Delta T_{lm} / R_{tot}$

$$R_{tot} = 1/(h_i 2\pi r_1 L) + \ln(r_2/r_1)/(2\pi kL) + 1/(h_o 2\pi r_2 L)$$

$$UA = 1/R_{tot}$$

Considering $\quad LMTD = F \times \Delta T_{lm}$

Form equation

$$\Delta T_{lm} = (\Delta T_2 - \Delta T_1) / \ln(\Delta T_2/\Delta T_1)$$

$$\Delta T_1 = (T_s - T_{wf,o}) = (100 - 90) = 10^oC$$

$$\Delta T_2 = (T_s - T_{wf,i}) = (100 - 30) = 70^oC$$

Therefore

$$\Delta T_{lm} = (10 - 70) / \ln(10 / 70) = 30.83^oC$$

From equation

$$P = (T_{wf,o} - T_{wf,i}) / ((T_s - T_{wf,i}) = (90 - 30) / (100 - 30) = 0.86$$

$$R = (T_s - T_s) / ((T_{m,o} - T_{m,i}) = (100 - 100) / (90 - 30) = 0$$

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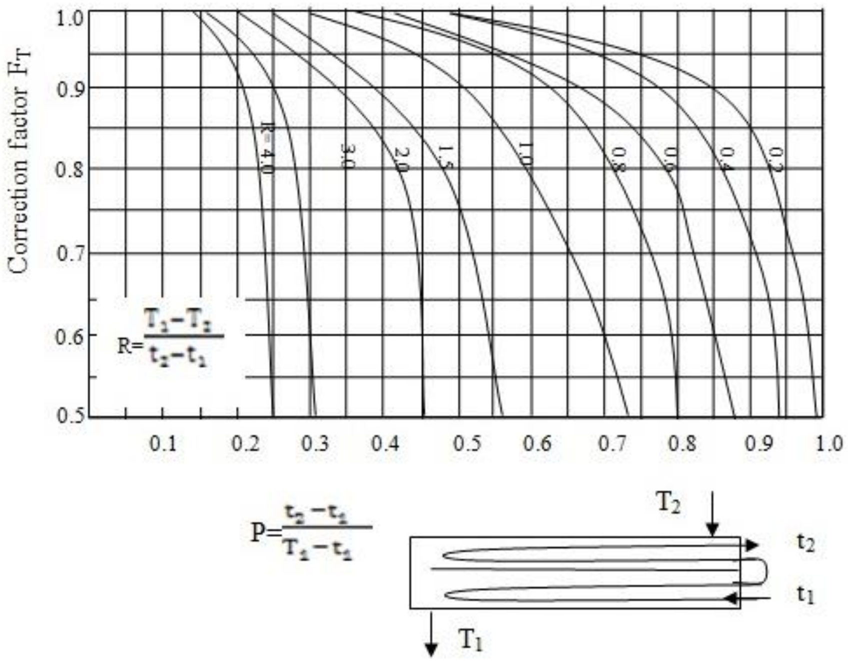

Figure B.12: Correlation factor of tube in the vapor generator (Incropera, 2005)

Correlation factor from Figure B.12, therefore; F = 1

The overall heat transfer coefficient at the vapor generator, U is define by

$$U = 1 /[1/h_i + r_1/k \ln r_2/r_1 + 1/h_o]$$

The total vapor generator heat exchanger area is given by

$$A_s = \pi d \text{ x } L \text{ x } N = \pi \text{ x } 0.0107 \text{ x } 4.512 \text{ x } 10 = 1.5167 \text{ m}^2$$

The cross section area of heat exchanger tube is

$$A = (\pi/4)\ d^2 \text{ x } N = (\pi/4) \text{ x } 0.0107^2 \text{ x } 10 = 0.0009 \text{ m}^2$$

The volumetric of heat exchanger tube is

$$V_{vg} = (\pi/4)\ d^2 \text{ x } L \text{ x } N = 0.00009 \text{ m}^2 \text{ x } 4.512 \text{ m x } 10 = 0.00406 \text{ m}^3$$

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Where d is the tube diameter, m

L is the tube length, m

N is the tube quantity.

Therefore 7,910 W $= U \times 1.5167\ m^2 \times 30.83^oC$

$U = 169.04\ W/m^{2o}C$

The considerations of the working fluid inlet and outlet temperature are 30^oC and 90^oC respectively.

$$T_{wf,avg} = (30 + 90)/2 = 60^oC$$

Prandt number (Pr) is the ratio of momentum diffusivity (kinematic viscosity) to thermal diffusivity. It can be related to the thickness of the thermal and velocity boundary layers. It is actually the ratio of velocity boundary layer to thermal boundary layer. When Pr = 1, the boundary layers coincide. When Pr is small, it means that heat diffuses very quickly compared to the velocity (momentum). This means the thickness of the thermal boundary layer is much bigger than the velocity boundary layer for liquid (www.cfd-online.com//Wiki/Prandtl_number).

The considerations of the Prandt number is

$$Pr = \mu Cp/k$$
$$= (296.3 \times 10^{-6}\ Pa.s)(4{,}392\ J/kg\text{-}K)/(78.7 \times 10^{-3}\ W/m\text{-}K)$$
$$= 16.46$$

The Reynolds number, Re_D is calculated from

$$Re_D = \rho VD/\mu$$
$$= 4m_f / \pi\mu D$$
$$= 4 \times 0.03\ kg/s / (\pi \times 296.3 \times 10^{-6}\ Pa.s \times 0.0107\ m)$$
$$= 12{,}048 \text{ (Turbulent flow)}$$

For a fully developed turbulent flow, analysis has to be relied solely by the experimental results. The friction factor for any Reynolds number can be conveniently found in Moody chart (Figure B.14). Whereas the friction factor (f) is depend upon the Reynolds number and the roughness factor of the pipe surface. Generally, the friction

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factor is increased corresponding to the increase of roughness factor (ε). The empirical formula is proposed as follow.

$$f = 0.184\ Re_D^{-1/5} \qquad \text{when} \qquad Re_D \geq 2 \times 10^4$$

Therefore

$$f = 0.184 \times 12{,}048^{-1/5} = 0.018$$

For the Re_D for the transition from laminar flow to turbulent flow is set at Re_D 2,300 and if greater than 0.5. However, the heat transfer rate significant to Nu. Therefore the calculation of Nu for a turbulent flow in smooth pipe cab be used the equation of Dittus-Boelter; i.e.,

$$\begin{aligned} Nu_D &= 0.023\ (Re_D^{0.8})\ (Pr^{0.4}) \\ &= 0.023\ (12{,}048^{0.8})\ (16.46^{0.4}) \\ &= 129.73 \end{aligned}$$

Where n = 0.4 for Heating ($T_s > T_m$), and n = 0.3 for cooling ($T_s < T_m$)
The equation rechecks that the calculation must be satisfied with these values;
[$0.7 \geq Pr \geq 160$, $Re_D \geq 10{,}000$, $L / D \geq 10$]

Therefore

$$\begin{aligned} h_{avg} &= (mCp / \pi DL) \times (T_{r,o} - T_{r,i}) / \Delta T_{LMTD} \\ &= (0.030\ kg/s)(4{,}392\ J/kg^oC)/[\pi/4\ (0.0107\ m)^2(45.12\ m)] \times [(90 - 30)\ ^oC/(30.83)^oC] \\ &= 63.19\ W/m^{2o}C \end{aligned}$$

The performance index normally used for any heat exchanger is the heat exchange effectiveness (ε_{HX}). For which can be expressed as follow;

$$\varepsilon_{HX} = \frac{Q_{avg}}{Q_{max}} = \frac{Q}{(\dot{m}Cp)_{min}\,\Delta T_{max}}$$

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The continuity equation of pipe

$$m = \rho_1 u_1 A_1 = \rho_2 u_2 A_2$$

The first law of energy (The Bernoulli's equation);

$$Q - W = m_2 (u + Pv + u^2/2 + gz)_2 - m_1 (u + Pv + u^2/2 + gz)_1$$

The working fluid pressure drop is determine using

$$\Delta P = \text{major loss} + \text{minor loss}$$

The working fluid temperature at 60ºC find from HCFC-141b thermo-physical properties

$\mu = 296.3 \times 10^{-6}$ Pa.s, $\rho = 1{,}159.1$ kg/m^3, $k_f = 78.7 \times 10^{-3}$ W/m-K, $Re_D = 12{,}048$

The working fluid volume flow rate in the pipe can be calculated from

$$\text{Volume flow rate} = A \times u = (m_f v)/A$$

Where u is the working fluid velocity in the pipe, v is specific volume of the fluid can be calculated from equation;

$$u_{avg} = (m_f v)/A = (0.03 \text{ kg/s} \times 0.08954 \text{ m}^3 / \text{kg}) / (10 \times \pi/4 \times 0.0107^2 \text{ m}^2)$$
$$= 2.99 \text{ m/s}$$

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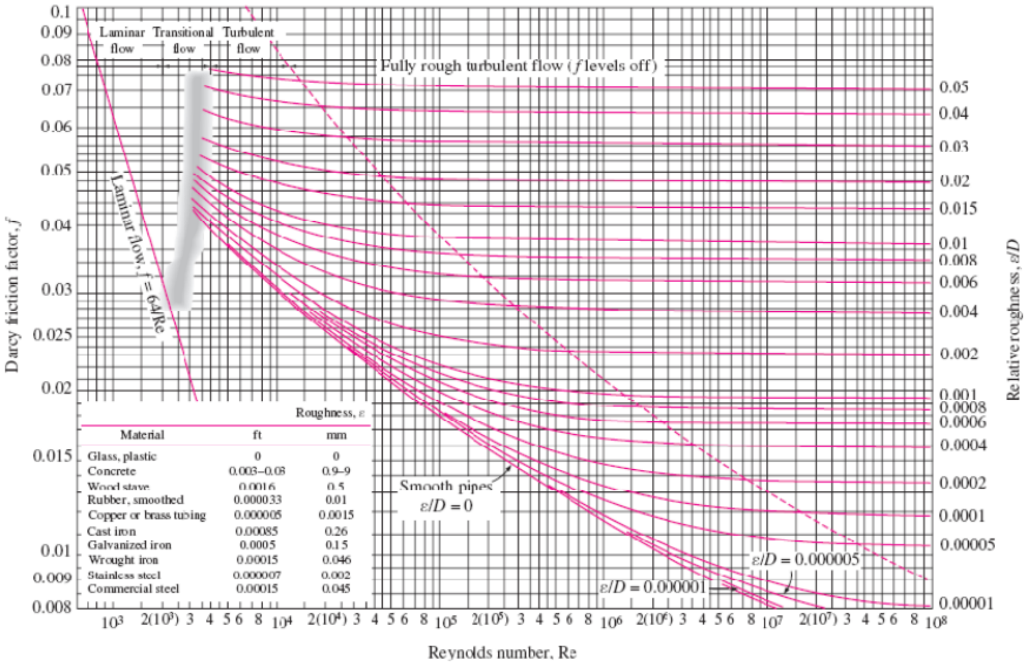

Figure B.14: Moody chart of pipe (http://www.engineeringtoolbox.com)

The pressure drop from Straight pipe can be calculated from

$$h = f\,(L/D)(u^2/2g)$$

Where L = 0.38 m x 10 = 3.80 m, D = 0.0107 m, ε = 0.0000015 m

Therefore $\varepsilon/D = 1.4 \times 10^{-4}$

And can read from $f = 0.018$

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Substitute into the equation

$$h_1 = 0.018\,(3.80 / 0.0107)(2.99^2/2 \times 9.81) = 2.84 \text{ m}$$

For major loss in the 180° is $f = 1.5$

Therefore

$$h_2 = K_L\, u^2/2g \times N = f\,(L_e/D)\, u^2/2g \times N$$

$$= 1.5 \times (2.99^2 / 2 \times 9.81) \times 9 = 6.14 \text{ m}$$

The total heat pipe head loss, therefore

$$H_{tot} = (H_1 + H_2)\,N = (2.84 + 6.14) \times 10 = 8.98 \text{ m}$$

The total pressure drop in vapor generator can be calculated from

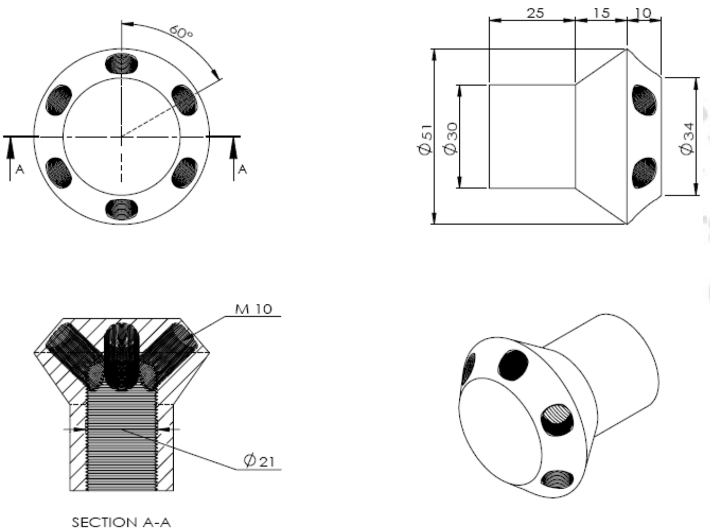
$$\begin{aligned}\Delta P &= \rho g h = 1{,}159.1 \text{ kg/m}^3 \times 9.81 \text{ m/s}^2 \times 8.98 \text{ m} / (1 \text{ kPa} / 1{,}000 \text{ kg m/s}^2) \\ &= 102.11 \text{ kPa}\end{aligned}$$

The working fluid pumping power is determined by

$$\begin{aligned}W_P &= V\Delta P \\ &= 0.002686 \text{ m}^3\text{/s} \times 102.11 \text{ kPa} = 0.27 \text{ kW}\end{aligned}$$

3. Nozzle calculation

A nozzle is properly shaped ducts which are used to increase the speed of the fluid flowing through it. Schematics of a typical nozzle are shown in Figure B.15. Nozzles are used for various applications such as to increase the speed of vapor through a garden hose, and to increase the speed of the vapor leaving the turbine. Since no shaft work is involved in a nozzle, and since the potential energy difference across a nozzle is usually negligible, the steady flow energy for flow through a nozzle becomes (Shanthini, 2008).



Note: All dimensions are in millimeter

Figure B.15: Detail of vapor distributor

The continuity equation of first law in the nozzle

$$Q_{tot} = Q_1 + Q_2 + Q_3 + Q_4 + Q_5 + Q_6 = 6Q_N$$

$$Q_{tot} = 6AV$$

And working fluid mass flow rate as,

$$\dot{m}_{wf} = \rho A u$$

where ρ is the working fluid density, kg/m^3

u is the working fluid velocity, m/s

A is the cross section area of nozzle, m^2

Therefore, the velocity of working fluid flow at the nozzle exit is

$$0.002686 \text{ m}^3/\text{s} = 6 (\pi/4)\ 0.003^2 \ V$$

$$V = (0.002686 \text{ m}^3/\text{s}) / (6 (\pi/4)\ 0.003^2)$$

$$= 63.34 \text{ m/s}$$

and

$$u = \sqrt{(2\ \Delta h)}$$

$$\Delta h = (498.38 - 496.38) \times 10^3 = 2{,}000 \text{ J/kg or } 2 \text{ kJ/kg}$$

Substitution into equation below

$$u = \sqrt{(2 \times 2{,}000)} = 63.25 \text{ m/s}$$

Table B.6: Designing condition

Stage	$\dot{m}_{wf}$ kg/s	T_{wf} °C	P kPa	h kJ/kg	s kJ/kgK	V m^3/s	ρ kg/m^3	*v* m^3/kg	u m/s
1	0.031	90.0	537.67	498.38	1.8634	0.0027	1,093.2	0.0432	2.99
2	0.031	86.9	501.92	496.38	1.8625	0.0027	1,093.2	0.0432	63.34

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4. Turbine phase (stage 3-4):

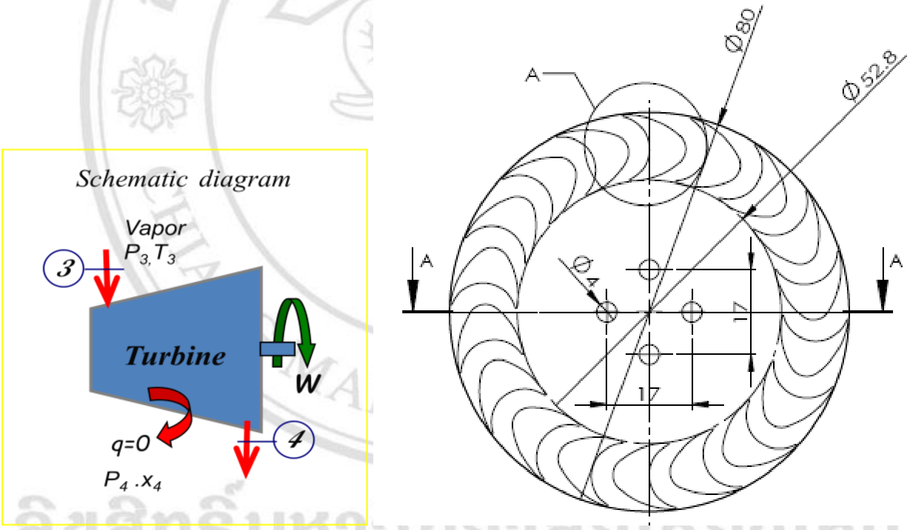
The turbine converts the potential energy of the highly pressurized gases into kinetic energy for power generated. The streams of high pressure vapor expand in the turbine and transfer its energy to rotating shaft of the turbine. Following assumed adiabatic expansion process, the vapor returning to low-pressure and low-temperature. Stipulating the turbine efficiency, turbine output is given by:

$$\dot{W}_t = \dot{m}(h_3 - h_4)$$

Where $\dot{m}$ is the working fluid mass flow rate, kg/h

h_3 is the specific enthalpy at the turbine inlet, kJ/kg

h_4 is the specific enthalpy at the turbine outlet, kJ/kg



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Note: All dimensions are in millimeter

Figure B.16: Turbine stage and Detail of turbine disk

Figure B.16 the impulse turbine is the simplest form to be constructed. It consists of one set of rotor impeller and 1 set of nozzle head. There are altogether 6 nozzles. A single stage impulse turbine is used in this design after the fluid impacted from the turbine blades, will then be collected to the condensing unit. The disadvantage of this configuration is that the high kinetic energy of the fluid leaving the turbine is not yet fully utilized. However, one main advantage is the simplicity of construction. At exit of the nozzle, the vapor velocity is 63 m/s at 5 bars. Consequently at 0.1 bars at the outlet of turbine will be 60 m/s.

