CHAPTER 3

Experimental Setup

This chapter describes about designing, installation and experiment setup of the ORC test rig, proposed in Figure 3.1, is given, focusing on the peculiar features of the main components. For the purpose of this study, a test rig was set up in the N.K. Mechanical Ltd, and the experiment test rig in Propulsion and Aerodynamics Research and Applications Laboratory (PARA Lab) in Chiang Mai University, Thailand. The aim is to proof the feasibility of the low pressure turbine designed on the ORC engine, to evaluate the potential low-temperature heat source convert to mechanical work, and to validate the models of the different components.

3.1 Description of ORC Test Rig

The design choice has been the selection of the working fluid, on the basic of preliminary study (Saiai *et al.*, 2013), HCFC-141b (1,1-dichloro-1-fluoroethane) has been taken into account, for its thermo-physical, environmental and safety features. Since the goal of this work is to achieve a general knowledge of the system and to learn how the controllable variables could affect the performances, a simple cycle has been chosen. In this classical arrangement of a Rankine cycle, the closed loop filled by the working fluid is formed by the pump, the vapor generator, the turbine, and the water cooled condenser, in this order, as show in Figure 3.1, which reports a sketch of the components and the different phases on P-h diagram.

The chosen pump is a reciprocating type, because the piston placed between the fluid chamber and the piston zone ensures both a perfect sealing of the circuit towards environment and the feasibility of high pressure ratio, even pumping a liquid as HCFC-141b that has a very low viscosity and has no lubricant properties. These features make impossible the use of other more common and cheap devices comparable to the reciprocating pump.

A vapor generator has been chosen to vaporize the working fluid; this seemed to be the good solution for an experimental prototype, since it allows setting directly the superheating temperature and reduces the thermal inertia with respect to other vaporizing systems, therefore decreases the time needed to reach an imposed steady state condition. Moreover, an electrical heater features a great flexibility in control strategies, allowing simulating also the dynamic behavior of different real heat sources. The heat source is composed of hot water tank at a temperature ranging from 70°C to 100°C. One line of the hot water flow goes to the vapor generator. The turbine prototype is a constructed from steel plate using CNC milling forming adapted to be run in turbine mode. It can be isolated and bypassed incorporating of 3 ways valves, in order to start the test in appropriate conditions.

The turbine is coupled to a torque measurement meter by the torque arm. The works either in motor mode depending on the power developed by the turbine. An asynchronous machine is chosen for its ability to impose the rotational speed to the turbine. The water cooled condenser is fed with tap water. Figure 3.1(a) shows its configuration with heat exchangers put in test rig. However, several dispositions were tested and will be discussed in the following chapters. The liquid condensate leaving the condenser is then pumped towards the higher pressure vapor generator.

