Design and Analysis of Low Speed Multi-Blades Wind Turbine with Compressed Air Energy Storage (Part 2) - Performance Evaluation of the Turbine

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Abstract

The objective of this research is to evaluate the performance of the electricity generation system using the low-wind speed multi-blade wind turbine with a reciprocating compressor to store the wind energy. The 30 blades turbine is chosen since it meets with the wind turbine standard for water pumping that are widely used in Thailand and it is suitable for wind-speeds less than 6 m/s. CAES is the technique to store the energy that can be simply acquired, engineered and easy for long-term maintenance. This technique is better than the use of a battery since the battery life of sealed lead-acid battery is less than 3 years and the price of a battery today is higher than the use of CAES. Under the particular of the small wind power farm with the low wind-speed technology, less than 6 m/s, can taking in-place in Thailand. Then, the system of the machine has been tested and evaluated in the real environment. Comparison in both isothermal efficiency and the mechanical efficiency between laboratory and onsite performance test has been discussed in this research activity. The results from the prototype onsite and laboratory showed that both tests are consistent in terms of volumetric efficiency, isothermal efficiency and mechanical efficiency. Under this particular study, the research guideline can be used as a benchmark to ensure environmental and equipment sustainability in the context of system use in Thailand.

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Keywords: Performance evaluation, Compressed air, Energy storage, Isothermal efficiency, Mechanical efficiency

I. Introduction

Ministry of Energy has been developed the Thailand Integrated Energy Blueprint (TIEB) with focused on (1) Energy security, to supply energy in response to the energy demand which consistent with the rate of economic growth of the country, (2) Economy, taking into account of the energy costs should be reasonable and leading to enhance the economic and social development and (3) Ecology, to increase the domestic renewable energy production and with high performance technologies for the purpose of environmental impact reduction for the community (Department of Alternative Energy Development and Efficiency, Ministry of Energy, 2015).

In the TIEB, five energy master plans have been reviewed during the year 2015-2036 in consistent with the national economic and social development plan. Nature supplies solar, geothermal and wind energy in unlimited quantities – classed as green energy sources for electricity production. The Alternative Energy Development Plan (AEDP) was developed in 2015 and focuses on promoting energy production by using the full potential of renewable domestic energy resources. It also develops appropriate renewable energy production taking socioeconomic and environmental impacts into account.

Wind power is a derivative form the solar energy. Wind turbines can convert the kinetic energy in the wind into the mechanical power and then the generator can convert mechanical power into the electricity. Wind energy normally always changes in both amplitude and direction so a wind turbine is used to produce electricity in areas which have high-speed wind and it can result in higher electrical current (Lemofouset, 2003; Guang-

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zheng et al., 2004). The World Bank has reported that only 0.2 percent of Thailand's landmass benefits from "good to excellent" winds appropriate for large-scale wind power farms. Therefore, only small wind power farms with low wind-speed technology, less than 6 m/s, can operate effectively. However, special techniques are needed to store backup energy for more benefits: in particular, daily use by the user. A Compressed Air Energy Storage System (CAES) increases the efficiency for all energy storage and requires a large storage tank, especially for the use of an air compressor for electricity production (Todescat et al., 1992). In this situation, the energy management processes for electricity production with low wind speed and an air compressor can be facilitated (Palasai et al., 2010; Palasai et al., 2013).

Previous studies have reported that, according to a numerical analysis model, a multi-blade turbine (30 blades) with a piston air compressor to store wind energy can harness wind speed of 2-5 m/s for electricity generation. Similarly, correlation lines between the torque and rotational speed of the multi-blade turbine at each velocity can be observed. The optimal rotational speed in the multi-blades wind turbine applications in the previous study was 5.2 rpm which is in the range of the maximum torque and power (Palasai et al., 2020). The technique to store the energy can be simply acquired, engineered and easy for long-term maintenance. The energy storage using CAES has the principle to accumulate the energy in form of compressed-air and stored in the energy storage tank before taking this stored energy to produce electricity. The advantage of this technique is that it is better than the use of a battery since the battery life of sealed lead-acid battery is less than 3 years and the price of a battery today is higher than the use of CAES. The CAES has a long life time of the compressed air tank and the price of the compressed air tank is cheaper compared over the same operation time.