From the Figure B.17 consider also as a continuity equation and adiabatic process and no heat loss from system, therefore;

$$-W = (h_4 - h_3) + (V_4^2 - V_3^2)/2$$

The consideration of the design and construction of micro radial impulse turbine will be control volume of the turbine and with isentropic condition; one can get the power output of the turbine as:

Table B.7: Numerical simulation of the turbine stage on the ORC system.

Stage $\Delta P = 5$	$\dot{m}_{wf}$ kg/s	T_{wf} ^oC	P kPa	h kJ/kg	s kJ/kg.K	V m^3/s	ρ kg/m^3	v m^3/kg	u m/s
Inlet	0.031	86.9	501.9	496.38	1.8625	0.003	1,093.2	0.0432	63.3
outlet	0.031	31.8	100.6	459.45	1.8574	0.023	4.8676	0.2089	33.2

Velocity Triangle Analysis

In the radial impulse turbine on the test rig, the velocity triangle is a triangle representing the various components of velocities of the working fluid in the turbine machine. Velocity triangles may be drawn for both the inlet and outlet sections of any turbine machine. The vector nature of velocity is utilized in the triangles, and the most basic form of a velocity triangle consists of the tangential velocity, the absolute velocity and the relative velocity of the fluid making up three sides of the triangle. Velocity triangles as show on the Figure B.17 (Ingram, 2009).

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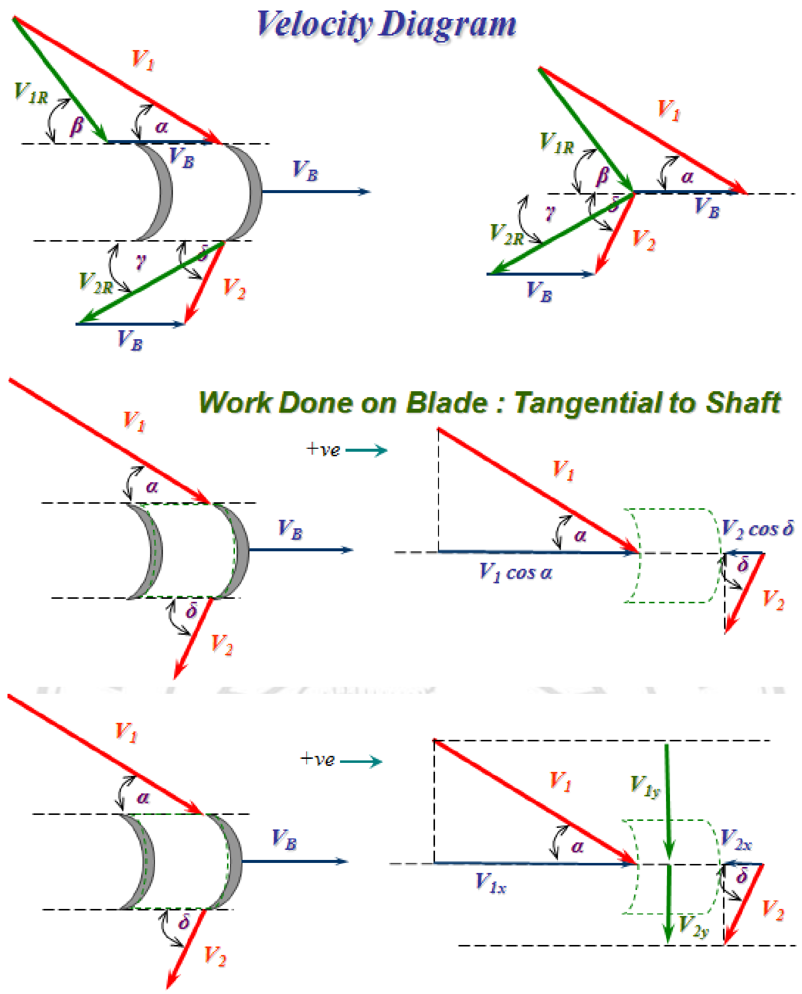

Figure B.17: The velocity triangle diagram of impulse turbine [Ref]

Where V_{1R} is the vapor velocity entering blades relative to blades or the absolute velocity (m/s)

V_1 is the vapor absolute velocity entering blades to blades or the absolute velocity is the blade velocity (m/s)

V_B is the blade velocity (m/s)

V_2 is the vapor velocity leaving blades relative (m/s)

V_{2R} is the blade velocity (m/s)

α is the inlet angle of absolute velocity (the nozzle angle is 25°)

β is the inlet angle relative velocity (the nozzle angle is 33.8°)

γ is the outlet angle of absolute velocity (the nozzle angle is 24.7°)

δ is the outlet angle relative velocity (the nozzle angle is 24.7°)

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Consider at the velocity triangle as;

$$V_1 = V_{nozzle}$$
$$= 63.3 \text{ m/s}$$

Determine V_{1R} as

$$V_{1R} = (V_1 \sin \alpha) / (\sin \beta)$$
$$= (63.3 \sin 25^o) / (\sin 33.8^o) = 48.1 \text{ m/s}$$

and $V_{1R \cos \beta}$ as

$$V_{1R \cos \beta} = 48.1 \cos 33.8^o$$
$$= 40.0 \text{ m/s}$$

The blade speed (V_B) can be calculated from the velocity vector diagram by:

$$V_B = V_1 \cos \alpha - V_{1R} \cos \beta$$
$$= 63.3 \cos 25^o – 48.1 \cos 33.8^o$$
$$= 17.4 \text{ m/s}$$

Consider also

$$V_{1R} = V_{2R} = 48.1 \text{ m/s}$$

Therefore from V_{2R} further calculation will be

$$V_2 \sin \delta = V_{2R} \sin \gamma = 48.1 \sin 24.7^o = 20.1 \text{ m/s}$$
$$V_2 \cos \delta + V_B = V_{2R} \cos \gamma = 48.1 \cos 24.7^o = 43.7 \text{ m/s}$$
$$V_2 \cos \delta = 43.7 – 17.4 = 26.3 \text{ m/s}$$

The angle δ consideration

$$\text{Cot } \delta = (V_2 \sin \delta) / (V_2 \cos \delta)$$
$$= (20.1 \text{ m/s}) / (26.3 \text{ m/s})$$
$$= 1.3085$$

Therefore

$$\delta = \tan^{-1} (1.3085)$$
$$= 37.4^o$$

And

$$V_2 = \sqrt{(V_2 \sin \delta)^2 \text{ x } (V_2 \cos \delta)^2}$$
$$= \sqrt{(20.1)^2 + (26.3)^2}$$
$$= 33.2 \text{ m/s}$$

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The Coefficient of the blade speed (k) is

$$k = V_2 / V_1$$

$$= 33.2 / 63.3$$

$$= 0.523$$

The angular velocity obtained from Eq.

$$\omega_{th} = V_1 \cos \alpha + V_2 \cos \delta$$

$$= 63.3 \cos 25^o + 33.2 \cos 37.4^o$$

$$= 83.8 \text{ m/s}$$

The angular velocity or tangential force of turbine disk as

$$F_{tan} = m (V_1 \cos \alpha + V_2 \cos \delta) = m\omega_{th}$$

$$= 0.031 \text{ kg/s x } (63.3 \cos 25^o + 33.2 \cos 37.4^o) \text{ m/s}$$

$$= 2.53 \text{ N}$$

The Axial velocity obtained from Eq.

$$f = V_1 \cos \alpha - V_2 \sin \delta$$

$$= 63.3 \cos 25^o - 33.2 \sin 37.4^o$$

$$= 37.2 \text{ m/s}$$

The axial thrust is the force in the axial direction acting along the rotor. Therefore, the total axial thrust acting on the rotor blade becomes:

$$F_{axial} = \dot{m}_{wf} (V_1 \cos \alpha + V_2 \cos \delta)$$

$$= 0.031 \text{ kg/s x } (63.3 \sin 25^o + 33.2 \sin 37.4^o) \text{ m/s}$$

$$= 0.20 \text{ N}$$

The sum of the moments of all the external force is equal to the rate of change of angular momentum of the system. Thus the torque delivered by a vapor tube of a considered the theoretical work output calculated from the velocity triangles.

$$w = V_B (V_1 \cos \alpha + V_2 \cos \delta)$$

$$= 17.4 \text{ m/s } (63.3 \cos 25^o + 33.2 \cos 37.4^o) \text{ m/s}$$

$$= 1{,}457 \text{ m}^2/\text{s}^2 \text{ x } [(\text{kJ/kg}) / (1{,}000 \text{ m}^2/\text{s}^2)]$$

$$= 1.46 \text{ kJ/kg}$$

The theoretical power output of the turbine stage P_{th} is the rate of the work done in a turbine stage w and can be calculated:

$$P_{th} = \dot{m}_{wf} \, w = 0.031 \text{ kg/s x } 1.457 \text{ kJ/kg}$$

$$= 0.0437 \text{ kW } \underline{\textbf{or}} \text{ } 43.7 \text{ watt}$$

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The consideration of the turbine rotation speed on the experiment result was 1,369 rpm,

$$\omega = 2\pi N/60$$
$$= (2 \times \pi \times 1{,}369 \text{ rad/min}) / (1 \text{ min} / 60 \text{ s})$$
$$= 143.4 \text{ rad/s}$$

The consideration of the turbine torque and angular on the experiment result were T = 0.0721 N.m, ω = 1,369 rpm.

$$F_{tan} = T / r$$
$$= 0.0721 \text{ N.m} / 0.25 \text{ m}$$
$$= 0.29 \text{ N.m}$$

The consideration of the power output on the experiment result as

$$P_{act} = T\omega$$
$$= 0.110 \text{ N.m} \times 143.4 \text{ rad/s}$$
$$= 15.77 \text{ W}$$

The consideration of continuity equation

$$Q - W = (h_4 - h_3) + (V_o^2 - V_2^2)/2$$

Consider the theoretical work output calculated from the triangle velocity

$$-W = (h_3 - h_4) + (V_4^2 - V_3^2)/2$$
$$-1.46 \text{ kJ/kg} = h_4 - 469.38 + [(33.2^2 - 63.3^2)/2 \times (\text{kJ/kg})/(1{,}000 \text{ m}^2/\text{s}^2)]$$

Specific kinetic energy

$$(V_2^2 - V_1^2)/2 = (33.2^2 - 63.3^2)/2 \times (\text{kJ/kg})/(1{,}000 \text{ m}^2/\text{s}^2)$$
$$= -1.452 \text{ kJ/kg}$$

Consideration of the turbine outlet specific enthalpy (h_4) such as

$$h_4 = -1.46 - 1.452 + 496.38 \quad \text{kJ/kg}$$
$$= 493.47 \text{ kJ/kg}$$

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The theoretical efficiency of the turbine rotor can be expressed as a ratio of the power output to the rate of the power input or an available kinetic energy produced by nozzles

$$\eta_{th} = (P_{out} / P_{in}) \times 100\%$$
$$= (15.73/778.3) \times 100\%$$
$$= 2.02\%$$

5. Condenser Phase (Stage 4-1)

The vapor from the turbine exit at low pressure undergoes isobaric phase change into saturated liquid form by transferring heat to environment or to the coolant. The pressure of the working fluid in the condenser is considered the same as the lower pressure of the system. The first law of thermodynamics of the condenser will be considerate by steady-flow system and the condenser load output, Q_{co} which defines the rate of latent heat transfer by working fluid, can be given by the equation:

$$\dot{Q}_{co} = \dot{m}(h_1 - h_4)$$

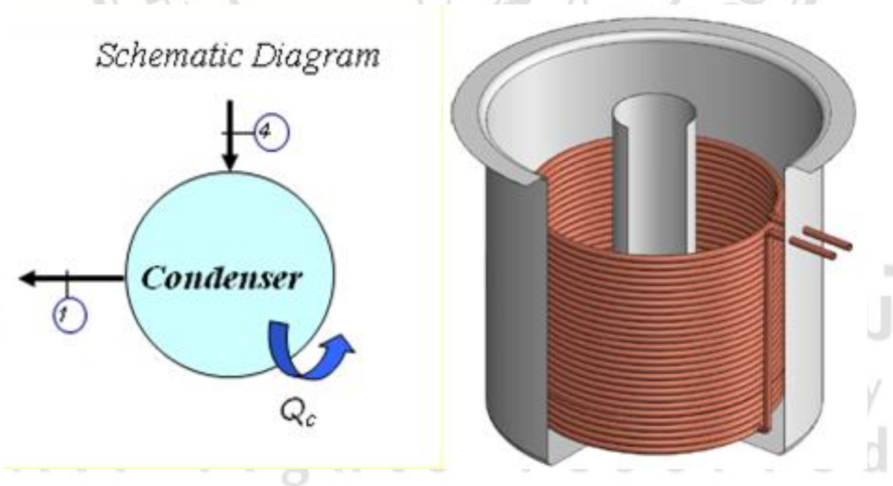

Figure B.19: Configuration of water cooled condenser

Design condition of condenser

In the design condition of the condenser, the considerate of heat rejection area where condensation was used for condenser cooling system. The working fluid used is HCFC-141b at inlet temperature 90°C and outlet temperature 30°C. The cooling water temperature flows into the inlet and outlet condenser are 10°C and 30°C respectively. The condenser tube is coiled round the number 1 position in the tube. The copper tube was used sizes 15 mm ID and 18 mm OD with the temperature difference (ΔT_{HX2} = 20°C). The continuity equation can be expressed as

$$Q - W = (h_o - h_i) + (V_o^2 - V_2^2)/2$$

Consider of the system, no work addition at the condenser therefore

$$Q_{co} \quad = (h_o - h_i) + (V_2^2 - V_1^2)/2$$

Figure B.20: Condenser coil constructed

Consider at the condensing area and tube length of the condenser required to comply with the cooling system with 6.77 kW and HCFC-141b as a working fluid. For the procedure to calculate in this design, the heat transfer rate, conduction heat transfer, and convection heat transfer. Then calculate the area and length of the pipe according to the equation.

$$Q_{co} = UA\ \Delta T_{LMTD} = U \times 0.773\ m^2 \times (70 - 30.37)^{o}C = 144.53U$$

Condition Heat rate at condenser; Q_{co} = 60.27 kJ/s or kW

Tube surface area; A_i = 0.773 m^2

Working fluid outlet temperature; $T_{wf,i}$ = 78°C

Working fluid outlet temperature; $T_{wf,o}$ = 30°C

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Water cooled inlet temperature; $T_{w,i}$ = 10°C

Water cooled outlet temperature; $T_{w,o}$ = 10°C

Working fluid mass flow rate; $\dot{m}_{wf}$ = 0.031 kg/s = 112.0 kg/h

Water cooled mass flow rate; $\dot{m}_{w}$ = 0.267 kg/s = 961.2 kg/h

Therefore

Q_{co} = UA ($T_{wf,i}$ – $T_{wf,o}$) = U x 1.815 m^2 x (100 - 20.37)°C = 144.53U

The condense coefficient equation

$$h_{co} = 0.725\left(\frac{g\rho^2 h_{fg} k^3}{\mu \Delta TND}\right)^{1/4}$$

The working fluid density (ρ) and latent heat of vaporization (h_{fg}) of HCFC-141b at temperature is 45°C, can be calculated from equation,

$$\rho = \frac{1}{0.90203\,L/k} = 1.109\,kg/L = 1109\,kg/m^3 \text{ and } h_{fg} = 160.9 \text{ kJ/kg}$$

The thermal conductivity (k) and viscosity (ν) of HCFC-141b at temperature is 45°C, can be expressed below;

k = 0.0779 W/m.K and ν = 0.000180 Pa.s

Consider the number of tube at this point is the temperature difference between the working fluid vapor and surface of tube. There are assume ΔT = 5°C can be calculated from this equation.

$$h_{co} = 0.725\left(\frac{9.81(1109)^2(160900)(0.0779)^3}{0.00018(5)(3.23)(0.016)}\right)^{1/4} = 1{,}528\,W/m^2K$$

Cycle efficiency

The cycle efficiency is the ratio of net useful work done to the heat input during the vaporization phase. The efficiency of the system is much less than the Rankine cycle due to its lower temperature range. The efficiency is defined as:

$$\eta_{cycle} = \frac{\dot{W}_t}{\dot{Q}_{vg}} = \frac{0.01573}{23.73} = 0.0104 = 0.07\%$$