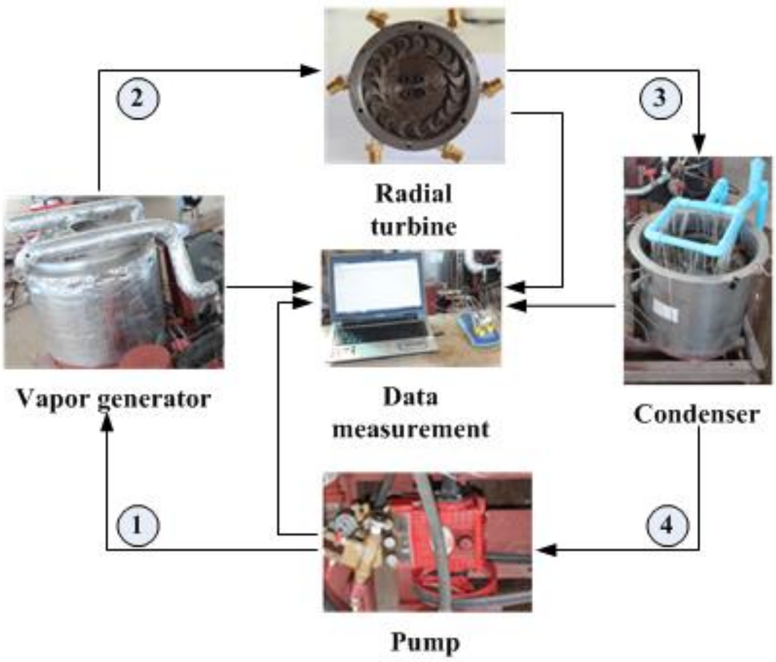


Figure 3.1 (a): ORC test rig diagram

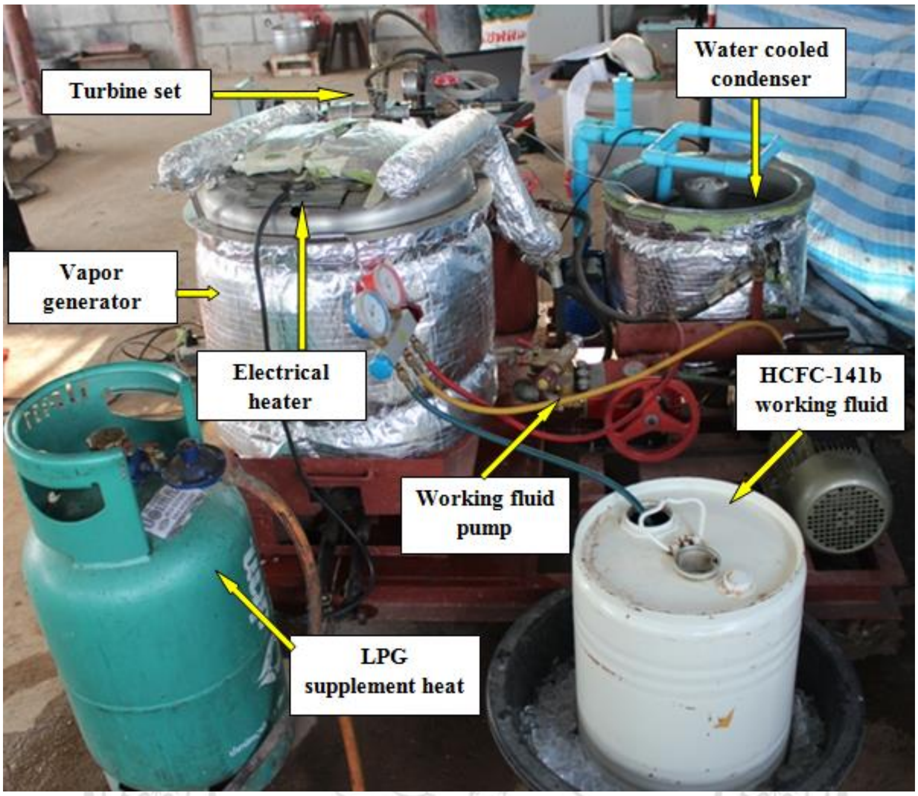


Figure 3.1 (b): ORC test rig

Figure 3.1: Prototype of ORC test rig

Table 3.1: Specifications of ORC system

1. Vapor generator	Heat transfer area 1.517 m^2 and Volume flow rate 0.244 m^3/min
2. Water cooled condenser	Heat transfer area : 0.773 m^2 and Volume flow rate 0.111 m^3/min
3. Impulse radial turbine	Diameter 80 mm. and Thickness 4 mm. and amounts of blade : 18
4. Hot source side	Hot water from LPG and electric heater supplemented and temperature range 70 to 100°C
5. Cold source side	Circulated water and temperature range 10 - 15°C
6. Pump	High pressure reciprocating pump and mass flow rate 112 - 372 kg/h
7. Working fluid	HCFC-141b (1,1-Dichloro-1-fluoroethane), molecular weight 116.95 and the boiling temperature : 32.07°C

3.2 System Component Design and Installation

3.2.1 Turbine

3.2.1.1 Turbine Design and Selection

Figure 3.2 described the characteristic curve of radial and reaction turbine type. In the experiment was selected impulse radial turbine type because easy design and construction. The radial turbine is machines which develop torque and shaft power as a result of a momentum change in the working fluid which flows through them. The working fluids are the saturated vapor or superheat vapor. For the fluid to achieve the high velocity required to provide worthwhile momentum changes, there must be significant pressure differences between the inlet and outlet of the turbine. Sources of pressurized vapor include previously compressed fluid as in a vapor turbine, or in the turbine of a turbocharger for an internal combustion engine. In order to operate the ORC, low-temperature heat source is used to vaporize amounts of working fluid into vapor at low-pressures. A turbine converts the energy of the vapor into work that drives electric generators.

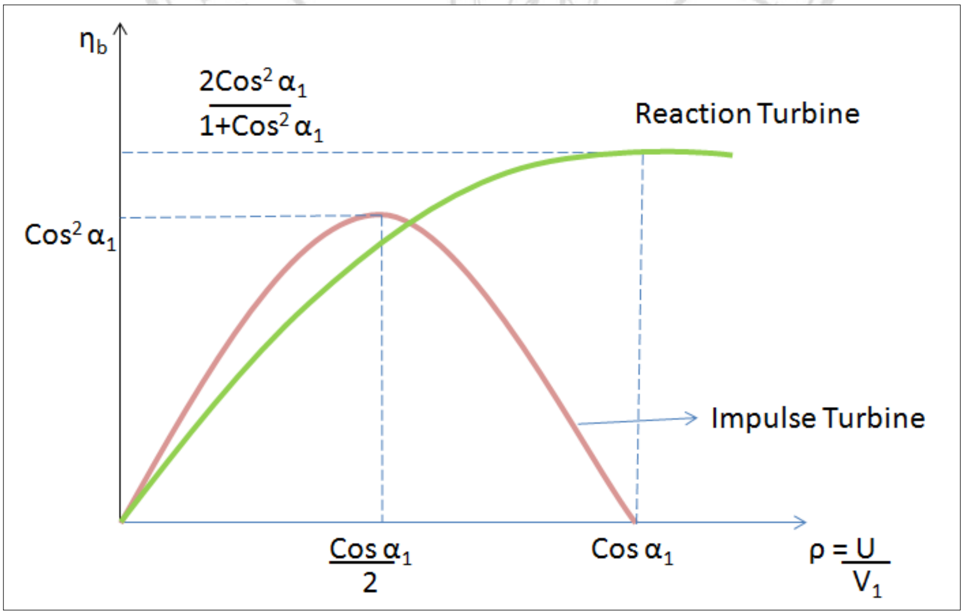
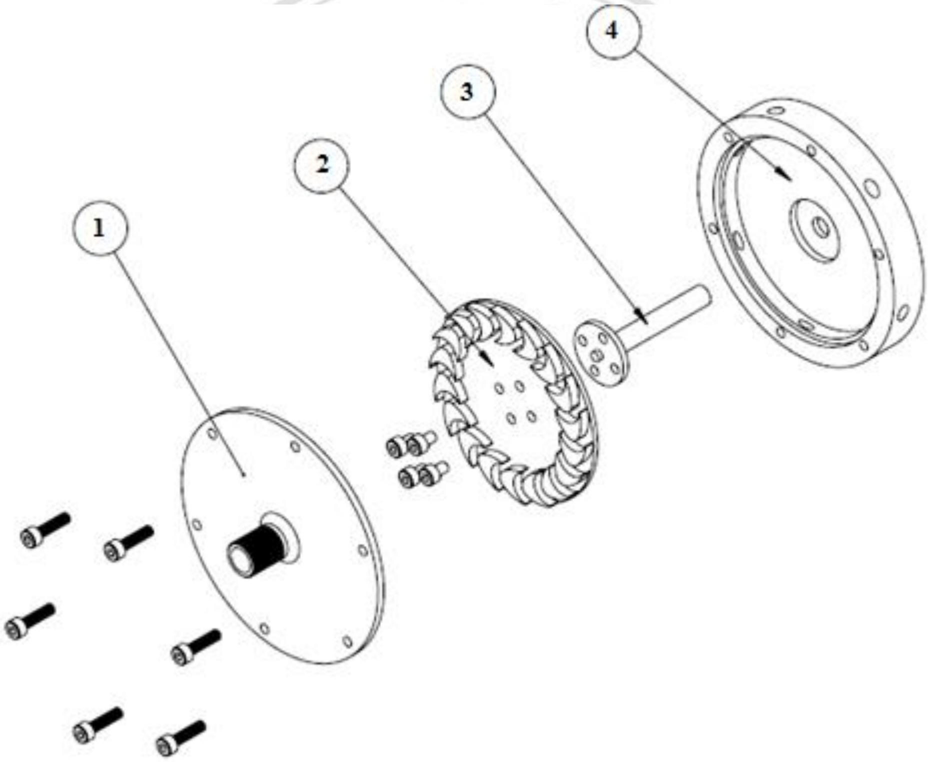