Therefore, under this particular research study, the performance of low speed multi-blades wind turbine has been tested and evaluated by focusing on volumetric efficiency, mechanical efficiency and isothermal efficiency, respectively.

II. Material and Method

Under this research studies, the performance evaluation of low speed multi-blade wind turbine have been tested in the laboratory and then installed and evaluated onsite at Department of Mechanical Engineering, Faculty of Engineering, Princess of Naradhiwas University from August to October 2019.

1. Methodology of the performance evaluation

(1) Theory of Calculation and Design

A compressor delivers a quantity of fluid at a particular pressure. A reciprocating compressor is a positive displacement device. A moving piston in a cylinder reduces the volume of fixed mass of air. According to Boyle's Law, the pressure (P) of a gas is inversely proportional to its volume (V) so the reduction in volume of the air increases its pressure. However, to move the piston, the compressor must receive an input of work (w). The amount of work needed relates to the force on the piston and the distance it moves. So, at any instant during the compression process for a unit mass of gas, this is expressed as

$$w=\int PdV$$

Where dV is the change in volume for a short moment during the whole compression process.

(1.1) Steady Compression of a Through flow of Gas

Thermodynamic theory shows that, for an internally reversible process, the work (w) needed to compress a steady unit mass of gas is given by:

$$w=\int_1^2 vdP$$

Where: w = specific work (kJ/kg); v = V/m = specific volume of the gas (m^3/kg); P = pressure of the gas (Pa)

This equation shows that the work needed to compress a gas depends on its specific volume. The specific volume of gas increases with increasing temperature. So, to achieve minimum work input for the compression process, the gas temperature should not increase. This can only be achieved if heat is continuously removed from the fluid during the process operation (in other words an isothermal process) (Cavallini et al., 1996). Some compressors have a water-cooling jacket on the compressor to keep it cool. If the gas temperature increases then the compression work needed depends on the amount of heat that leaves the gas through the cylinder walls. On the other hand, if the cylinder is perfectly insulated without heat transfer, an adiabatic process will result. In most real compressors, there will be some heat transfer, creating a polytropic process. The term 'polytropic' describes any reversible process on any open or closed system of gas or vapor which involves both heat and work transfer.

(1.2) Isothermal process work needed

$$W_{(iso,needed)} = mRT_1 \ln (P_2/P_1)$$

Where: $W_{(iso,needed)}$ = Isothermal process work needed; m = mass of the air (kg); R = Gas constant for air (J/kg K);

T_1= Initial temperature (K); P_2 = Final absolute pressure (Pa) and P_1 = Initial absolute pressure (Pa)

(1.3) Mechanical Speed, Torque and Shaft Power Speed

$$N_c = 0.5N_D \quad (1)$$

Where: N_c = Compression speed (rpm);

N_D = Dynamometer speed (rpm)

(1.4) Torque and Shaft Power

The motor drive of the universal dynamometer automatically calculates and displays the mechanical shaft power at the dynamometer. It measures the torque and multiplies it by the speed to give the power, so that:

Shaft power = (Torque × 2π × speed) /60

where the speed unit is rpm.

(1.5) Air flow through the orifice – Volumetric Flow

The pressures upstream and downstream of the orifice plate help to calculate the flow rate of air through the compressor. Equation 2 gives the airflow in cubic meters of air per second (volumetric flow), needed for volumetric efficiency calculations

$$Q_v = C_d A_1 \left[\frac{2\Delta_{P1}}{\rho(\frac{A_1}{A_2} - 1)} \right]^{0.5} \quad (2)$$

Where: Q_v = Air flow through the orifice (m^3/s);

C_d= Discharge coefficient (-); A_1 = Inlet area (m^2)

A_2 = Outlet area (m^2); ΔP_1 = Difference pressure across orifice (Pa) and ρ = Air density (kg/m^3)

Where the air density obtains from the pressure (p_o) divided by the gas constant (R_{air}) and temperature (T_3):

$$\rho = p_o (R_{air} T_3) \quad (3)$$

where p_o is a pressure prior the orifice, which is calculated from $p_4+\Delta p_1$ when p_4 is absolute atmospheric pressure (Pa).