Appendix C

Proportion of Torque and Power output from Experiments

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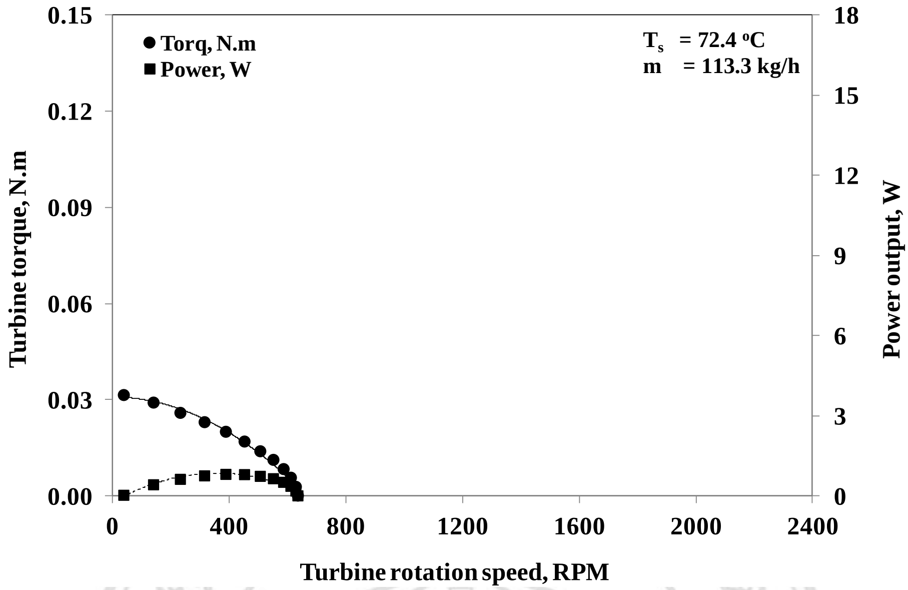
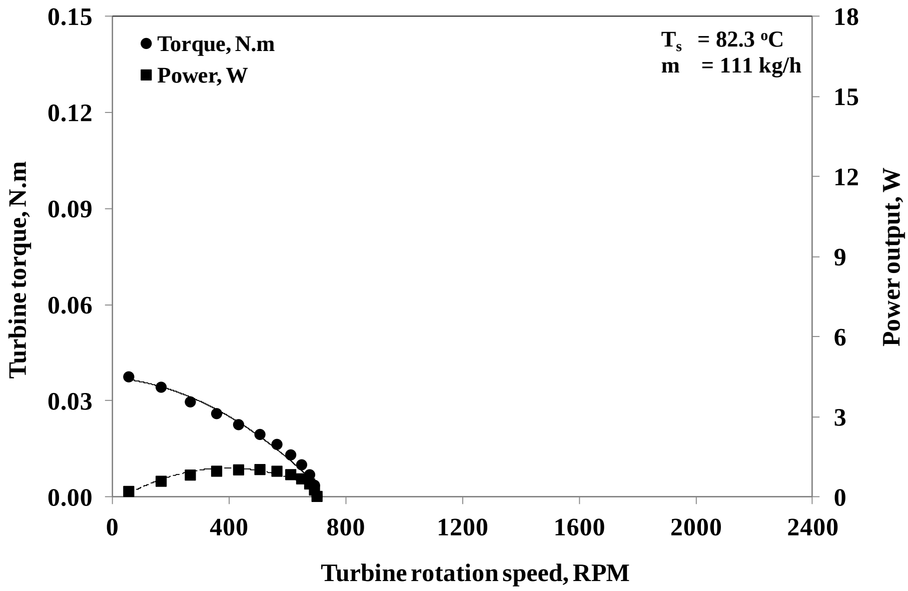
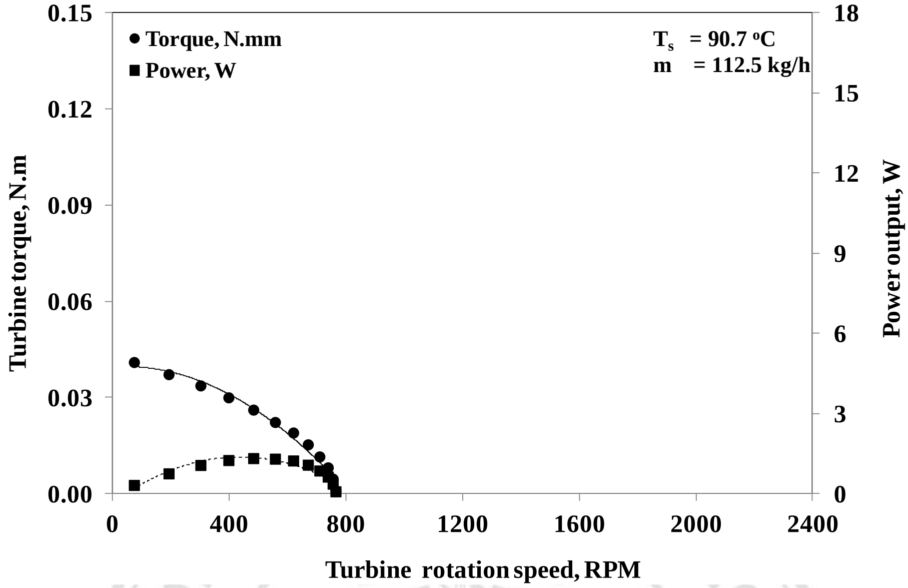


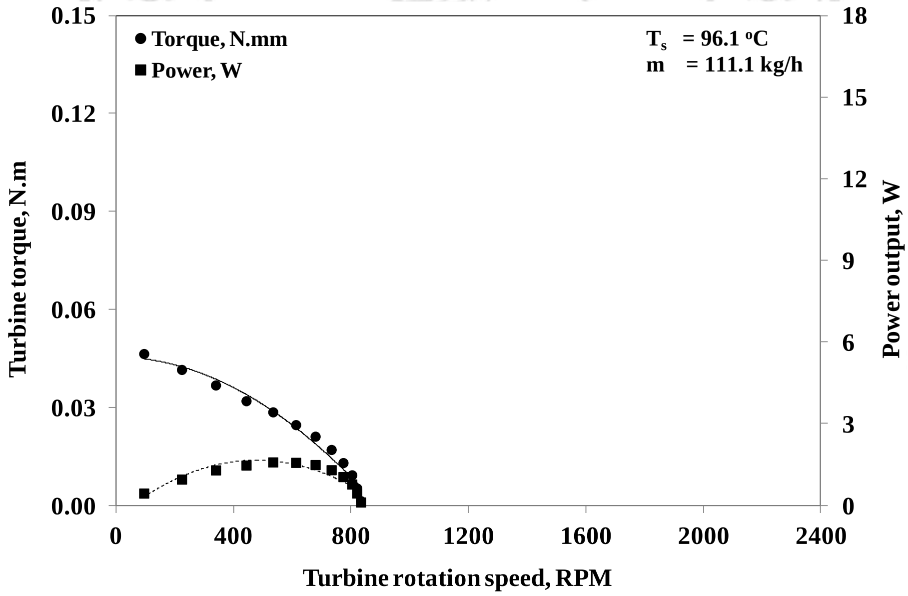
Proportion of torque and power output for $T_{so,avg}$ = 72.4°C and $\dot{m}_{avg}$ = 113.3 kg/h



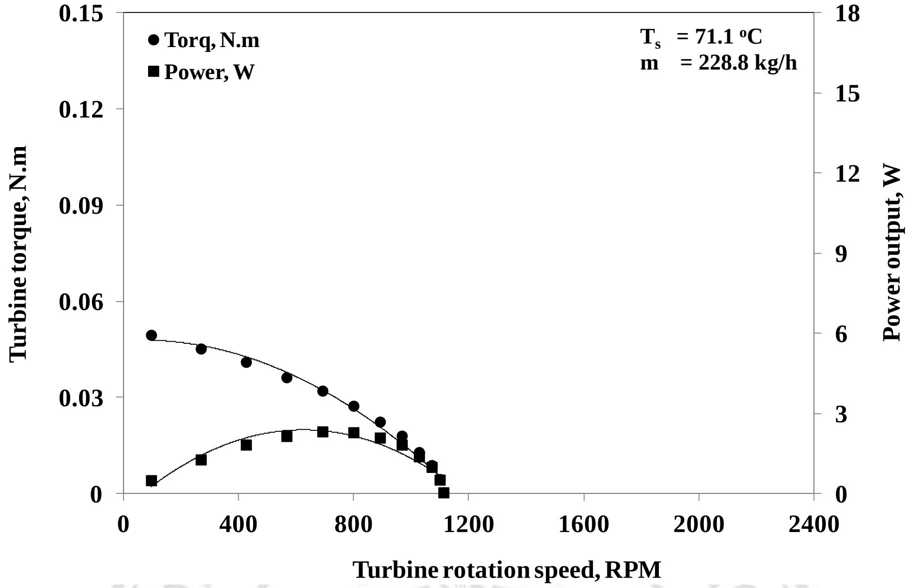
Proportion of torque and power output for $T_{so,avg}$ = 82.3°C and $\dot{m}_{avg}$ = 111.0 kg/h



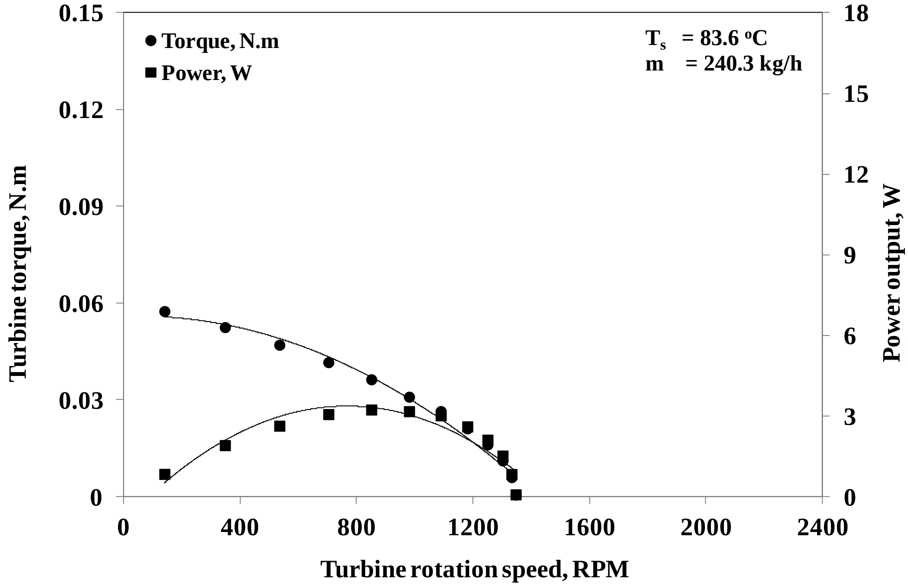
Proportion of torque and power output for $T_{so,avg}$ = 90.7°C and $\dot{m}_{avg}$ = 112.5 kg/h



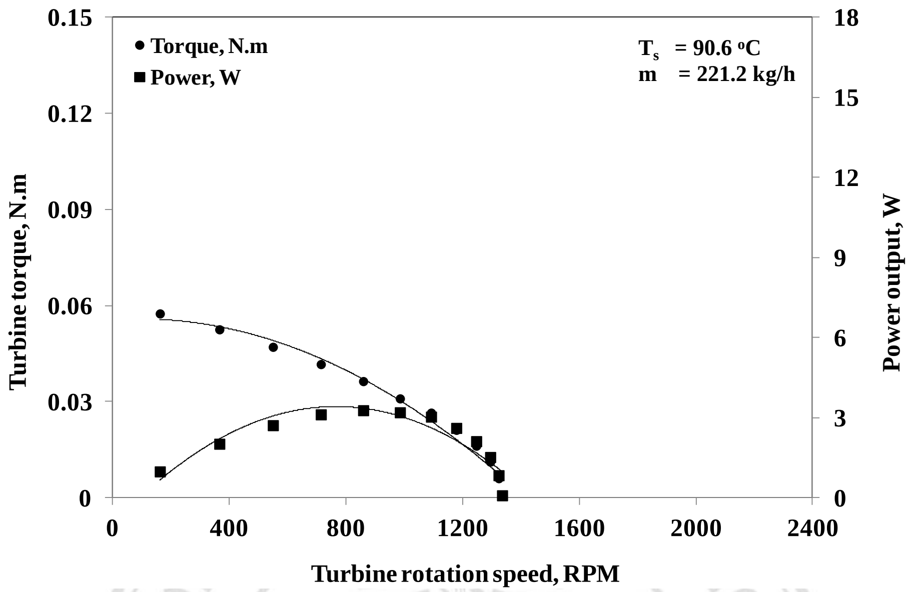
Proportion of torque and power output for $T_{so,avg}$ = 96.1°C and $\dot{m}_{avg}$ = 111.1 kg/h



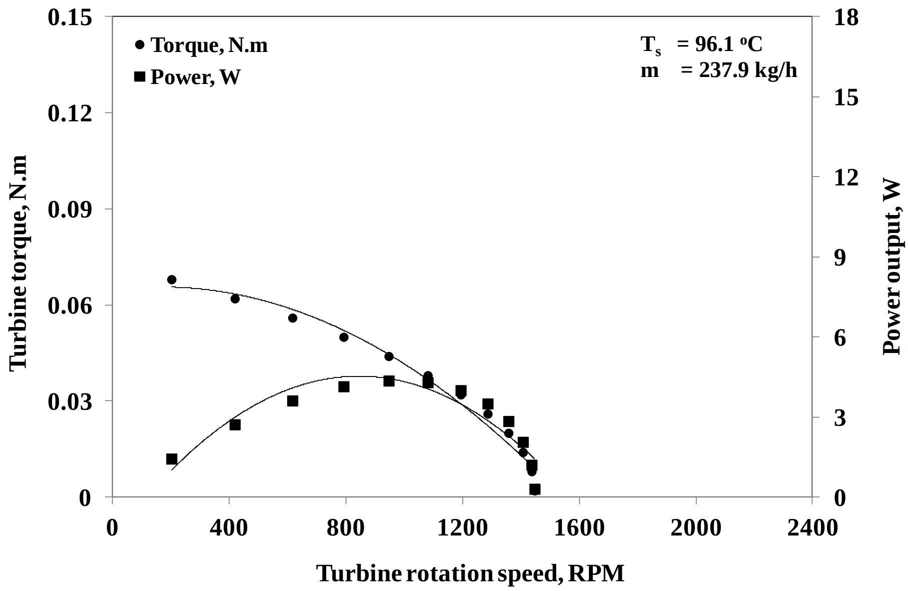
Proportion of torque and power output for $T_{so,avg}$ = 71.1°C and $\dot{m}_{avg}$ = 228.8 kg/h



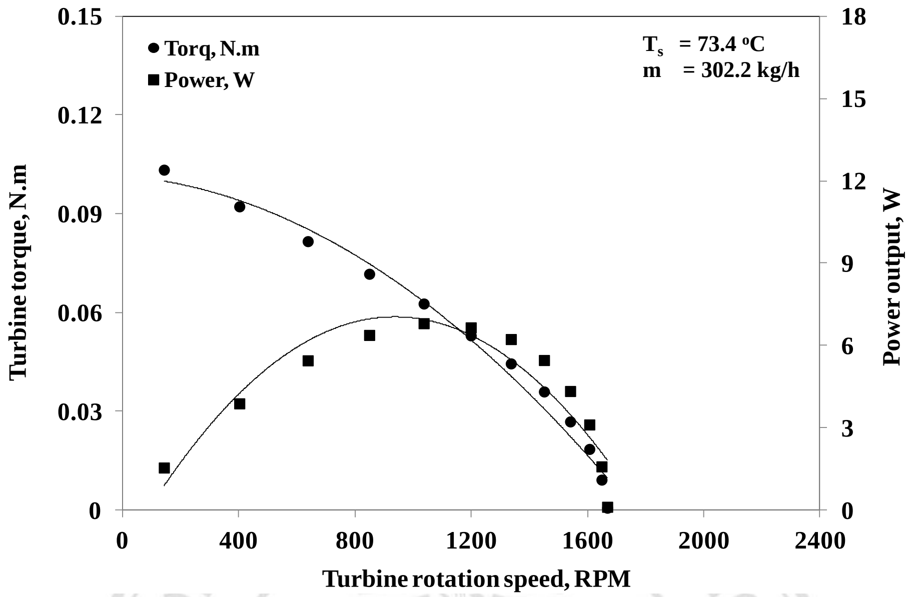
Proportion of torque and power output for $T_{so,avg}$ = 83.6°C and $\dot{m}_{avg}$ = 240.3 kg/h



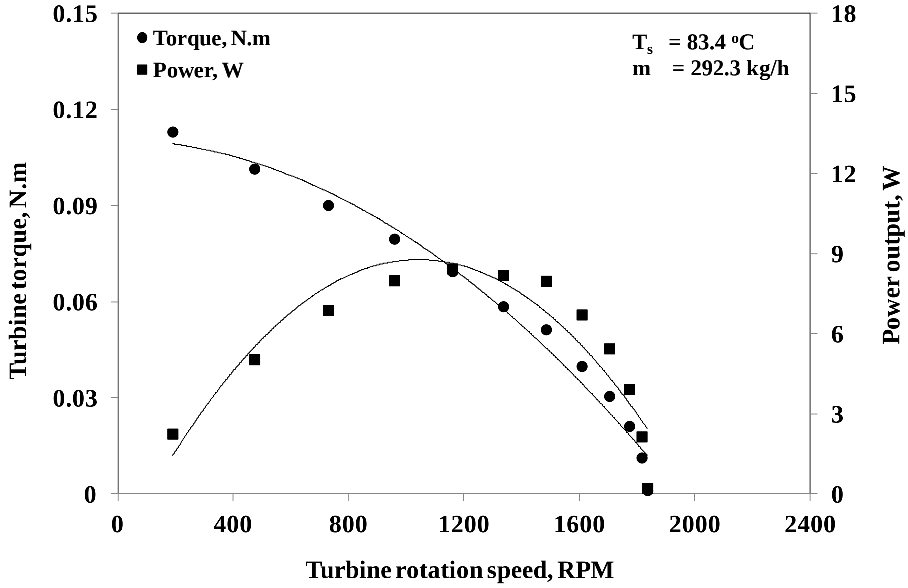
Proportion of torque and power output for $T_{so,avg}$ = 90.6°C and $\dot{m}_{avg}$ = 221.2 kg/h



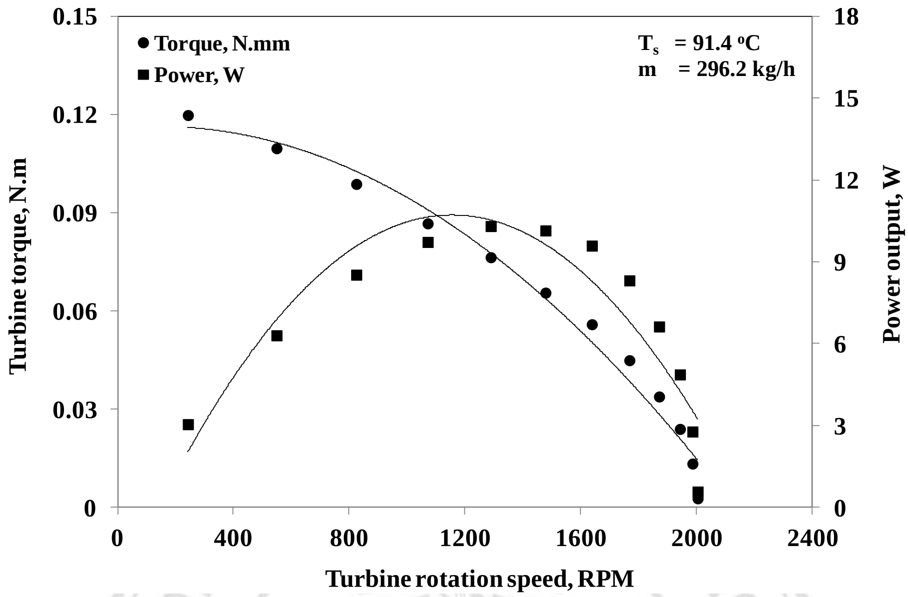
Proportion of torque and power output for $T_{so,avg}$ = 96.1°C and $\dot{m}_{avg}$ = 237.9 kg/h