Figure 3.2: Characteristic curves for efficiency of turbines

(Korner, 1982)

3.2.1.2 Turbine Design Concept and Construction

The geometry of the radial turbine under development of this study is shown in Figure 3.3. The vapor of working fluid, in the case of this study, enters the turbine at the circumference and exits the center of the stator. The working fluid then expands radically outward through alternating, concentric stator and rotor blade rows, where its enthalpy drop is converted to shaft power by the rotating blade rows as show in Figure 3.4.



(1) Turbine cover
(2) Turbine blade
(3) Turbine shaft
(4) Turbine case with radials inlet of 6 holes for working fluid vapor

Figure 3.3: Impulse radial turbine designed and constructed

Figure 3.4: Assembly of impulse radial turbine set

Table 3.2: Specification of Micro-radial turbine

Dimension of radial turbine part			
Parts		**unit**	
Nozzle	Total	holes	6
	Inner diameter, D_i	mm	10
	Outer diameter, D_o	mm	3
	Angle, α	degree	25
Rotor	pitch diameter	mm	4
	shaft diameter	mm	8
Turbine blades	total	blades	18
	high	mm	8
	width	mm	13.5
	Angle, β	degree	33.8
	Angle, γ	degree	24.7
	Inside radius, r_i	mm	26.5
	Outside radius, r_o	mm	40
	Radius of curvature, R	mm	6.66
	Blade distance	mm	17

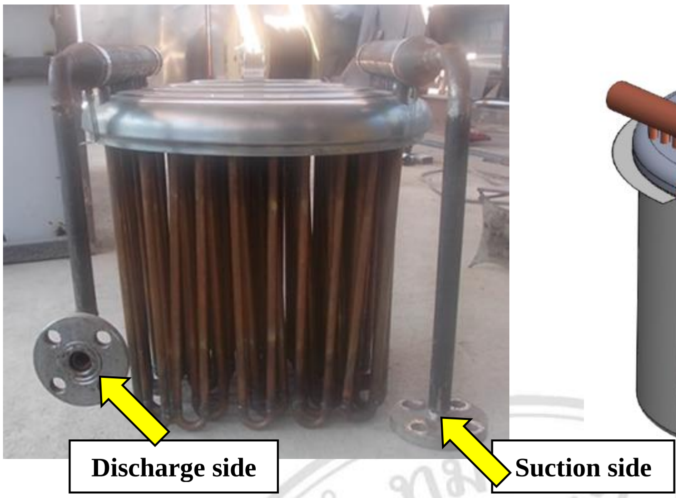
The micro turbine is the only non-positive displacement device considered. It operates in a similar manner to the expansion portion of a vapor turbine engine. The low pressure vapor is directed past turbine blades causing them to rotate as the vapor expands. The rotor can be a centrifugal type, with the centrifugal being more common because of its frequent use in turbochargers. The turbine is standard for micro-scale ORC due to its good efficiency. One such experiment in which a turbine used in a low-power application was shaped by CNC Milling Machine. Further research investigates the performance of a power turbines is conducted by the test rig.

3.2.2 Vapor Generator Design and Installation

The heat exchangers are comprised of the vapor generator rated to 24.14 kW at the mass flow rated of 370.8 kg/h (0.103 kg/s) and the water cooled condenser rated to 22.54 kW at the mass flow rated of 225.4 kg/h (0.105 kg/s). The actual flow rate through the vapor generator and the water cooled condenser are approximately 350 kg/h, yielding a capacity of 24.14 kW and 22.54 kW, respectively. The heat exchangers are good sized for this system which absorbs 30 kW and rejects approximately 29 kW. All heat exchanger types are shell and tube type which requires less volume for equivalent capacities.

3.2.2.1 Vapor Generator Installation

Figure 3.5 the vapor generator is a form of low water content boiler. The usual construction is as a U-shape coil of water-tube, arranged as a ten row. Circulation is once-through and pumped under pressure, as a forced-circulation vapor generator. The narrow-tube construction, with any small diameter tanks and worked at low pressures. The pump flow rate is adjustable, according to the quantity of vapor required at that time. The heater output is throttled to maintain a constant working temperature. The heater output required varies according to the quantity of water being vaporized: this can be either adjusted by open-loop control according to the pump throughput, or by a closed-loop control to maintain the measured temperature.



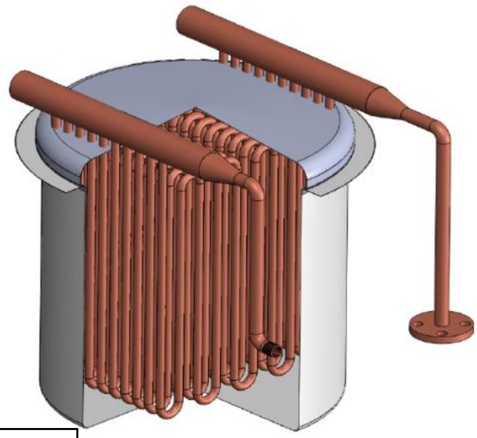


Figure 3.5 (a): Frontal general arrangement **Figure 3.5 (b):** 3D drawing arrangement