Air mass flow (Q_m) is simply to calculate from volumetric flow (Q_v) which multiplied by air density (ρ)

$$Q_m = \rho Q_v \quad (4)$$

(2) Volumetric Efficiency (η_v)

The volumetric efficiency is defined as the ratio between the actual volume of the intake air (Q_v) into the cylinder/engine and the theoretical volume of the engine/cylinder (V_s) during the intake engine cycle (N_c).

$$\eta_v = (Q_v/N_c V_s) \times 100\% \quad (5)$$

Where: η_v = Volumetric Efficiency; Q_v = Actual volume (dm^3/min); N_c = Revolution speed (rpm) and V_s = Volume of compressor cylinders (dm^3)

(3) Mechanical Efficiency (η_m)

Mechanical efficiency is the ratio of the actual power that is used by the compressor to compress air, against the input shaft power applied to the compressor. It allows for all power losses.

$$\eta_m = [(W_D - W_L)/W_D] \times 100\% \quad (6)$$

Where: η_m = Mechanical efficiency;

W_D = Input shaft power (W);

W_L = Power loss (W)

Power loss is mainly due to two things: Mechanical Power Losses and Heat Losses, so that:

$$W_L = \text{Mechanical Power Losses} + \text{Heat Losses} \quad (7)$$

(3.1) Mechanical Power Loss of Torque

Mechanical power loss of torque (measured when the compressor is not doing useful work) and multiply it by the dynamometer shaft revolution speed at test to find the mechanical power losses, so that:

$$\text{Mechanical Power Losses} = \text{Mechanical Loss Torque} \times 2\varpi \times N_1/60 \quad (8)$$

Where: N_1 = dynamometer shaft speed (rpm)

It is the torque needed to overcome the slipping friction during mechanical movement. It is a constant factor through the tests, However the power losses by this mechanical loss of torque increase, because the speed increases.

(3.2) Heat Transfer Power Loss

Working compressor transfers heat to surrounding air through exposed surface called heat transfer power loss, (W_h). The heat loss is calculated when the heat transfer of the compressor becomes steady.

$$W_h = Q_m \times 718(T_1((P_2+P_4)/P_4)^{0.286} - T_2) \quad (9)$$

Where: Q_m = Air mass flow (kg/s);

T_1 = Inlet temperature (K);

T_2 = Outlet temperature (K);

P_2 = Delivery pressure (Pa) and

P_4 = Absolute atmospheric pressure (Pa)

(3.3) Isothermal Work Done (Power)

It is product of the air mass flow, its initial property and the pressure increase. It does not allow for the internal energy increase of the air. The pressure increase is with respect to absolute atmospheric pressure.

$$W_{iso} = Q_m R_{air} T_1 \times \ln((P_2+P_4)/P_4) \quad (10)$$

Where: W_{iso} = Isothermal work done (W);

Q_m = Air mass flow (kg/s);

R_{air} = Gas constant (J/kg K);

T_1= Air temperature at the inlet (K);

P_2 = Delivery pressure (Pa) and

P_4 = Absolute atmospheric pressure (Pa)

(3.4) Overall Isothermal Efficiency (η_{oiso})

Overall isothermal efficiency is a measure of how efficient the compressor is at turning input (shaft) power into work done by compressing the air. It is an overall efficiency of the system, including all losses.

$$\eta_{oiso} = W_{iso}/W_D \ (\times 100\%) \quad (11)$$

Where: η_{oiso} = Overall isothermal efficiency;

W_{iso} = Isothermal work done (W) and

W_D = Shaft power (W)

(4) Isothermal Efficiency (η_{iso})