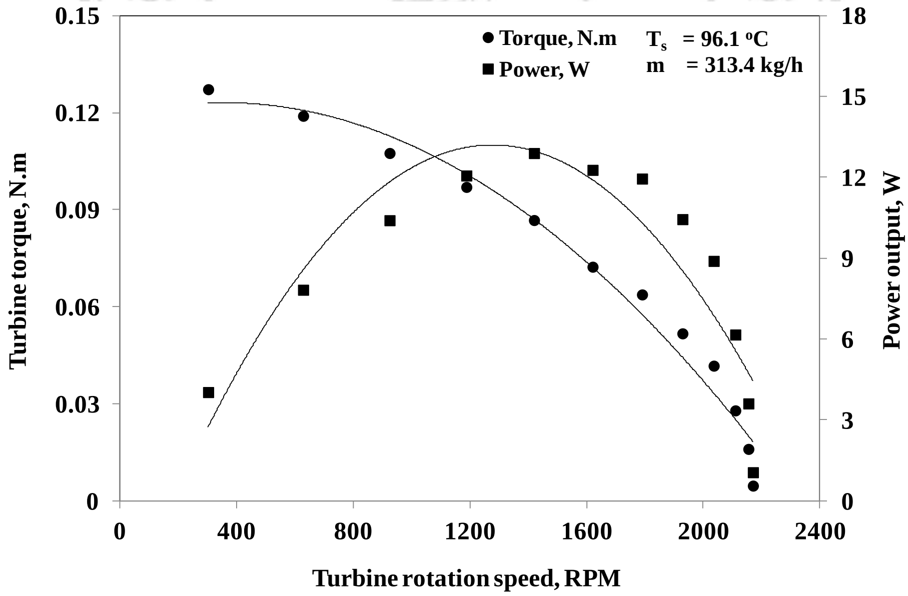
Proportion of torque and power output for $T_{so,avg}$ = 73.4°C and $\dot{m}_{avg}$ = 302.2 kg/h



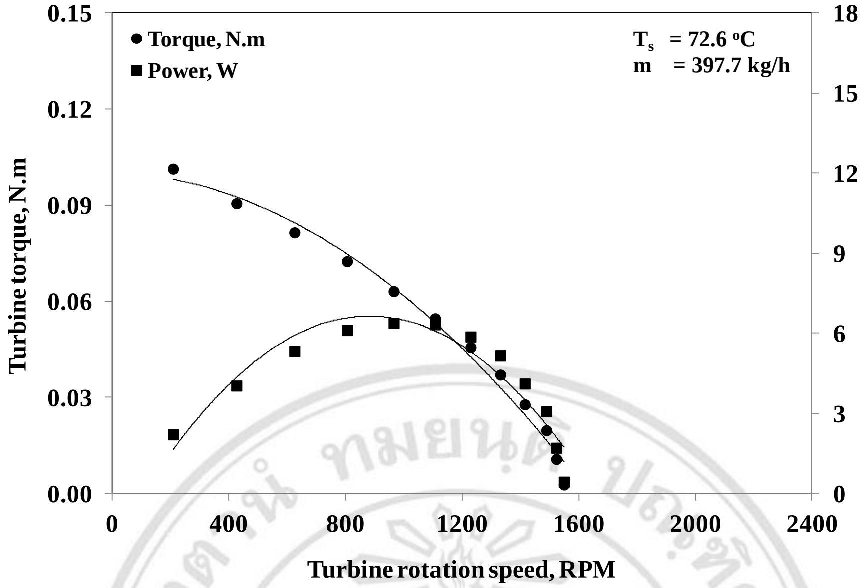
Proportion of torque and power output for $T_{so,avg}$ = 83.4°C and $\dot{m}_{avg}$ = 292.3 kg/h



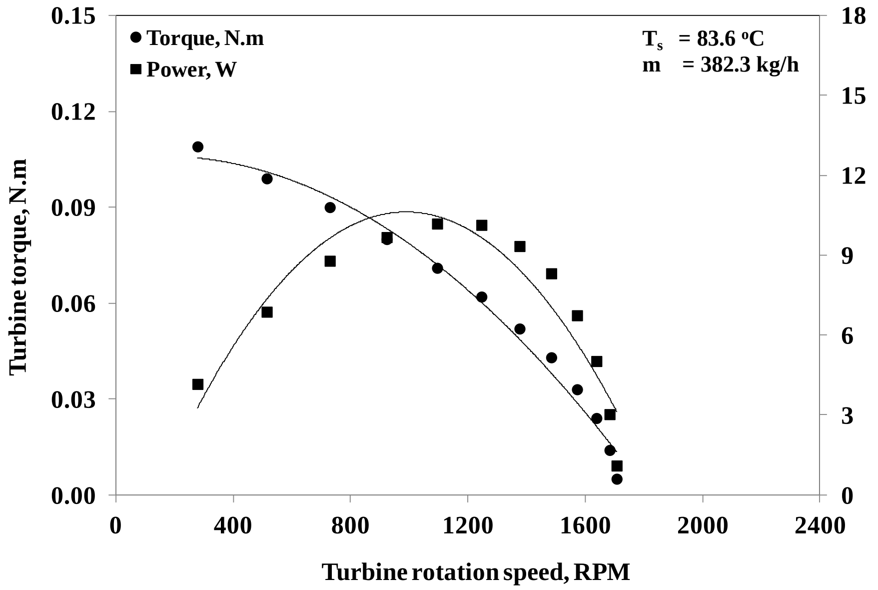
Proportion of torque and power output for $T_{so,avg}$ = 91.4°C and $\dot{m}_{avg}$ = 296.2 kg/h



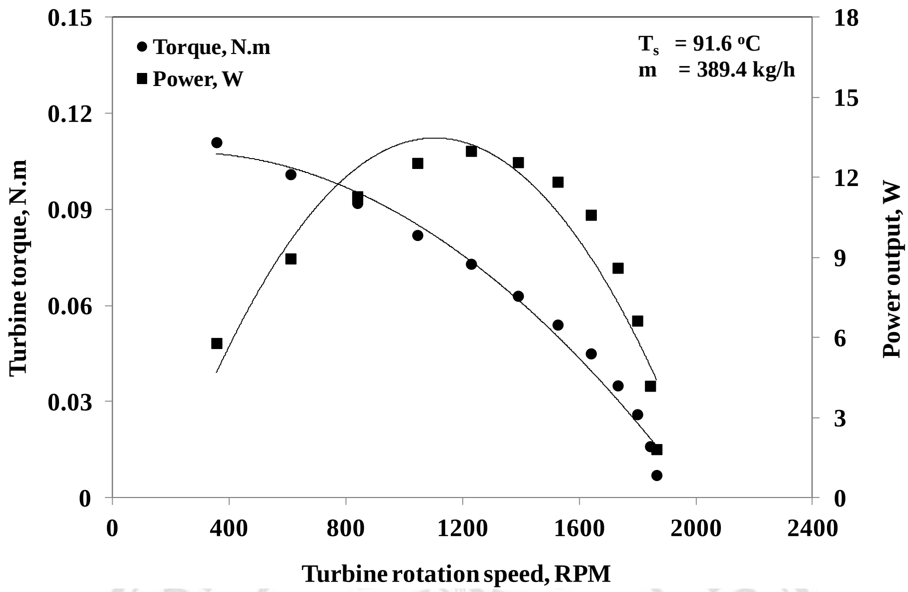
Proportion of torque and power output for $T_{so,avg}$ = 96.1°C and $\dot{m}_{avg}$ = 296.2 kg/h



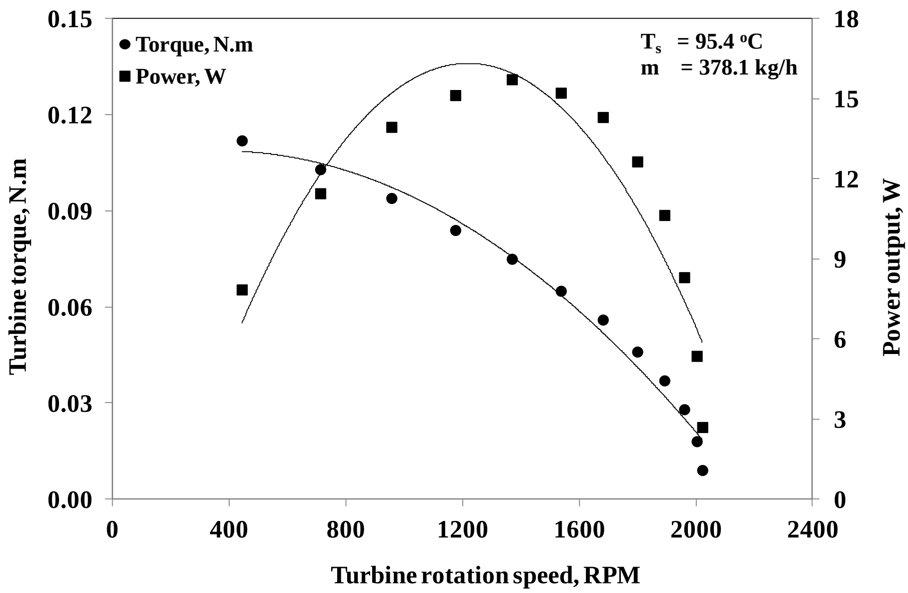
Proportion of torque and power output for $T_{so,avg}$ = 72.6°C and $\dot{m}_{avg}$ = 397.7 kg/h



Proportion of torque and power output for $T_{so,avg}$ = 83.6°C and $\dot{m}_{avg}$ = 382.3 kg/h



Proportion of torque and power output for $T_{so,avg}$ = 91.6°C and $\dot{m}_{avg}$ = 389.4 kg/h



Proportion of torque and power output for $T_{so,avg}$ = 95.4°C and $\dot{m}_{avg}$ = 378.1 kg/h

Table C.1: Experimental results of average heat source temperature 72.4°C, 82.3°C, 90.6°C, 96.1°C and working fluid mass flow rate setting 112.0 kg/h

Average heat source temperature 72.4°C			Average heat source temperature 82.3°C			Average heat source temperature 90.6°C			Average heat source temperature 96.1°C		
Average working fluid mass flow rate 120.3 kg/h			Average working fluid mass flow rate 124.6 kg/h			Average working fluid mass flow rate 127.9 kg/h			Average working fluid mass flow rate 129.3 kg/h		
Speed, RPM	Torque, N-m	Power, W	Speed, RPM	Torque, N-m	Power, W	Speed, RPM	Torque, N-m	Power, W	Speed, RPM	Torque, N-m	Power, W
37	0.032	0.12	54	0.038	0.21	73	0.041	0.31	94	0.047	0.46
139	0.029	0.43	165	0.034	0.59	192	0.037	0.75	222	0.042	0.97
231	0.026	0.63	265	0.030	0.83	301	0.034	1.06	338	0.037	1.31
314	0.023	0.76	355	0.026	0.97	397	0.030	1.25	442	0.032	1.49
387	0.020	0.81	431	0.023	1.02	482	0.026	1.32	533	0.029	1.60
451	0.017	0.80	504	0.020	1.03	557	0.022	1.30	611	0.025	1.58
505	0.014	0.74	562	0.016	0.97	619	0.019	1.23	677	0.021	1.50
550	0.011	0.65	609	0.013	0.84	670	0.015	1.07	732	0.017	1.31
585	0.008	0.52	647	0.010	0.68	709	0.012	0.86	772	0.013	1.06
610	0.006	0.37	674	0.007	0.49	738	0.008	0.63	802	0.009	0.79
627	0.003	0.19	691	0.004	0.27	755	0.005	0.36	819	0.005	0.46
634	0.000	0.01	700	0.000	0.03	764	0.001	0.08	832	0.001	0.13

Table C.2: Experimental results of average heat source temperature 71.1°C, 83.6°C, 90.6°C, 96.1°C and working fluid mass flow rate setting 223.0 kg/h

Average heat source temperature 71.1°C		
Average working fluid mass flow rate 228.8 kg/h		
Speed, RPM	Torque, N-m	Power, W
95	0.049	0.49
268	0.045	1.27
425	0.041	1.83
566	0.036	2.15
691	0.032	2.32
799	0.027	2.29
891	0.022	2.09
967	0.018	1.82
1,027	0.013	1.39
1,071	0.009	0.99
1,099	0.004	0.51
1,112	0.000	0.04

Average heat source temperature 83.6°C		
Average working fluid mass flow rate 240.3 kg/h		
Speed, RPM	Torque, N-m	Power, W
127	0.057	0.76
316	0.053	1.74
486	0.047	2.40
639	0.042	2.79
773	0.036	2.94
891	0.031	2.89
990	0.026	2.75
1,073	0.021	2.37
1,136	0.016	1.92
1,183	0.011	1.38
1,211	0.006	0.76
1,224	0.001	0.07

Average heat source temperature 90.6°C		
Average working fluid mass flow rate 221.2 kg/h		
Speed, RPM	Torque, N-m	Power, W
162	0.060	1.02
366	0.054	2.05
550	0.048	2.78
714	0.042	3.16
859	0.037	3.31
985	0.032	3.27
1,092	0.027	3.09
1,178	0.022	2.67
1,247	0.016	2.15
1,295	0.012	1.57
1,324	0.007	0.91
1,336	0.001	0.19

Average heat source temperature 96.1°C		
Average working fluid mass flow rate 237.9 kg/h		
Speed, RPM	Torque, N-m	Power, W
202	0.068	1.43
419	0.062	2.72
616	0.056	3.61
792	0.05	4.15
946	0.044	4.36
1,080	0.038	4.30
1,193	0.032	4.00
1,286	0.026	3.50
1,357	0.02	2.84
1,407	0.014	2.06
1,437	0.008	1.20
1,447	0.002	0.30

Table C.3: Experimental results of average heat source temperature 73.4°C, 83.4°C, 91.4°C, 96.5°C and working fluid mass flow rate setting 298.0 kg/h

Average heat source temperature 73.4°C		
Average working fluid mass flow rate 302.2 kg/h		
Speed, RPM	Torque, N-m	Power, W
143	0.103	1.54
402	0.092	3.88
638	0.082	5.45
849	0.072	6.38
1,037	0.063	6.80
1,199	0.053	6.65
1,337	0.044	6.23
1,451	0.036	5.46
1,541	0.027	4.33
1,607	0.019	3.11
1,649	0.009	1.58
1,668	0.001	0.11

Average heat source temperature 83.4°C		
Average working fluid mass flow rate 292.3 kg/h		
Speed, RPM	Torque, N-m	Power, W
190	0.113	2.25
474	0.102	5.03
729	0.090	6.89
959	0.080	8.00
1,160	0.069	8.44
1,337	0.059	8.19
1,485	0.051	7.98
1,609	0.040	6.72
1,704	0.030	5.44
1,774	0.021	3.93
1,817	0.011	2.14
1,836	0.001	0.21

Average heat source temperature 91.4°C		
Average working fluid mass flow rate 296.2 kg/h		
Speed, RPM	Torque, N-m	Power, W
243	0.120	3.05
549	0.110	6.31
824	0.099	8.53
1,071	0.087	9.73
1,289	0.076	10.31
1,478	0.066	10.15
1,638	0.056	9.59
1,768	0.045	8.32
1,870	0.034	6.63
1,942	0.024	4.87
1,985	0.013	2.78
2,003	0.003	0.58

Average heat source temperature 96.5°C		
Average working fluid mass flow rate 313.4 kg/h		
Speed, RPM	Torque, N-m	Power, W
302	0.127	4.03
628	0.119	7.83
924	0.108	10.41
1,188	0.097	12.07
1,420	0.087	12.90
1,620	0.072	12.27
1,790	0.064	11.95
1,929	0.052	10.45
2,036	0.042	8.90
2,110	0.028	6.16
2,155	0.016	3.61
2,170	0.005	1.05

Table C.4: Experimental results of average heat source temperature 72.6°C, 83.6°C, 91.6°C, 95.4°C and working fluid mass flow rate setting 372.0 kg/h

Average heat source temperature 72.6°C			Average heat source temperature 83.6°C			Average heat source temperature 91.6°C			Average heat source temperature 95.4°C		
Average working fluid mass flow rate 387.7 kg/h			Average working fluid mass flow rate 382.3 kg/h			Average working fluid mass flow rate 389.4 kg/h			Average working fluid mass flow rate 378.1 kg/h		
Speed, RPM	Torque, N-m	Power, W	Speed, RPM	Torque, N-m	Power, W	Speed, RPM	Torque, N-m	Power, W	Speed, RPM	Torque, N-m	Power, W
208	0.106	2.31	306	0.145	4.65	427	0.152	6.82	576	0.153	9.23
426	0.096	4.29	565	0.130	7.72	732	0.138	10.55	926	0.135	13.09
625	0.087	5.70	802	0.118	9.88	1,007	0.126	13.26	1,243	0.121	15.73
805	0.077	6.50	1,015	0.103	10.91	1,254	0.112	14.68	1,528	0.106	16.98
965	0.069	6.93	1,205	0.091	11.52	1,475	0.098	15.17	1,780	0.092	17.21
1,107	0.059	6.85	1,371	0.079	11.32	1,668	0.085	14.85	1,998	0.079	16.63
1,229	0.051	6.57	1,514	0.067	10.67	1,831	0.071	13.67	2,185	0.066	15.16
1,331	0.042	5.80	1,632	0.056	9.57	1,968	0.059	12.15	2,339	0.054	13.26
1,415	0.033	4.91	1,729	0.043	7.86	2,078	0.045	9.74	2,460	0.040	10.40
1,489	0.025	3.91	1,802	0.032	5.98	2,159	0.032	7.34	2,548	0.028	7.60
1,523	0.016	2.56	1,851	0.020	3.80	2,212	0.019	4.39	2,604	0.015	4.14
1,549	0.008	1.30	1,878	0.009	1.69	2,238	0.007	1.55	2,629	0.004	1.05