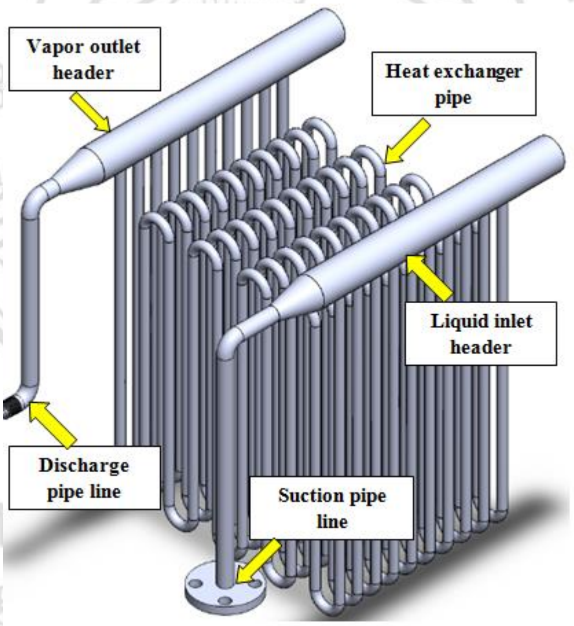


Figure 3.5 (c): Inside arrangement of vapor generator

Figure 3.5: Vapor generator for thermal energy produced from heat source

3.2.3 Water Cooled Condenser Installation

The theoretical analysis performed shows that the ORC achieves an overall thermal efficiency of less than 15%, which means that 85% of the energy put into the system needs to be removed at the condenser. The simplest approach to remove this amount of energy is with a large thermal sink. In this case, a plastic tub was filled with 30 Liters of water, and a 1/2 hp sump pump was utilized to circulate the water through the condenser heat exchanger as show in the Figure 3.6. This approach works well at first because the temperature of the water is low enough to condense the HCFC-141b. However, after the rejected heat warms up the thermal sink, the working fluid is condensed less efficiently.

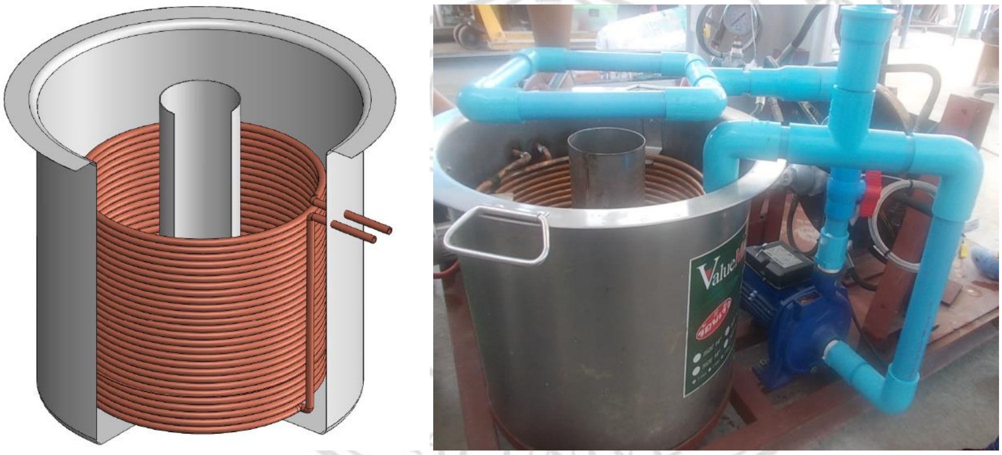


Figure 3.6: Water cooled condenser design and installation

3.2.4 Pump Selection and Installation

The principle of the reciprocating piston pump is shown in the Figure 3.7. The piston expels liquid through a one-way valve or check valve. The pumping rate is usually adjusted by controlling the distance the piston retracts, thus limiting the amount of liquid pushed out by each stroke, or by the cam rotating speed.

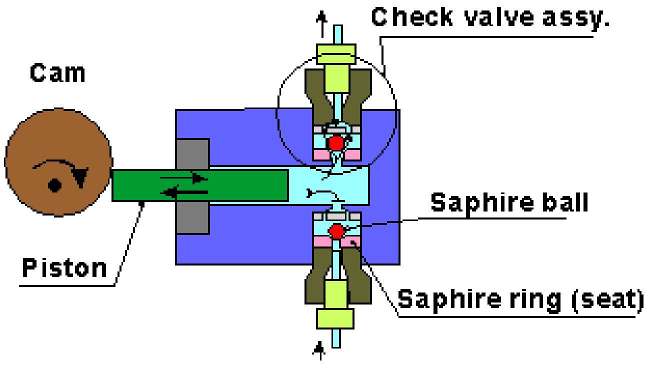


Figure 3.7: Schematic of reciprocating piston pump
(https://hplc.chem.shu.edu/NEW/HPLC_Book/Instrumentation/pmp_recp.html)