Isothermal efficiency is similar to overall isothermal efficiency but allows for mechanical losses. It is a ratio of work done over the actual power used to do the work. Therefore, isothermal efficiency is usually higher than overall isothermal efficiency.

$$\eta_{iso} = [W_{iso}/(W_D - W_L)] \times 100\% \quad (12)$$

Where: η_{iso} = Isothermal efficiency;

W_{iso} = Isothermal work done (W);

W_D = Shaft power (W) and

W_L = Power losses (W)

2. Experimental design and installation of the multi-blades wind turbine prototype with a compressed air

The focus for optimal efficiency of wind energy use in this research was the suitability of the turbine for air compression and local area installation. With the limitation of wind speed performance in Thailand, the energy management processes for electricity production using low wind speed and air compressor shall supplementally be included. A wind turbine can produce energy if the wind speed is neither too high nor too low. Once the turbine stops, the rotor cannot produce energy. This special turbine can obtain maximum power. To evaluate the shaft power, the axel of the multi-blade wind turbine was connected with the motor and the pressure was set in the range of 0.2-1 bar (starting from 0.2, 0.4, 0.6, 0.8 to 1.0 bar). The power source for the compressed air system was the multi-blade wind turbine. To assess the precision of the compressed air testing system, an airflow meter was installed to control the pressure and temperature during the onsite evaluation as shown in Figure 1 (a) and Figure 1 (b). The multi-blade wind turbine for wind energy storage is depicted in Figure 1 (c) and Figure 1 (d).

The measuring equipment and data acquisition has been shown in Figure 2 which comprises of 5 main parts as follow:

(1) Pressure transmitter model ifm PA 3024 to record the pressure in the air compressed tank

(2) Air Flow transmitter model ifm SD 6000 to record the airflow in the pipe

(3) Pressure Regulator to control the pressure during releasing of the compressed air

(4) Map of the wind speed during data recording

(5) Data Logger model DL2000 to record the data for each period of time (Record every 1 minute)

Figure 1(a). Compressed air installation

Figure 1(b). Side view of compressed air

Figure 1(c). Multi-blade wind turbine onsite installation

Figure 1(d). Multi-blade wind turbine in operation

Figure 1. Onsite testing of the multi-blade wind turbine with compressed air

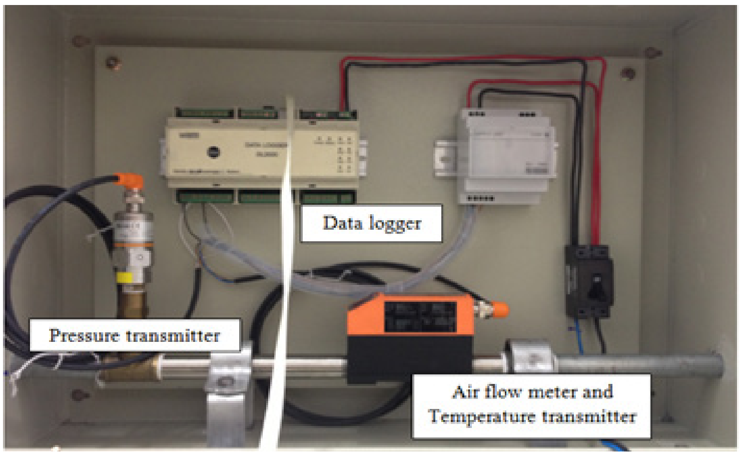

Figure 2. Equipments and data acquisition in operation

Before analysis of the performance of the multi-blade wind turbine prototype with a compressed air system, a laboratory experiment was set up that evaluated the performance (Table 1). After calibration, the measuring and data acquisition equipment were then installed onsite to record the data and analyze the efficiency of the prototype (Exp), as shown in Table 2. A comparison of results between the laboratory experiment and onsite experiment was conducted subsequently.

III. Results and Discussion

1. Laboratory experiments and onsite experiments

The comparative results in terms of energy accumulation between electricity generation using the multi-blade wind turbine with air compression and the motor used in the laboratory are shown in Tables 1 and 2 respectively. The results of the significant parameter values of the performance test of both systems comprised power, pressure, volumetric flow rate performance, volumetric and isothermal efficiency, and overall isothermal and mechanical efficiency and were discussed for onsite setting of the operation of the machine.