Table C.5: Numerical model form experimental conditions of heat source temperature 70-100^{o}C and working fluid mass flow rate 120-390 kg/h

No.	Average Heat source temperature (^{o}C)	Average Working fluid mass flow rate (kg/h)	Torque (N.m)		Power output (W)	
			Numerical model	R^2	Numerical model	R^2
1	72.4	120.3	$T = -7 \times 10^{-8}N^2 - 4 \times 10^{-7}N + 0.031$	0.986	$P = -8 \times 10^{-6}N^2 + 0.0060\,N - 0.240$	0.904
2	82.3	124.6	$T = -6 \times 10^{-8}N^2 - 7 \times 10^{-6}N + 0.037$	0.982	$P = -8 \times 10^{-6}N^2 + 0.0065\,N - 0.216$	0.861
3	90.6	127.9	$T = -7 \times 10^{-8}N^2 + 5 \times 10^{-6}N + 0.040$	0.983	$P = -9 \times 10^{-6}N^2 + 0.0078\,N - 0.347$	0.865
4	96.1	129.3	$T = -6 \times 10^{-8}N^2 - 1 \times 10^{-6}N + 0.046$	0.979	$P = -9 \times 10^{-6}N^2 + 0.0088\,N - 0.443$	0.850
5	71.1	228.8	$T = -4 \times 10^{-8}N^2 + 5 \times 10^{-6}N + 0.048$	0.986	$P = -8 \times 10^{-6}N^2 + 0.0095\,N - 0.586$	0.886
6	83.6	240.3	$T = -3 \times 10^{-8}N^2 + 3 \times 10^{-6}N + 0.056$	0.982	$P = -7 \times 10^{-6}N^2 + 0.0111\,N - 0.894$	0.858
7	90.6	221.2	$T = -3 \times 10^{-8}N^2 + 6 \times 10^{-6}N + 0.056$	0.980	$P = -8 \times 10^{-6}N^2 + 0.0116\,N - 1.023$	0.851
8	96.1	237.9	$T = -3 \times 10^{-8}N^2 + 1 \times 10^{-5}N + 0.065$	0.979	$P = -9 \times 10^{-6}N^2 + 0.0144\,N - 1.560$	0.848
9	73.4	302.2	$T = -3 \times 10^{-8}N^2 - 7 \times 10^{-6}N + 0.102$	0.984	$P = -1 \times 10^{-5}N^2 + 0.0183\,N - 1.544$	0.873
10	83.4	292.3	$T = -3 \times 10^{-8}N^2 - 2 \times 10^{-6}N + 0.111$	0.981	$P = -1 \times 10^{-5}N^2 + 0.0211\,N - 2.234$	0.860
11	91.4	296.2	$T = -3 \times 10^{-8}N^2 + 8 \times 10^{-6}N + 0.116$	0.981	$P = -1 \times 10^{-5}N^2 + 0.0241\,N - 3.206$	0.856
12	96.5	313.4	$T = -3 \times 10^{-8}N^2 + 2 \times 10^{-5}N + 0.119$	0.976	$P = -1 \times 10^{-5}N^2 + 0.0281\,N - 4.750$	0.831
13	72.6	387.7	$T = -4 \times 10^{-8}N^2 - 3 \times 10^{-6}N + 0.100$	0.988	$P = -1 \times 10^{-5}N^2 + 0.0195\,N - 1.942$	0.899
14	83.6	382.3	$T = -4 \times 10^{-8}N^2 + 1 \times 10^{-5}N + 0.105$	0.986	$P = -1 \times 10^{-5}N^2 + 0.0288\,N - 3.610$	0.890
15	91.6	389.4	$T = -3 \times 10^{-8}N^2 + 2 \times 10^{-5}N + 0.106$	0.984	$P = -2 \times 10^{-5}N^2 + 0.0347\,N - 5.685$	0.884
16	95.4	378.1	$T = -3 \times 10^{-8}N^2 + 2 \times 10^{-5}N + 0.104$	0.984	$P = -2 \times 10^{-5}N^2 + 0.0395\,N - 7.728$	0.872

Appendix D

Test Rig Drawing and Construction Cost

ลิขสิทธิ์มหาวิทยาลัยเชียงใหม่
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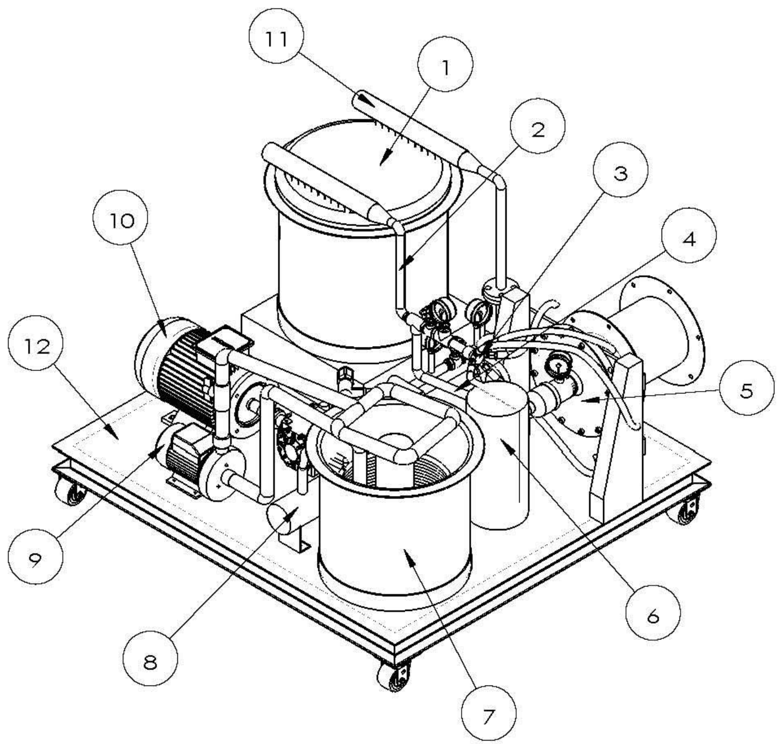

Number	List
1	Vapor Generator Set
2	Vapor Header
3	Vapor Distributor
4	Bypass Vapor
5	Turbine Set
6	Pressure Reducer Tank
7	Condenser Set
8	Liquid Receiver Tank
9	Water Cooling Condenser Set
10	Liquid Pump Set
11	Liquid Header
12	Base

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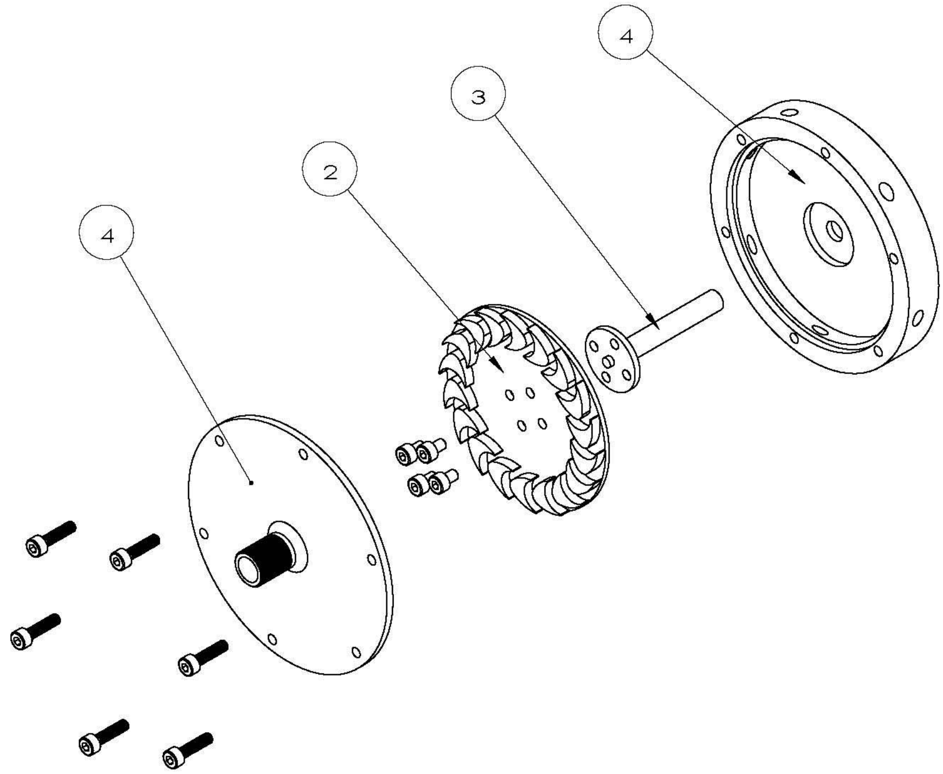
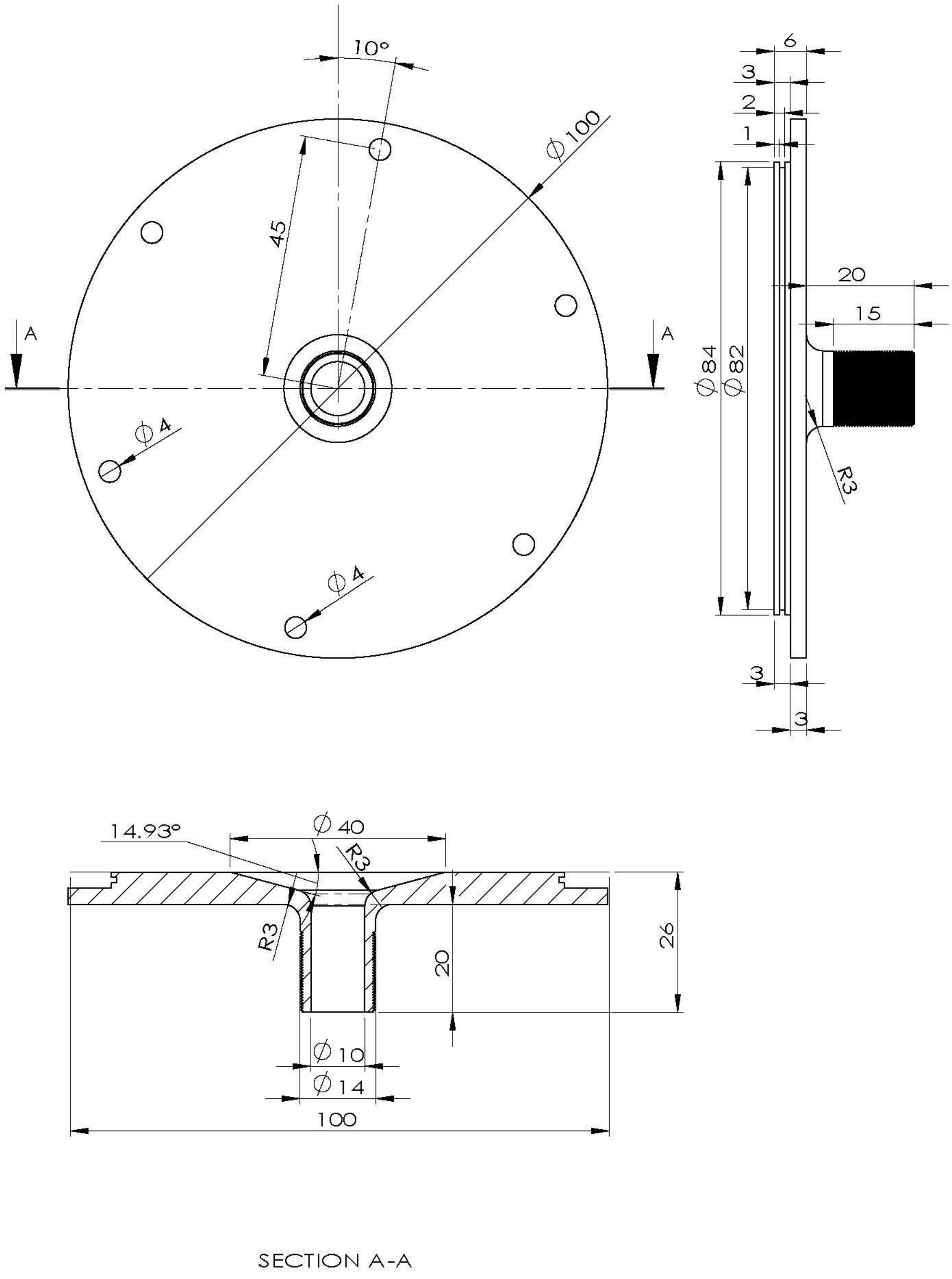
TITLE : Low pressure turbine assembly

DN.BY Pattanachok	Plate 00	Date
Scale 1 : 15	Material	Appoved



4	ฐาน Turbine	
3	แกนหมุน	
2	Turbine	
1	ฝาปิด	
หมายเลข	**รายการ**	**หมายเหตุ**

มาตราส่วน	**ชื่อชิ้นงาน**	**หมายเลขแบบ**
1:2	Turbine Assembly	0000



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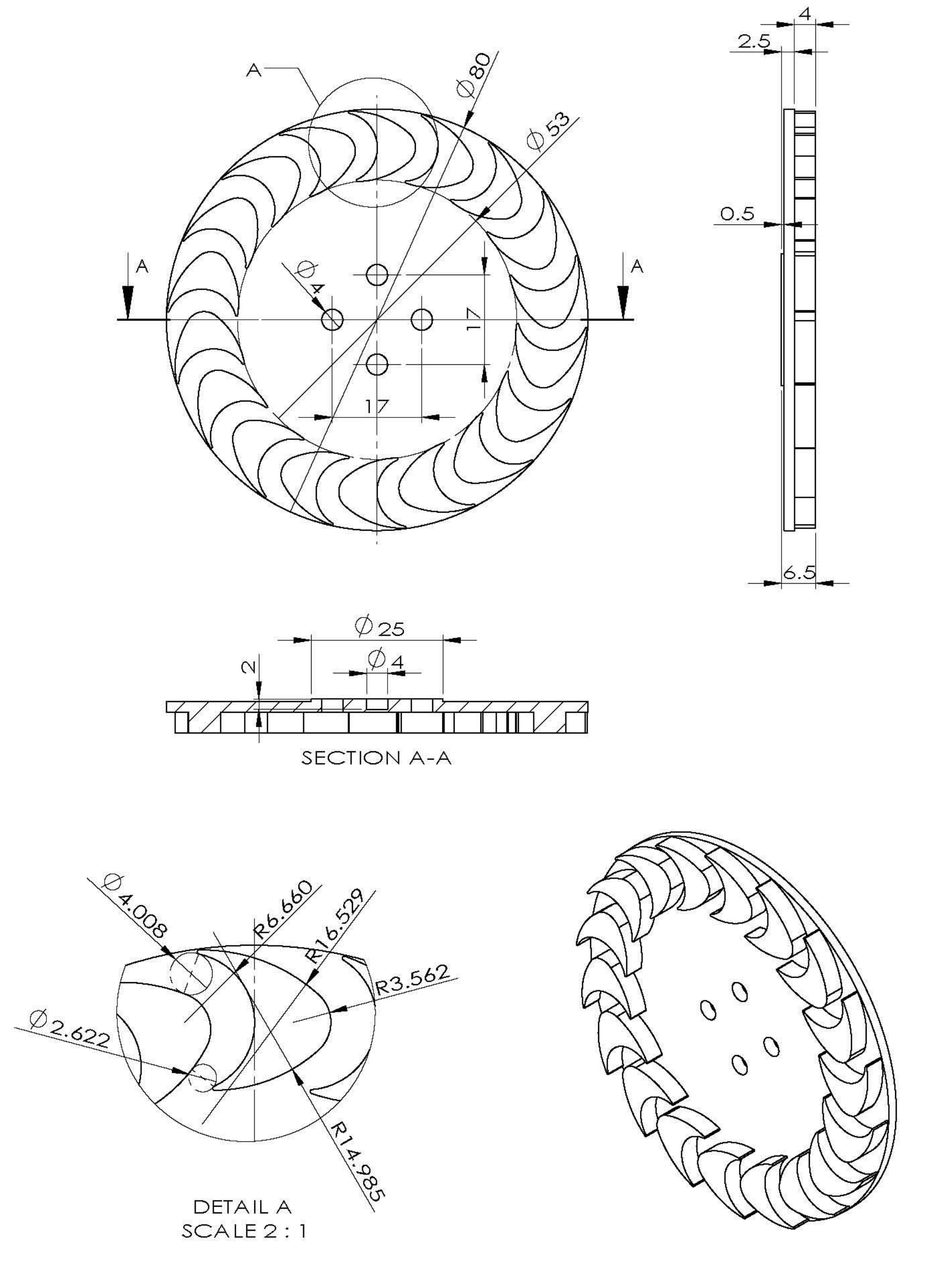
1:1	ฝาปิด	0001