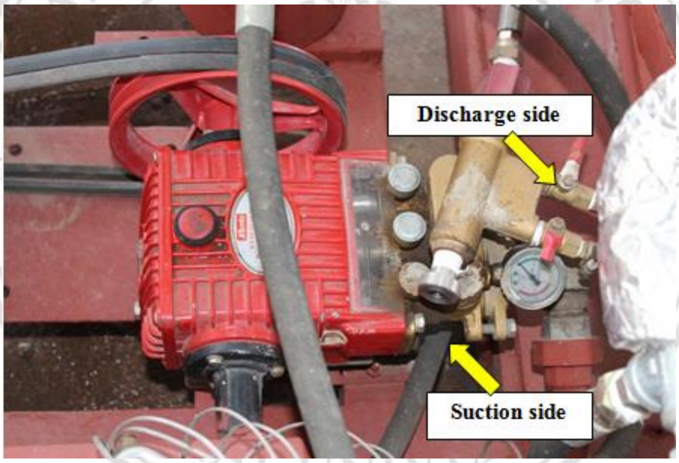


Figure 3.8: Working fluid pump installation

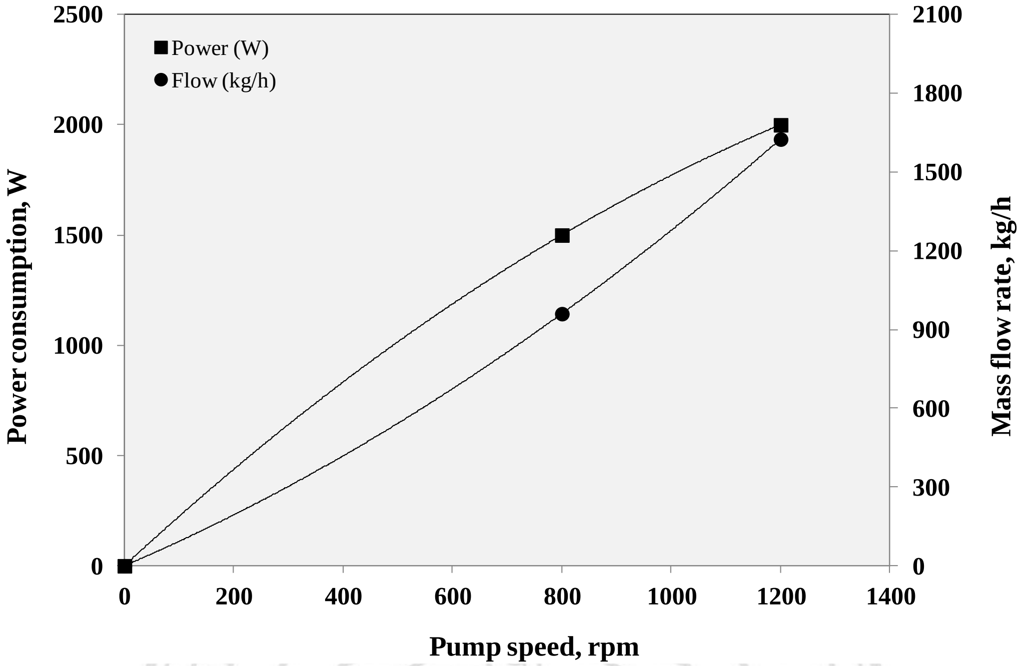


Figure 3.9: Characteristic of working fluid pump.
(https://hplc.chem.shu.edu/NEW/HPLC_Book/Instrumentation/pmp_recp.html)

In the Figure 3.9, the working fluid mass flow rate, power consumption, and pressure of pump stage are

$$\dot{m}_{wf} = 0.0004\,n^2 + 0.8928\,n + 6x10^{-12} \quad 3.1$$

And

$$p = -0.005\,n^2 + 2.2917\,n + 6x10^{-12} \quad 3.2$$

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

p is the power consumption of working fluid pump, kW

n is the pump speed, rpm

The equation 3.1 and 3.2, considered valid for the pump speed of range 0-1,200 rpm

3.2.5 Liquid Receiver Tank

The liquid receiver tank as shown in the Figure 3.11, serves to the condenser for the reserve working fluid, to provide storage for off-peak operation, and to permit pumping down of the system. The receiver also serves as a seal against the entrance of liquid working fluid into the liquid line. When stop valves are provided at each side of the receiver for confinement of the liquid working fluid, a pressure relief valve is generally installed between the valves in the receiver and condenser equalizing line to protect the receiver against any excessive hydraulic pressure being built up.

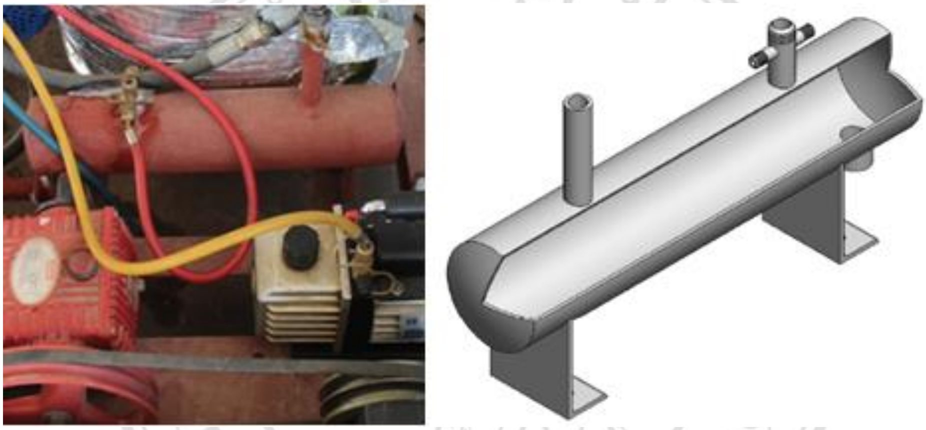


Figure 3.10: Receiver tank design and installation

3.3 Working Fluid Selection and Charging

As the closed loop working fluid circuit is completely evacuated and modified after the all tests, a new evaluation of the working fluid charge is needed. The volume of each element has to be calculated. The regions of the cycle where the fluid is in vapor state are not taken into account, the density of the vapor being negligible compared to that of the liquid.

The amount of working fluid that needs to be considered in charging into each component, the volumes taken into account are the following,

1. The piping: the tubes concerned are the tubes between the outlet of the condenser and the inlet of the vapor generator. The pipe total length is 7 m and internal diameter is 16 mm.

2. The vapor generator: the total volume of the vapor generator is given in section 3.2.2. The working fluid only occupies half of that volume, the other half being filled with hot water. It is assumed that 1/2 of the vapor generator volume is filled with liquid. The adjustment of the HCFC-141b charge to get the desired level is done by adding or removing working fluid during the test.
3. The pressure reducer tank: the approach is the similar to the condition set for the vapor generator. It is assumed that 1/4 of the reducer tank are filled with liquid.
4. The condenser: the approach is the similar to the condition set for the vapor generator. In this case, it is assumed that 3/4 of the condenser are filled with liquid.
5. The receiver tank: the approach is the similar to the condition set for the receiver tank. In this case, it is assumed that 3/4 of the condenser are filled with liquid.
6. The working fluid pump: It is evaluated by the product between the piston area and the stroke length,

The working fluid charge to introduce in the circuit is thus evaluated to 10 kg, in order to take into account the working fluid mass in vapor state and the possible working fluid losses during the transfer.