It was found that when the torque of the system was increased, mechanical heat loss increased. On the other hand, the ideal heat due to the loss was less than the input power that led to decrease in isothermal efficiency: (η_{iso}) falling into the range of 1.80-2.18 bar. The compressor had high energy with delivery pressure between 0.2-1 bar as shown in Figure 3. The values from the prototype (Exp) and the values from the laboratory (Lab) are shown in Figure 4. However, the power efficiency was low due to the friction of the respective machine parts.

Table 1 Data from experiments using motar in the laboratory (Lab)

Test Speed (rev.min-1): 2000 dynamometer (1000 compressor)
Mechanical Loss(W): 120

Delivery Pressure (P_2) (bar)	Shaft Power (W_D) (Watt)	Flow Q_v L. min^{-1}	Flow Q_m kg. s^{-1}	η_v	η_{iso}	η_{oiso}	η_m	W_{iso} (Watt)	W_h (Watt)
0.2	402.0	37.44	0.0007	20.80	9.80	6.75	68.88	27.14	5.1
0.4	469.6	37.35	0.0007	20.75	16.76	11.40	68.02	53.55	30.2
0.6	514.8	37.13	0.0007	20.63	21.26	14.56	68.53	74.99	42.0
0.8	560.6	36.99	0.0007	20.55	24.32	16.71	68.75	93.73	55.2
1.0	593.7	37.29	0.0007	20.72	24.02	16.62	69.19	98.68	62.9

Table. 2 Data from prototype of Multi-blade wind turbine for compressed air (Exp)

Test Speed (rev.min-1): 2000 dynamometer (1000 compressor)
Mechanical Loss(W): 230

Delivery Pressure (P_2) (bar)	Shaft Power (W_D) (Watt)	Flow Q_v L. min^{-1}	Flow Q_m kg. s^{-1}	η_v	η_{iso}	η_{oiso}	η_m	W_{iso} (Watt)	W_h (Watt)
0.2	1,160	66.73	0.0013	37.07	2.18	1.73	79.39	20.1	9.0
0.4	2,310	66.43	0.0013	36.09	1,80	1.61	89.16	37.2	20.2
0.6	3,000	66.03	0.0013	36.68	1.91	1.73	91.31	52.0	29.6
0.8	3,350	65.86	0.0013	36.58	2.04	1.88	92.20	65.1	39.0
1.0	3,850	65.80	0.0013	36.55	2.13	2.04	92.74	76.8	48.8

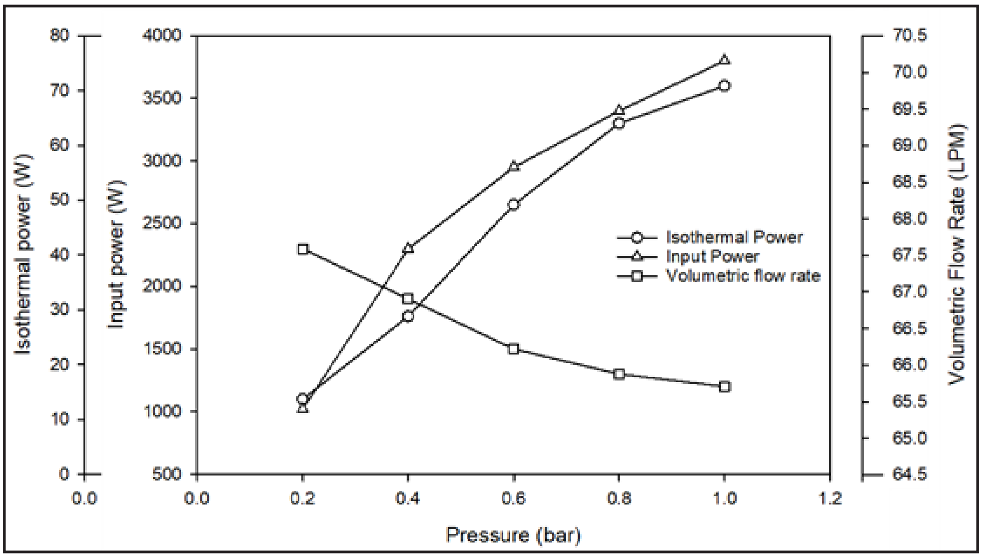

Figure 3 Relationship of input power, isothermal power and volumetric flow rate with the pressure from the prototype of multi-blade wind turbine with compressed air