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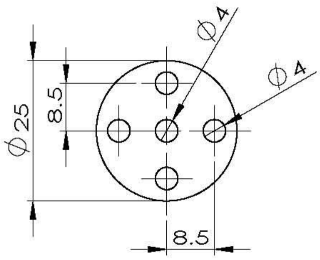
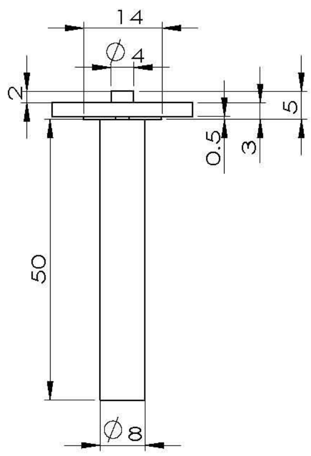
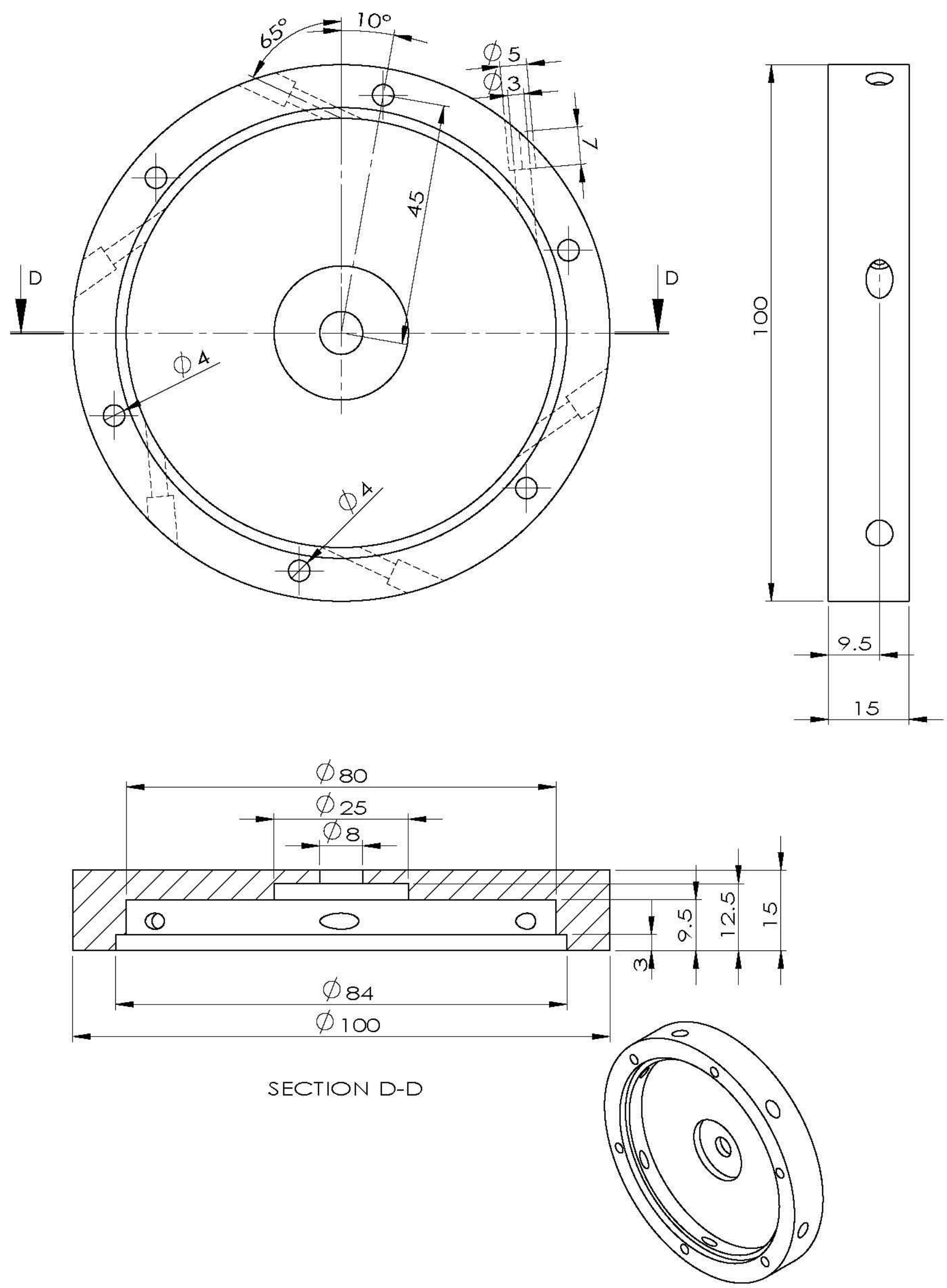
1:1	Turbine	0002





มาตราส่วน	**ชื่อชิ้นงาน**	**หมายเลขแบบ**
1:1	แกนหมุน	0003



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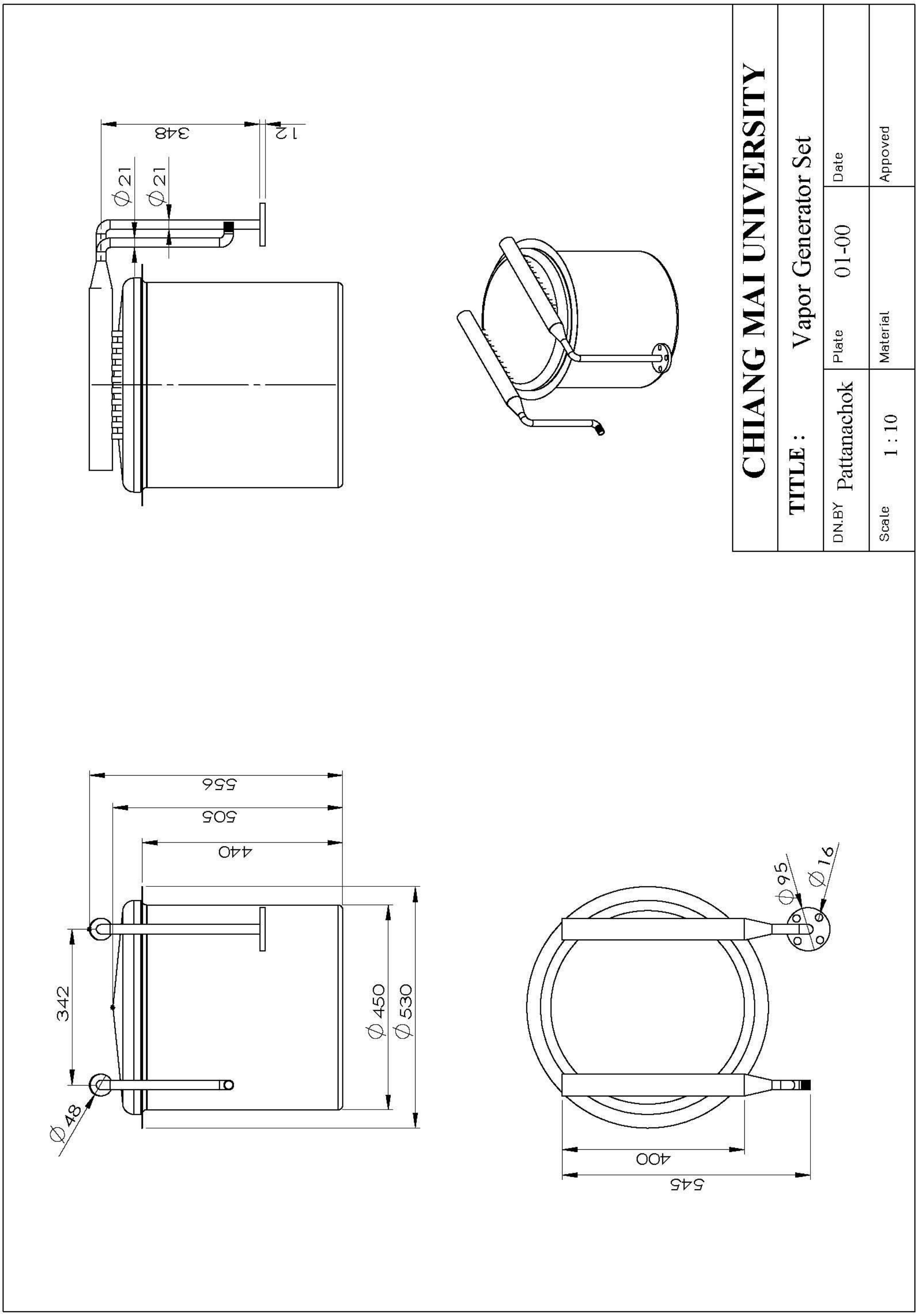
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Date
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Appoved
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Ø21
556
505
440
342
Ø48
Ø450
Ø530
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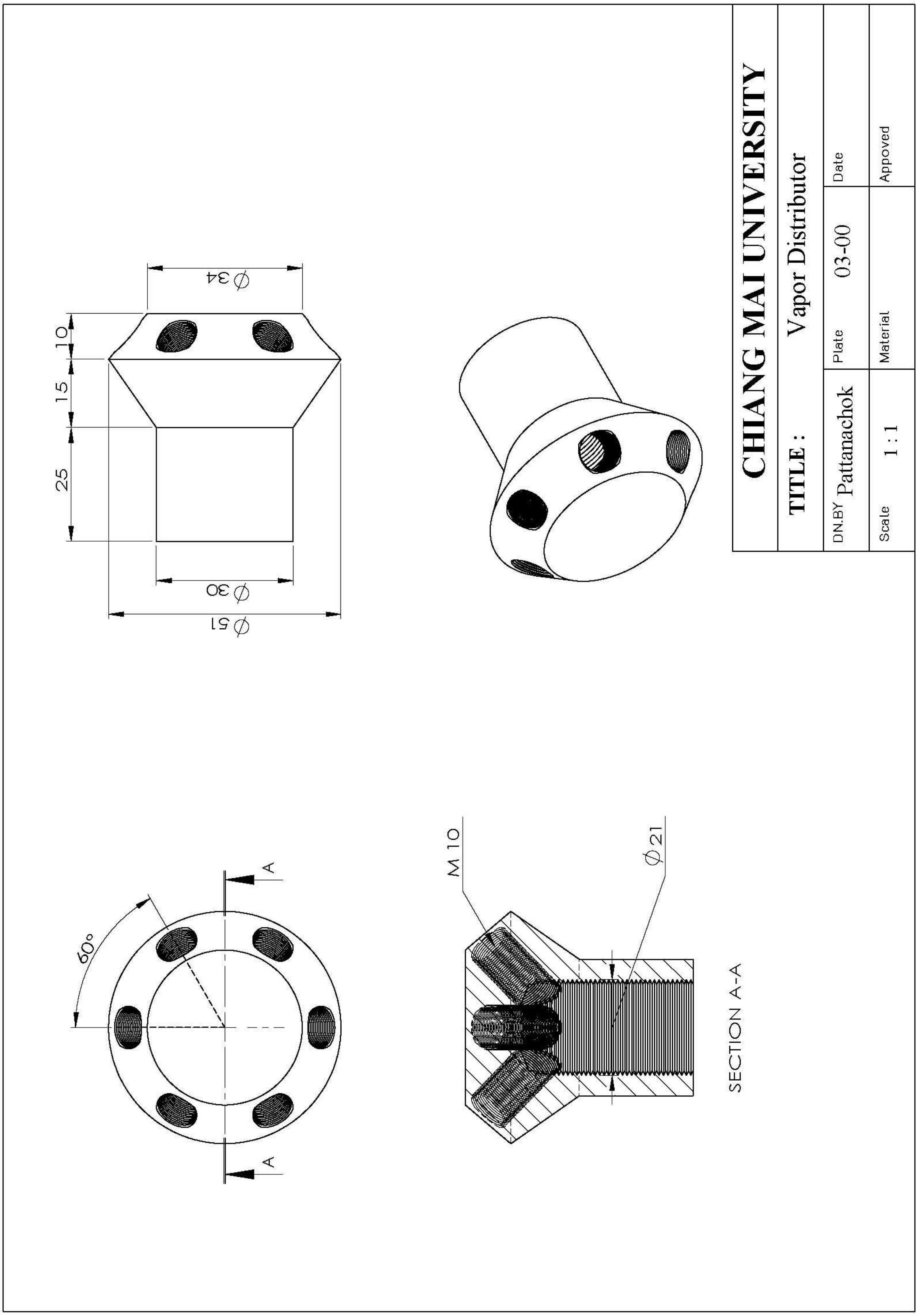
Ø16
400
545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TITLE :
Vapor Distributor
DN.BY
Pattanachok
Plate
03-00
Date
Scale
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Material
Appoved
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10
15
25
∅30
∅51
60°
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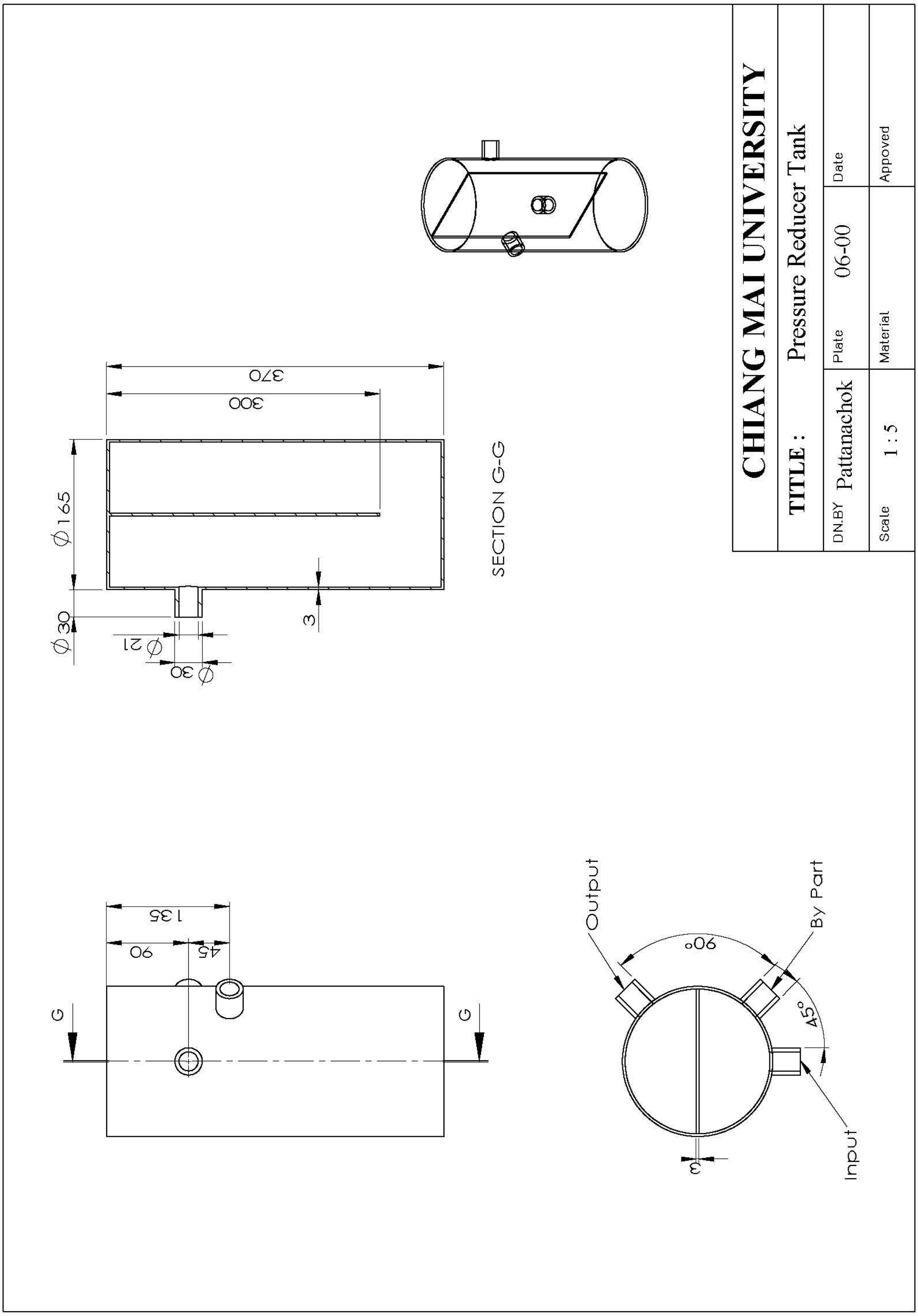
A
M10
∅21
SECTION A-A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TITLE :
Pressure Reducer Tank
DN.BY
Pattanachok
Plate
06-00
Date
Scale
1 : 5
Material
Appoved
SECTION G-G
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Ø165
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Ø21
Ø30
3
135
90
45
G
G
Output
By Part
Input
90°
45°
3