Figure 3.11: Working fluid leak checked and charging

Table 3.3: Physical and chemical properties of HCFC-141b (http://www.inchem.org)

HCFC-141b physical and chemical properties		
Molecular weight		116.95
Boiling point (1 atm)	°C	32.07
Freezing point (1 atm)	°C	-103.5
Density of liquid at 25 °C	g/cm^3	1.227
Vapor of density (Air = 1)		4.1
Vapor pressure at 25 °C	MPa	0.079
Ozone destroy potential (ODP)		0.11
Percent volatiles by volume (20 °C)		100
Critical pressure	MPa	4.25
Critical density	g/cm^3	0.433
Latent heat of vaporization at boiling point	kJ/kg	223
Conductivity of heat, vapor (1 atm, 25 °C)	mW/mK	8.3
Solubility in water at 25 °C	w%	0.509
Specific heat (25 °C), aqua	kJ/kg.K	1.16
Global warming potency (GWP)		0.09
Critical temperature	°C	204.5

3.4 Measurement Devices

3.4.1 Thermocouple

Thermocouple type K (chromel – alumel) is the most common general purpose thermocouple with a sensitivity of an approximately 41 µV/°C. It is inexpensive, and a wide variety of probes are available in its −200 – 1,350°C range. Type K was specified at a time when metallurgy was less advanced than it is today, and consequently characteristics may vary considerably between samples. One of the constituent metals, nickel, is magnetic; a characteristic of thermocouples made with magnetic material is that they undergo a deviation in output when the material reaches its Curie point; this occurs for type K thermocouples at around 350°C.

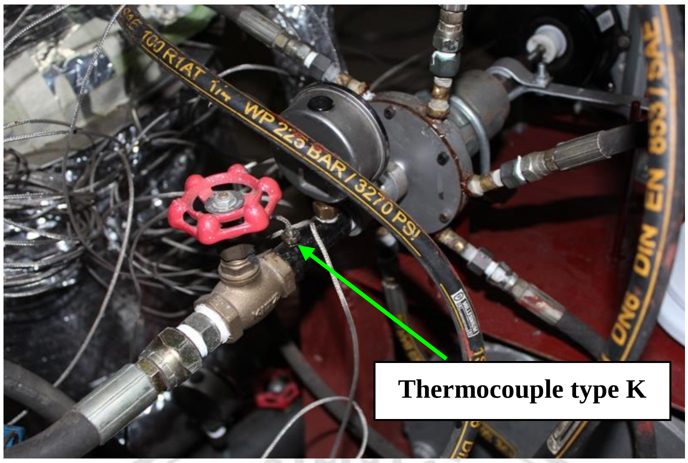


Figure 3.12: Thermocouple type K installation

3.4.2 Temperature Data Logger

The Pico TC-08 is a complete thermocouple input device for use with personal computers. It can be used with the supplied Pico-Log data logging program. The TC-08 was used to collect and analyze data from the experiments.

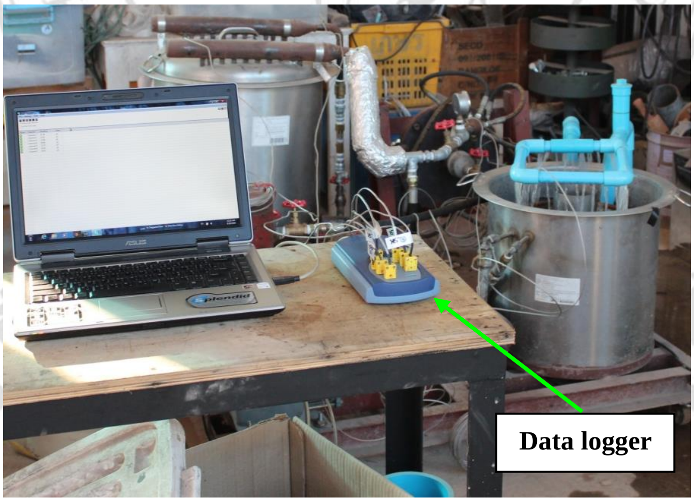


Figure 3.13: Temperature data logger measured

Table 3.4: Specification of TC-08 thermocouple data logger (http://www.picotech.com/thermocouple)

USB TC-08 Thermocouple Data Logger Specification	
Number of channel	8
Maximum number of channels	160
Conversion time	100 ms (thermocouple and cold junction compensation)
Temperature accuracy	Sum of ±0.2% of reading and ±0.5 °C
Voltage accuracy	Sum of ±0.2% of reading and ±10 μV
Overload protection	±30V
Maximum common mode voltage	±7.5V
Input impedance	2MΩ
Input range (voltage)	±70mV
Resolution	20 bits
Noise free resolution	16.25 bits
Thermocouple types supported	B, E, J, K, N, R, S, T
Input connector	Miniature thermocouple

3.4.3 Pressure Gauge

The Bourdon's gauge is a pressure instrument device to measure the internal pressure and vacuum of a tube in the system. The pressure gauges are offered in a variety of styles, sizes, and wetted part materials to meet the demands of standard and special applications. It is constructed with a Bourdon tube sensing element. When the sensing element is subjected to pressure, it flexes and the resulting motion is transmitted as a measurement through a mechanical movement to the dial face pointer.