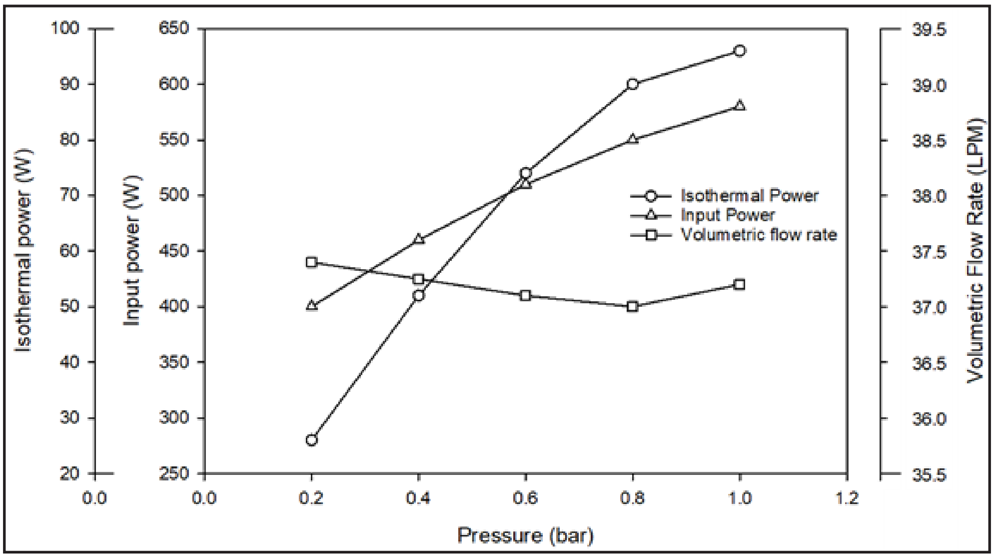

Figure 4 Relationship of input power, isothermal power and volumetric flow rate from the experimental setup in the laboratory (Lab)

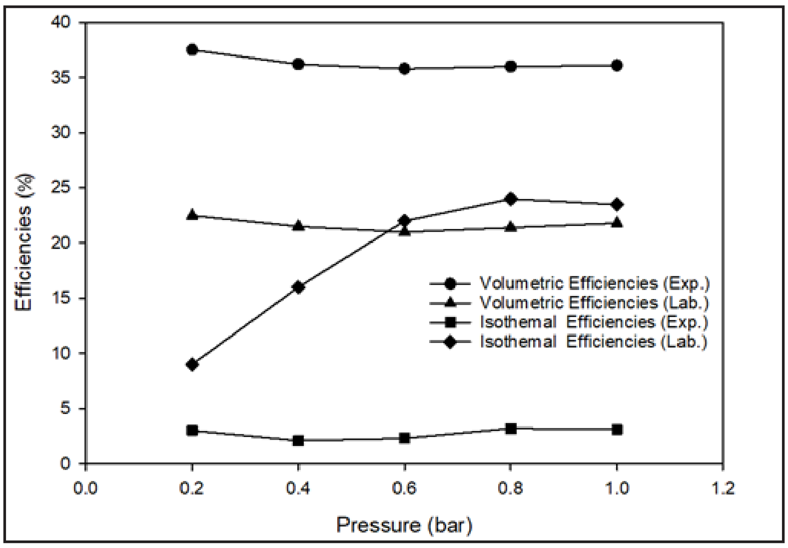

Figure 5 Relationship between volumetric and isothermal efficiencies and pressure