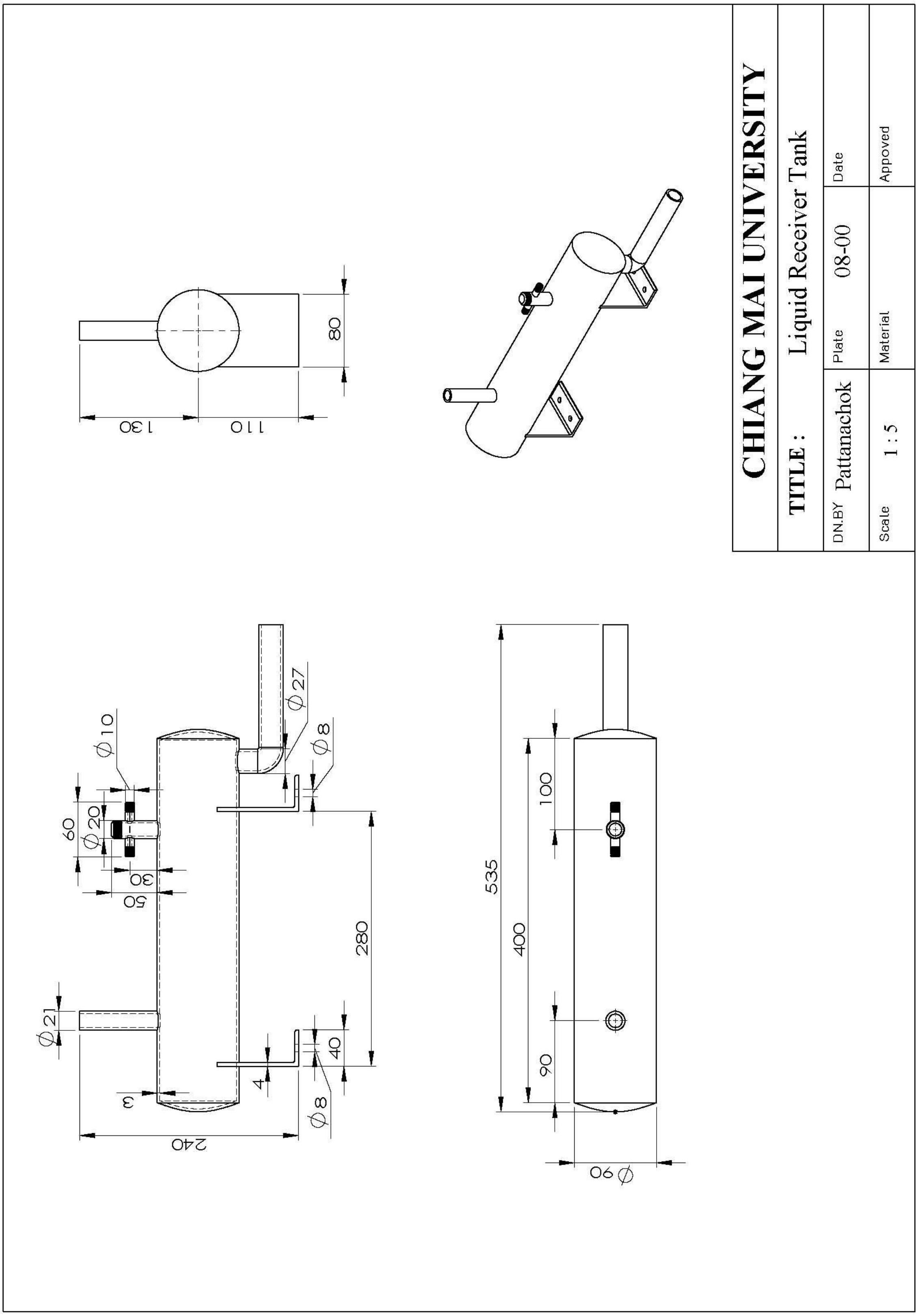
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Plate 08-00
Date
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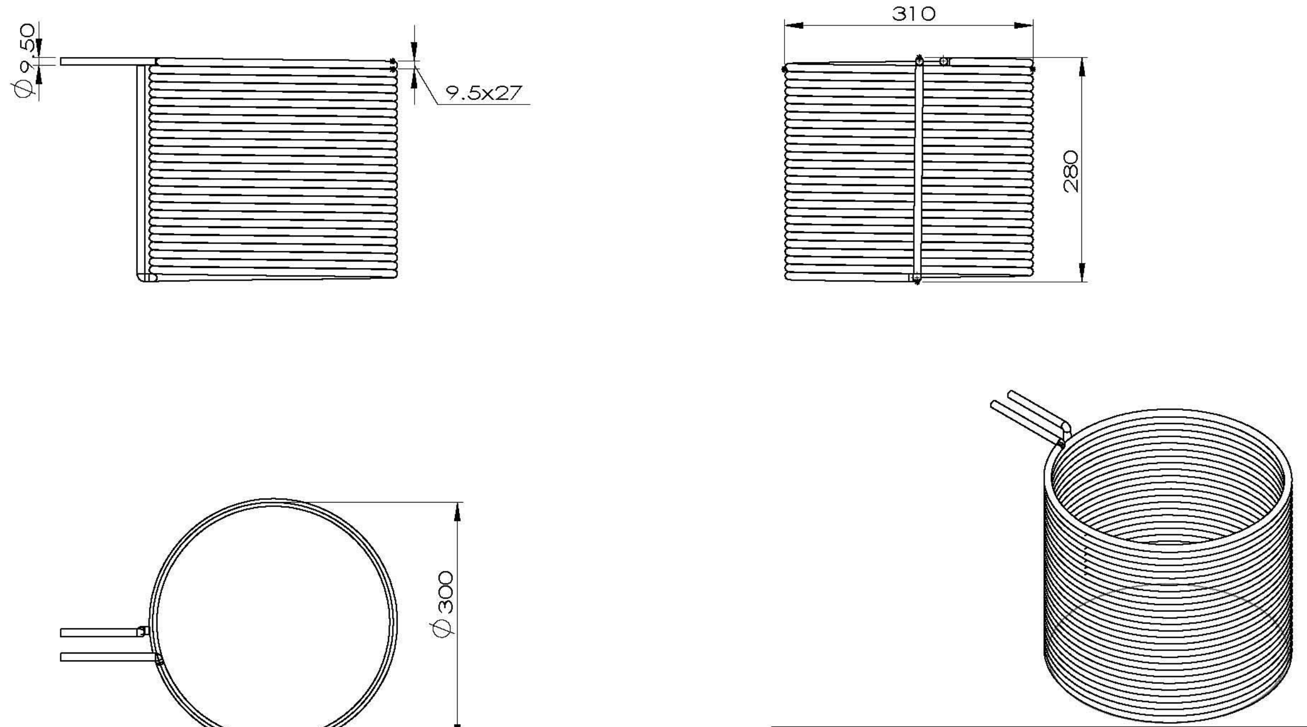
535
400
100
90
Ø90



CHIANG MAI UNIVERSITY					
TITLE :	Condensor Pipe				
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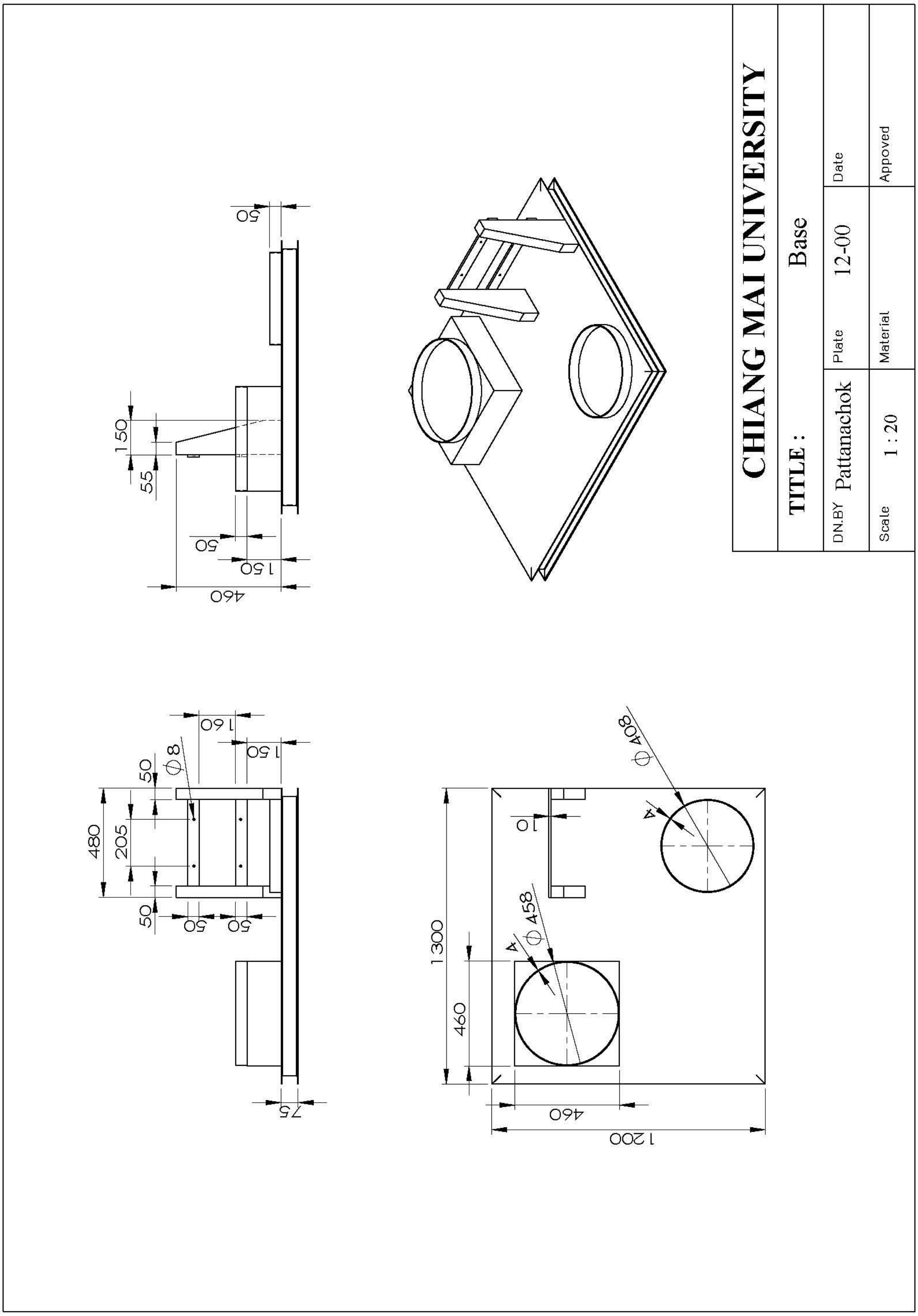

Table C1: List of test rig construction cost detail

Test rig construction cost			
No.	Description	Cost	
		Baht	$
1	Vapor generator set	30,000	925
2	Vapor header	1,500	46
3	Vapor distributer	1,000	31
4	Bypass vapor pipe	500	15
5	Turbine set	30,000	925
6	Pressure reducer tank	2,000	62
7	Condenser set	30,000	925
8	Liquid receiver tank	4,000	123
9	Water cooling condenser set	10,000	308
10	Liquid pump (working fluid pump)	10,000	308
11	Liquid header	1,500	46
12	Test rig base	20,000	617
13	Pipe and fitting	9,500	293
14	Labor cost	50,000	1,542
	Total	200,000	4,625

http://www.bot.or.th/Thai/Statistics/FinancialMarkets/ExchangeRate/_layouts/Application/ExchangeRate/ExchangeRate.aspx

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Appendix E

List of Publications

ลิขสิทธิ์มหาวิทยาลัยเชียงใหม่
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International Journal

1) **Saiai, P.**, Chaitep, S., Bundhurat, D., and Wattanawanyoo, P., (2014). An Experimental Investigation of Vapor Generator Characteristics in a Low-Pressure Turbine Engine, **Indian Journal of Science and Technology,** Vol.7 (8), **PP: 1130-1136.**
2) **Saiai, P.,** Chaitep, S., Bundhurat, D., and Wattanawanyoo, P., (2014)**, Experimental study and performance evaluation of an Organic Rankine Cycle using micro radial turbine, International Journal of Applied Engineering Research,** Vol.9 (16), PP: 3853-3862.
3) **Saiai, P.**, Chaitep, S., Bundhurat, D., and Wattanawanyoo, P., (2014), Effects of Vapor Generator on Organic Rankine Cycle for Low Temperature Heat Source, Int. J. of Emerging Technology and Advanced Engineering, Vol.4(1), PP: 656-662.

International Conference

4) **Pattanachok Saiai**, Sumpun Chaitep, Damorn Bundhurat, and Pipatpong Watanawanyoo, Performance Assessment and Thermal Efficiency of a Compact Vaporizers Used in Low Pressure Turbine Cycle, the 2013 International National Conference on Alternative Energy in Developing Countries and Emerging Economies (2013 AEDCEE), 30-31 May 2013, Pullman Bangkok King Power, Bangkok, Thailand.

National Journal

5) **Saiai, P.**, Chaitep, S., Bundhurat, D., and Wattanawanyoo, P., (2014), Design and Testing of Vapor Generator for Low Pressure Turbine, Journal of Engineering and Technology, College of Engineering, Rungsit University, (in-Thai), Vol.16 (2), **PP: 10-18**

National Conference

6) **Saiai, P.**, Chaitep, S., Bundhurat, D., Na Lampang, T., and Wattanawanyoo, P., (2013), Preliminary Design and Experimental Studies of Low Pressure Turbine for Organic Rankine Cycle Engine, National Conference on 12^{th} Heat and Mass Transfer in Equipment and Process, March, 14-15, Imperial Golden Triangle Resort Hotel, Chiang Rai, Thailand., PP: 275–280.

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Indian Journal of
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TECHNOLOGY
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Rod
Frame work
Spherical
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Treadmill
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ISSN (Print) : 0974-6846
ISSN (Online) : 0974-5645

An Experimental Investigation of Vapor Generator Characteristics in a Low-pressure Turbine Engine

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[2]Mechanical Engineering Program, College of Engineering, Rangsit University, Pathumthanee, 12000, Thailand; tum1879@hotmail.com

Abstract

This paper proposes an experiment using a vapor generator for a low-temperature heat source to drive a turbine engine. The system consists of a heat source to heat the water in the vapor generator apparatus, and thus heating the water in the system of the working fluid increases the vapor turbine driving force. In this study, HCFC-141b is used as a working fluid in the system because it has better thermo-physical properties, is a non-flammable liquid, is non-destructive to the atmosphere, and has a high molecular mass and low boiling point. The experimental conditions comprised operating temperatures of 70 to 100°C and a starting temperature of 30°C. The variables studied were the heating rate of vapor generator, mass flow rate of the working fluid flow through the vapor generator, inlet and outlet temperatures and pressures through the flow vapor generator, and power output. These results were recorded to determine the performance and thermal efficiency of the vapor generator in the vaporized for driving the turbine. The results of this study show the potential of using a vapor generator for small-scale electricity production.

Keywords: Low-Temperature Heat Source, Low-pressure Turbine, Organic Rankine Cycle, Vapor Generator

1. Introduction

In recent years, the escalating consumption of fossil fuels has caused many serious environmental problems, such as global warming, ozone layer destruction, and atmospheric pollution. New energy conversion technologies are required to utilize energy resources suitable for power generation without causing environmental pollution. Low-temperature heat sources are considered as candidates for the new energy sources. Solar heat, waste heat, and geothermal energy are typical examples of low-temperature heat sources with their available temperatures ranging between 60 to 200°C [1]. The use of such low-temperature heat sources as an alternative energy source to generate electricity has long been investigated using power turbine cycles. The temperature of the exhaust from most industrial processes and power plants is less than 370°C. If this kind of waste heat is released into the environment directly, it leads to not only waste but also heat pollution to the environment[2,3].

The Organic Rankine Cycle (ORC) system exhibits great flexibility, high safety, and low maintenance requirements in recovering this grade of waste heat. By integrating the ORC into energy systems, such as power plants, the use of low-grade energy to generate high grade energy (power) could be achieved, easing the power burden, and enhancing system efficiency[4]. Since the ORC consumes virtually no additional fuel, for the same added power, the emission of environmental pollutants such as Carbon Dioxide (CO_2), Sulphur Dioxide (SO_2), and so on will be decreased. Moreover, according to the local demand, the exhaust heat exiting from the ORC could be

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To,

Mr. Pattanachok Saiai,

Subject: Acceptance of your paper for IJAER

Dear **Pattanachok Saiai,**

We are very pleased to inform you that your following paper:-

Paper Title: Experimental study and performance evaluation of an Organic Rankine Cycle using micro radial turbine.

Author's: Pattanachok Saiai,a,* Sumpun Chaitep,a Damorn Bundhurat,a Pipatpong Watanawanyoob

Paper Code: 25146 : IJAER

is peer reviewed and accepted by our Editor for publication in our international journal **International Journal of Applied Engineering Research. Print ISSN 0973-4562**
Again many thanks for giving us the opportunity to publish your work in our journal.

With kind regards,

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Experimental Study and Performance Evaluation of an Organic Rankine Cycle Using Micro Radial Turbine

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Abstract

This paper proposes an experiment using a vapor generator for a low-temperature heat source to drive a turbine engine. The system consists of a heat source to heat the water in the vapor generator apparatus, and thus heating the water in the system of the working fluid increases the vapor turbine driving force. In this study, HCFC-141b is used as a working fluid in the system because it has better thermo-physical properties, is a non-flammable liquid, is non-destructive to the atmosphere, and has a high molecular mass and low boiling point. The experimental conditions comprised operating temperatures of 70 to 100 ^{o}C and a starting temperature of 30 ^{o}C. The variables studied were the heating rate of vapor generator, mass flow rate of the working fluid flow through the vapor generator, inlet and outlet temperatures and pressures through the flow vapor generator, and power output. These results were recorded to determine the performance and thermal efficiency of the vapor generator in the vaporized for driving the turbine. The results of this study show the potential of using a vapor generator for small-scale electricity production.

Keywords: low-pressure turbine, organic Rankine cycle, vapor generator, low-temperature heat source

Introduction

In recent years, the escalating consumption of fossil fuels has caused many serious

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Date: February 03, 2014

Acceptance Letter

Author Name	**Pattanachok Saiai, Sumpun Chaitep, Damorn Bundhurat, Pipatpong Watanawanyoo**
Paper ID:	**IJETAE_0114_251**
Paper Title	**Effects of Vapor Generator on Organic Rankine Cycle for Low Temperature Heat Source**

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Effects of Vapor Generator on Organic Rankine Cycle for Low Temperature Heat Source

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[2]*Assoc.Prof.,* [3]*Lect., Department of Mechanical Engineering, Chiang Mai University, Thailand.*
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Abstract – This paper proposes an experimental study of the vapor generator for low temperature and low pressure to drive a micro–turbine engine. The thermodynamic performances of an ORC system under this designed configuration have been analyzed. The vapor generator constructed from copper tube. The turbine consisted of a single stage radial impulse turbine with a rotor diameter of 80 mm and 18 blades. The blade thickness was 4 mm. and radial blade width is 10 mm. The turbine designed to the incline angle of the nozzle is 25 degree with respect to the tangential line. The working fluid selected is HCFCs-141b (1,1-Dichloro-1-fluoroethane) is used in the system, which preferable thermo - physical properties, i.e., non-flammable liquid, non-destructive to the atmosphere, high molecular mass and a low boiling point. Experiment was conducted with following set up conditions, i.e., of operating temperatures between 90°C - 100°C, as well as at the starting heat of 30°C. The variables parameters were observed, i.e., heat rate of vapor generator, mass flow rate of working fluid flow through the vapor generator, inlet and outlet temperature and pressure through the flow vapor generator, and power output. These were being recorded in order to determine the performance and thermal efficiency of the vapor generator. The results in this study show the potential of using a vapor generator for the driving of a low pressure turbine cycle in a small electricity production.