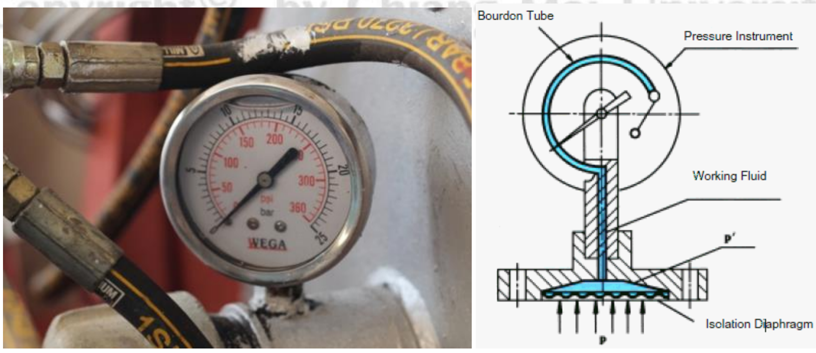


Figure 3.14: Pressure measurement by pressure gauge

Specification

Designed: ASME B40.100 & EN 837-1

Size 2½” (63 mm)

Accuracy 2½”: ± 2/1/2% of span (ASME B40.100 Grade A)

Pressure ranges Pressure from 0 – 25 Bars gauge (0 – 360 psig)

Operating temperature Medium: +200 °C (+392 °F) maximum – dry, and +100 °C (+212 °F) maximum – liquid

3.4.4 Torque Measurement

In order to measure the turbine power, a torque meter is installed between the turbine and the arm prony brake. An also measures the rotational speed of the torque meter shaft.

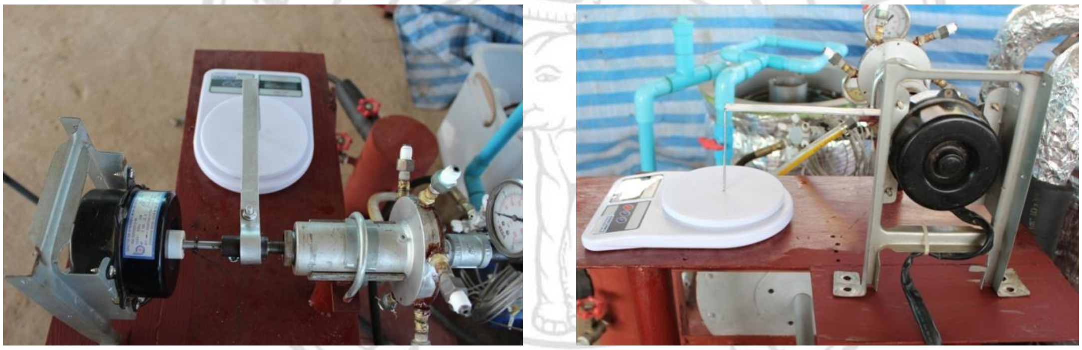


Figure 3.15: Prony brake installation for torque measurement

The mechanical power is calculated by the following analysis,

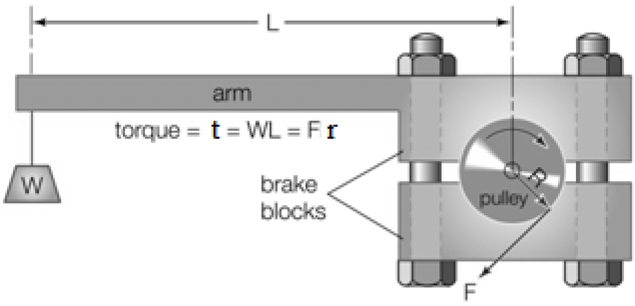


Figure 3.16: Schematic diagram of torque measurement

(http://yefrichan.wordpress.com/2010/12/21/cara-kerja-rem-prony)

From

$$t = W L = F r \qquad \text{N.m} \qquad 3.3$$

$$p = 2\pi T n/60 \qquad \text{N. m/s or W} \qquad 3.4$$

where t is the torque, N.m

F is the force measured at radius, N

r is the length of reaction arm, m

W is the weight of mass, N

L is the length of arm, m

p is the power, W

n is the shaft speed, rpm

3.4.5 Working Fluid Flow Measurement

The NITTO FM-03A rotameter is utilized for the flow rate measurement of working fluid with direct readout of flow rate. The specification is a single jet flow meter, whose working conditions range from 0 to 1.08 m^3/ h, 0 to 5 bars and a maximum temperature of 60°C. The flow rate information is sent to the acquisition device under the form of electrical impulses. Its accuracy is not given by the constructor, but its calibration in section shows an error of approximately 2 to 3%.

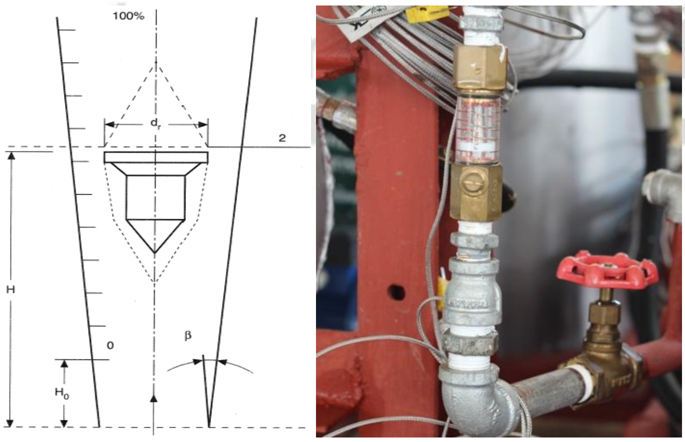


Figure 3.17: Rotameter measured for working fluid flow rate

(http://www.thermopedia.com/content/770/?tid=104&sn=1416)

Table 3.5: Specification of rotameter (www.nitto-kohki.co.jp/FlowMeter, 2013)

Material	Body		Brass	
	Graduated tube		Polycarbonate	
Size	Both ends RC3/8 (PT3/8) female thread			
Working pressure MPa(kgf/cm^2)	0.5 [5]			
Pressure resistance MPa(kgf/cm^2)	0.8 [8]			
Packing material, working temperature range	Packing material	Nitto Symbol	working temp	Remarks
	NBR	SG	+10ºC ~ +60ºC	standard material
Max. flow rate	Liter/min (0 to 18 lit./min adjustable)			

3.4.6 Rotation Speed Measurement

The tachometer is device for indicating the angular speed of a rotating turbine shaft. The term is usually restricted to mechanical or electrical instruments that indicate instantaneous values of speed in revolutions per minute, rather than devices that count the number of revolutions in a measured time interval and indicate only average values for the interval. The mechanical tachometers utilize the fact that the centrifugal force on a rotating mass depends on the speed of rotation and can be used to stretch or compress a mechanical spring. A resonance, or vibrating-reed, tachometer uses a series of consecutively tuned reeds to determine engine speed.