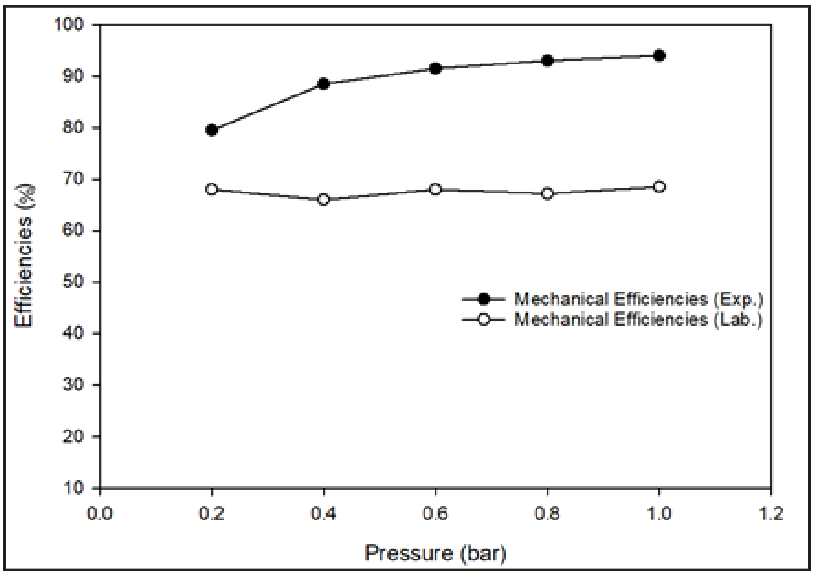

Figure 6 Relationship between mechanical efficiencies and pressure

The results of the study of volumetric efficiencies showed that they decreased once the pressure increased. Normally, the piston position cannot reach the top of cylinder since there is a safety distance in the system and this means in the cycle of the piston there is air left and it cannot be driven; therefore the volume of compressed air is less than the input into the cylinder. It was also found that once the power was increased, the volume was reduced due to the friction and size of the cylinder of the piston as shown in Figures 3 and 5. This also is consistent with the values of the experiment in Figures 4 and 5. The study results of mechanical efficiencies showed that mechanical efficiency increased as pressure was increased. Although heat loss was increased, it was increased at a rate lower than the input power to the air compressor as shown in Figure 6.

The study results of piston mechanical efficiencies depended on the cylinder size and this affected the volumetric efficiencies of the compressor. The piston ring was similar to piston rings used in a combustion engine. The piston ring was low in friction, however the ring needed space at the end of air-compression to be able to expand, therefore, the wear of the ring could affect the volumetric efficiencies as shown in Figures 3 and 4. Once the pressure was increased, the air compression needed to expand before the ID valve was opened (the valve was opened while the cylinder pressure was lower than the atmosphere) which affected the valve cycle. At high pressure, the valve was opened in a shorter time; this related to slight compression and did not have high efficiency in terms of thermal principles. This was a step to compress the air; it was not efficient, but it had advantages owing to its small size and low cost. The prototype results onsite and in the laboratory showed that both tests were consistent in terms of volumetric efficiency, isothermal efficiency and mechanical efficiency. For example, if the volumetric efficiency was reduced, the mechanical efficiency tended to decrease as shown in Figures 5 and 6.

IV. Conclusions and Recommendation

The results of this study of an electricity generator using a multi-blade turbine (30 blades) and a piston air compressor to store wind energy are given and compared with the same system in a laboratory. It was found that the isothermal efficiency could be calculated to be between 1.80-2.18 bar and mechanical efficiency was increased. In this experiment, there were relationships between the values of speed, pressure and friction. The tested results from the site and the laboratory showed that they were consistent in terms of total isothermal efficiency and mechanical efficiency. Volumetric efficiency decreased and this led to mechanical efficiency being slightly reduced. Then, the economic worthiness analyses in terms of electricity generating cost per unit and payback period will conducted to evaluate the performance in the next research study. This research can be used as a benchmark to ensure environmental and equipment sustainability in the context of system use in Thailand.

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