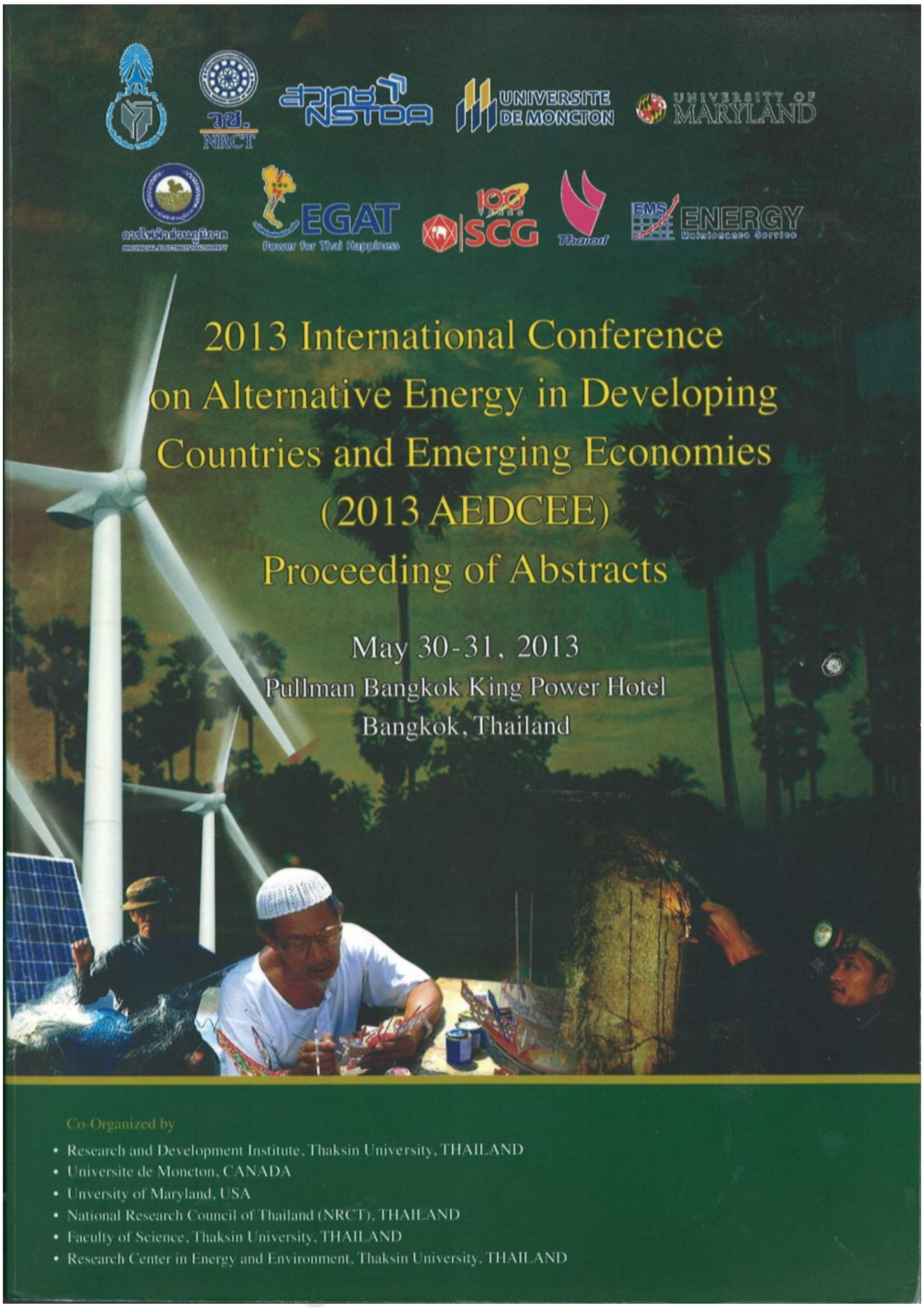
Keywords **–** low pressure turbine, organic Rankine cycle, vapor generator, low temperature heat source

I. INTRODUCTION

The present day energy situation of the world is beginning into crisis. As the energy demand is rapidly increase and with escalating rate the future. International Energy Agency (IEA) predicts the energy demand of the world in 17 years (2030) in the future, that it will be increased 2 in 3 parts of energy demand in present or 9,179 Mtoe. [1] The research and development of heat energy ~~for~~ from other source such as geothermal energy, exhaust gas from engine, waste heat from industrial or solar energy to achieve maximum benefit with a closed loop Rankine cycle which uses organic chemical (ORC) and change heat energy at low temperature to electric energy. The use of these heat sources could be studied [2]. This approach is particularly interesting to development of energy production system.

Maizza *et al.*, (2001) [3] reported that the fluid thermodynamic characteristics give rise to thermodynamic limitations to the amount of energy that can be extracted from the heat source. Some refrigerants satisfy the above mentioned criteria more than the others. One such refrigerant is HFCs-245fa. Liu *et al*, (2002) [4] reported performed a simulation on an ORC with various working fluids for a hot temperature of 150°C and a cold temperature of 30°C. It turned out in this simulation that HCFCs-123 had a slightly better efficiency than iso-pentane. HFCs-245fa and n-pentane were not taken into account in that study. Badr et. al., [5] was developed ORC machine including of working fluid and amplifier device. From the research of variables design of Lee et., al., [6] concluded that saturated vapor temperature in evaporator, condense temperature at condenser, and superheated vapor temperature from high heat vapor generator are important to the economics of energy recovery system. Hung et. al., [7] is studied dry working fluid for ORC which use waste heat recovery and the efficiency of system. This cycle was uses low temperature working substance such as benzene, ammonia, CFCs-11, CFCs-12, HFCs-134a and CFCs-113. Furthermore, there are the other researches which use Rankine organic cycle with other cycle such as solar energy using, space energy cycle, geothermal energy, other efficiency energy using.

The organic Rankine cycle (ORC) system exhibits great flexibility, high safety, and low maintenance requirements in recovering this grade of waste heat. Integrating the ORC to the energy system, such as power plants, could achieve using low grade energy to generate high grade energy (power), easing the power burden, and enhancing system efficiency [8]. Since the ORC consumes virtually no additional fuel, for the same added power, the emission of environmental pollutants such as carbon dioxide (CO_2), sulfur dioxide (SO_2) and so on will be decreased. Moreover, according to the local demand, the exhaust heat exiting from the ORC could be further utilization such as absorption chillers for supplement of cooling capacity.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Monday, 22 April 2013

Dear Pattanachok Saiai,

It is our pleasure to inform you that your paper entitled:

Performance Assessment and Thermal Efficiency of a Compact Vaporizers Used in Low Pressure Turbine Cycle

Pattanachok Saiai, Sumpun Chaitep, Damorn Bundhurat, Pipatpong Watanawanyoo

has been accepted for presentation and publication in the Proceedings of the 2013 International Conference on Alternative Energy in Developing Countries and Emerging Economies (2013 AEDCEE), which will be held on 30-31 May 2013 in Bangkok, Thailand.

Besides the Conference Proceedings, the Technical Committee will review all accepted paper and a selection of papers will be published in a special number of Energy Procedia by Elsevier. We will inform you once a decision will be made on the papers to be published in Energy Procedia.

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We look forward to welcoming, and to meet you in Bangkok, Thailand.

Best regards,

Asst. Prof. Dr. Jompob Waewsak
B.Sc., M.Sc. Ph.D./D.Sc.

General Co-Chair of 2013 AEDCEE

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Session : Wind Energy - Wind Farm Development

Session : Applied Energy

Performance Assessment and Thermal Efficiency of a Compact Vaporizers Used in Low Pressure Turbine Cycle

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[2]Department of Mechanical Engineering, College of Engineering, Rangsit University (*Thailand*)

ABSTRACT

This assessment of performance and thermal efficiency of the compact vaporizer to drive the low pressure micro – turbine, using a low temperature heat source. The system consists of a heat source to heat the water in the vaporizer apparatus, thus heating the water in the system of the working fluid, increases the vapor turbine driving force. In this study the refrigerant HCFC-141b (1,1-Dichloro-1-fluoroethane) as a working fluid is used in the system, because of the better thermo physical properties, non-flammable liquid, non-destructive to the atmosphere, high molecular mass and a low boiling point. Experiment conditions, of temperatures from 80 °C to 100 °C at operating temperature, as well as at the starting heat of 30 °C. The variables study, heat rate of vaporizer, mass flow rate of working fluid flow through the vaporizer, inlet and outlet temperature and pressure through the flow vaporizer, and heat exchanger effectiveness. This is being recorded in order to determine the performance and thermal efficiency of the compact vaporizer in the vapor for driving the turbine. The results in this study are to potential of the using a compact vaporizer for the driving of a low pressure micro – turbine in a small electrical unit.

Keywords: Low pressure micro - turbine, organic rankine cycle, compact vaporizer, heat rate of vaporizer, HCFC-141b (1,1-Dichloro-1-fluoroethane).

Corresponding Author: pattanachok@nnr.nstda.or.th

Certificate of Presentation

This is to certify that

Pattanachok Saiai

has presented during the 2013 International Conference on Alternative Energy in Developing Countries and Emerging Economies which is held 30-31 May 2013, Bangkok, Thailand

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บทความวิจัย

บทความวิชาการ

การออกแบบและทดสอบเครื่องกำเนิดไอสำหรับกังหันแรงดันต่ำ

(Design and Testing of Vapor Generator for Low Pressure Turbine)

พัฒนโชค สายอ้าย[1*], สัมพันธ์ ไชยเทพ[1], ดามร บัณฑุรัตน์[1] และ พิพัฒน์พงศ์ วัฒนวันยู[2]

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บทคัดย่อ

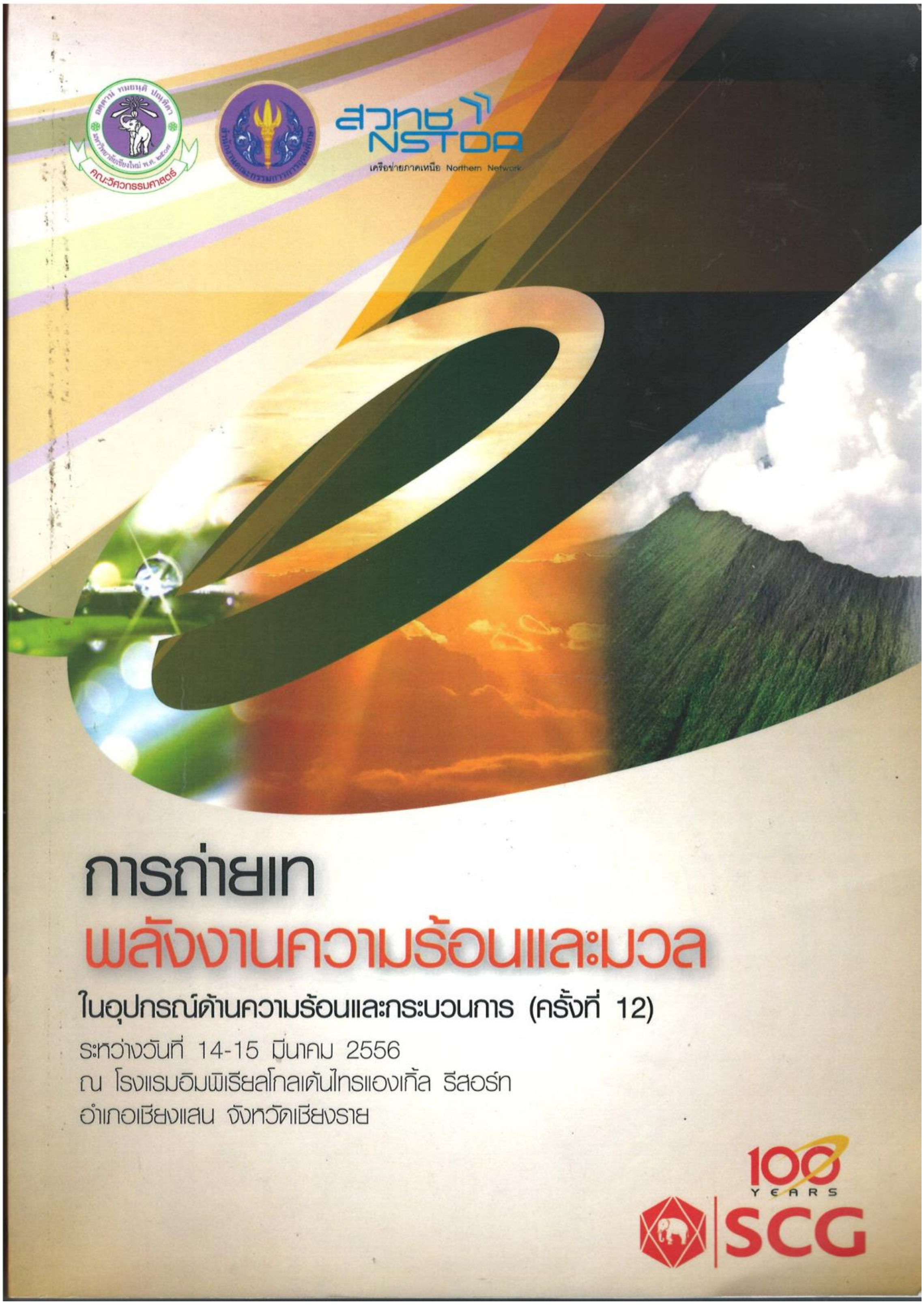
บทความนี้นำเสนอผลการจำลองเชิงตัวเลขและการทดสอบเครื่องกำเนิดไอสำหรับนำไปใช้ขับกังหันไอแรงดันต่ำจากแหล่งความร้อนอุณหภูมิต่ำ โดยที่วัฏจักรแรงคินถูกใช้คำนวณการออกแบบขนาดอุปกรณ์ภายในระบบ ซึ่งประกอบด้วยเครื่องกำเนิดไอ กังหัน ถังลดความดัน เครื่องควบแน่น ถังเก็บสารทำงาน และปั๊ม สารทำงานที่ใช้ทดสอบระบบคือ HCFC-141b ในระบบใช้น้ำเป็นสื่อตัวกลางการจำลองสภาพการทำงานของเครื่องกำเนิดไอที่อุณหภูมิ 70-100 องศาเซลเซียส และอัตราการไหลเชิงมวลของสารทำงาน 112 กิโลกรัมต่อชั่วโมง และทดสอบในสภาวะความดันบรรยากาศ ผลการจำลองเชิงตัวเลขและการทดสอบแล้วมีความเป็นไปได้ในการนำเครื่องผลิตไอมาใช้ผลิตไอร่วมกับการทำงานของระบบกังหันไอแรงดันต่ำได้

คำสำคัญ : กังหันแรงดันต่ำ วัฏจักรแรงคิน แหล่งความร้อนอุณหภูมิต่ำ

ABSTRACT

This paper proposes a numerical simulation and testing of vapor generator for driving of low pressure turbine engines using low temperature heat source. The thermodynamic performances of an LPT system under this designed configuration have been analyzed. The test rig consists of a vapor generator, turbine, reducer tank, condenser, receiver tank, and pump. The working fluid selected is HCFC-141b because of its high molecular mass and high efficiency in run. An experimental study was carried out on a system recovering heat from hot water at temperature ranging from 70-100°C and mass flow rate of working fluid about 112 kg/h. This work is part of the theoretical analysis of the waste heat from various thermal processes. The goal of this research is to develop a numerical modeling for optimize system performance.

Keywords: low pressure turbine, Rankine cycle, low temperature heat source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PRELIMINARY DESIGN AND EXPERIMENTAL STUDIES OF LOW PRESSURE TURBINE FOR ORGANIC RANKINE CYCLE ENGINE

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บทคัดย่อ

บทความนี้จะนำเสนอผลการออกแบบและพัฒนาเครื่องจักรกังหันไอขนาดเล็กโดยใช้แหล่งความร้อนอุณหภูมิต่ำเพื่อผลิตไฟฟ้าโดยใช้สารอินทรีย์เป็นสารทำงานภายใต้วัฏจักรแรงคิน ภายใต้เงื่อนไขการออกแบบได้วิเคราะห์เชิงตัวเลขของกังหันไอแรงดลขนาดเล็กที่มีอุณหภูมิระหว่าง 70-100 องศาเซลเซียส และเลือกทดสอบการจำลองภาระความร้อนที่เครื่องกำเนิดไอมีอุณหภูมิเฉลี่ย 91.0-97.5 องศาเซลเซียส สารทำงานที่เลือกใช้เป็น HCFC-141b (1,1-Dichloro-1-fluoroethane) เนื่องจากมีจุดเดือดต่ำที่ความดันบรรยากาศ มวลโมเลกุลสูง และมีค่าความร้อนแฝงในการกลายเป็นไอสูง ในการศึกษาจะพิจารณาถึง ความดัน อุณหภูมิ แรงบิด และกำลังที่ได้ ผลที่ได้จากการศึกษาเบื้องต้นนี้จะเป็นส่วนหนึ่งของการนำไปประเมินความเป็นไปได้ในการวิเคราะห์เชิงตัวเลขและทางปฏิบัติของการพัฒนาเครื่องจักรไอสำหรับนำความร้อนทิ้งจากกระบวนการทางความร้อนต่าง ๆ ในภาคอุตสาหกรรมกลับมาใช้ประโยชน์ เพื่อนำไปสู่การพัฒนาแหล่งพลังงานไฟฟ้าขนาดย่อมและสร้างเสถียรภาพทางพลังงานที่ยั่งยืนให้กับประเทศต่อไป

คำสำคัญ : กังหันความดันต่ำ วัฏจักรแรงคินใช้สารอินทรีย์ กังหันแรงดล แหล่งความร้อนอุณหภูมิต่ำ

Abstract

This paper proposes a design and development of micro radial impulse turbine using low temperature heat source for driving organic Rankine cycle engines. The thermodynamic performances of an ORC system under this designed configuration have been analyzed. An experimental study was carried out on an ORC recovering heat from hot water at temperature ranging from 80-100°C. The working fluid selected is HCFC-141b (1,1-Dichloro-1-fluoroethane) because of its easy procure, low costs and high efficiency in ORC. In order to achieve results, this experiment has been investigated the effects of pressure, temperature, torque, and power output of the turbine. This work is part of the theoretical analysis of the waste heat from various thermal processes. The goal of this research is to develop a numerical modeling for optimize system performance.

Keywords: low pressure turbine, organic Rankine cycle, radial impulse turbine, low temperature heat source

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Scholarship	Research Graduate Student Grants 2012, Energy Conservation Promotion Fund, Energy Planning Policy Office, Ministry of Energy. Research Graduate Student Grants 2011, Graduate School, Chiang Mai University.
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ลิขสิทธิ์มหาวิทยาลัยเชียงใหม่
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Research Interest: Energy Conversion Technology, Renewable Energy, Drying Technology, Energy Integrated in Equipment.

Qualification: Professional Engineer License (No.3863), Council of Engineering, Thailand.

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