Figure 3.18: Tachometer measured for turbine shaft rotating

3.5 Research Methodology

- Compile all relevant information in power turbine cycle and energy conversion such as a theory, literature review, conventional design, fabricate, and installation procedure, etc.
- Study the parameters and theoretical concept of power turbine cycle with low pressure and low temperature with a simple Rankine cycle.
- Design, construct, and setup of model for study power generating in the low pressure turbine power cycle with HCFC-141b refrigerant as a working fluid.
- The experiments are carried out from various temperatures of $70^{o}C$ to $100^{o}C$, operates at atmospheric pressure and improvement of test rig.
- Determine the appropriate operating conditions which provide the thermodynamics balance and high performance of the low pressure turbine.
- Comparison the numerical results with experimental results for performance optimize of system.
- Develop simple numerical model of a low-pressure turbine from experimental results for the optimize performance to yield efficiency.

3.6 Cycle Thermodynamic Simulation

In this research, the numerical simulation to determine the optimum operating condition carried out by thermodynamics analysis. The power cycle model system is determined from the effects of heat source at vapor generator, mass flow rate of working fluid, turbine inlet pressure, and turbine inlet temperature on the performance is determined. The overall efficiency, which can evaluate the system performance, is selected as the target for optimizing system design. The components of the system for converting low heat source into electrical power are shown in Figure 2.1 (a).

Assumptions of the cycle simulation

The outline of the procedure involves the system to determine the cycle efficiencies as well as irreversibility for ORC diagram, presented in Figure 3.19. The cycle simulation model in this research uses assumptions as following.

(1) The operation of the cycle is in the steady state conditions.

(2) The power cycle system is reversible process.

(3) The working fluid is saturated vapor at the inlet turbine and is saturated liquid at the condenser exit.

(4) The turbine and pump operates at isentropic process.

(5) No pressure drops in the vapor generator, condenser, and pipe.

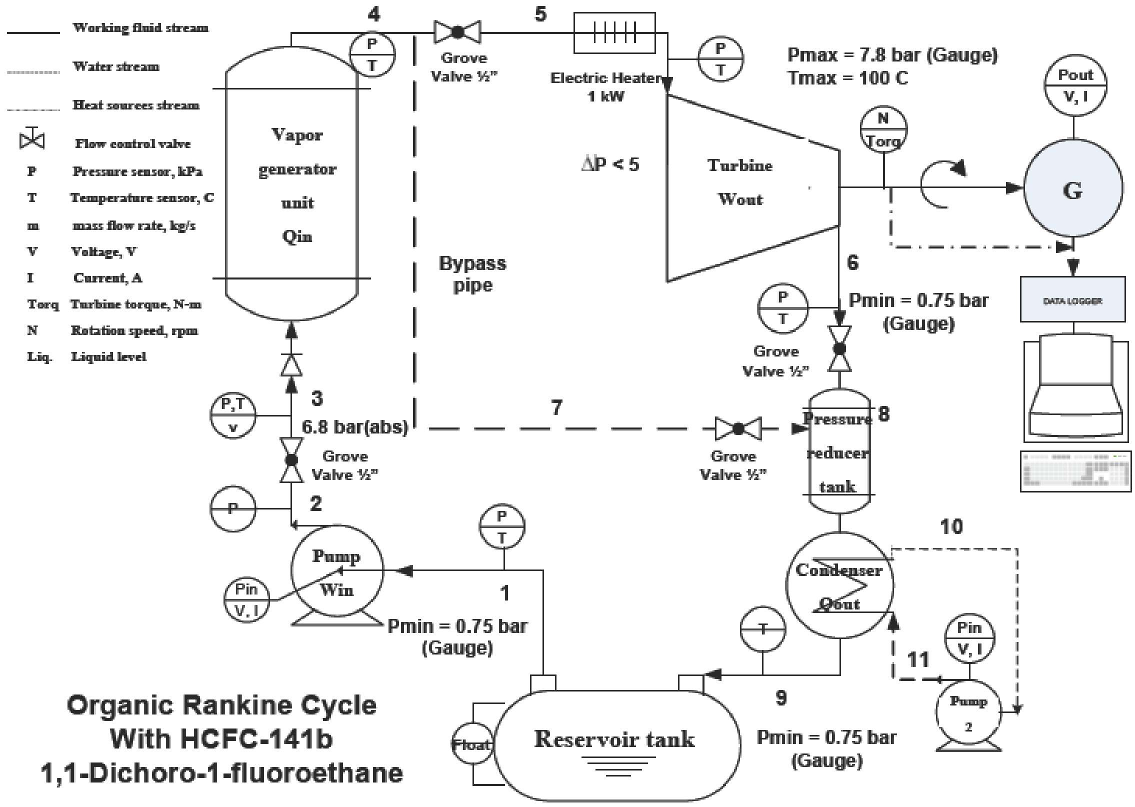


Figure 3.19: Schematic diagrams of experimental apparatus components

3.7 Description of the Experimental Conditions

The experiment carried out of on the Figure 3.19 is set up by the following conditions.

- The heat source composed of two fluid flows and the heat input at the vapor generator was controlled at the temperature ranging 70 - 100°C.
- The working fluid mass flow rate was controlled at the ranging 112 – 397 kg/h by feed pump.
- The system operating at the atmospheric condition.

- The turbine inlet and outlet pressure calculated from inlet and outlet temperature at turbine and used in this experiment were calculated from the cycle efficiency.
- The rotation speed of the turbine shaft is fixed. The experimental apparatus is tachometer measured.
- The instruments are installed to measure the temperature at inlet and outlet of turbine, vapor generator, condenser, receiver tank, and pressure at inlet and outlet of turbine.
- The experiment is measured an inlet and outlet temperature and pressure of turbine, condenser, vapor generator and pump, and measured working fluid mass flow rate at vapor generator inlet.
- The performance evaluation and power output of an optimum condition to find the appropriate operating of system and verify between numerical simulation and experimental results.