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Energy Efficiency Analysis of a Hydraulic Power Unit (HPU) System on a Winch during Tensile Load Testing

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Abstract: This study aims to analyze the energy efficiency of a Hydraulic Power Unit (HPU) system in driving a winch during tensile load testing. Experiments were conducted on a hydraulic winch with a maximum capacity of 10 tons by applying tensile loads gradually from 2 to 10 tons. The measured parameters include hydraulic pressure, flow rate, pulling force, and rope winding speed. Hydraulic input power and mechanical output power were calculated to evaluate system efficiency. The results indicate that the HPU system is capable of operating the winch stably under all tested load conditions. System efficiency tends to increase from low to medium load levels and then becomes relatively constant or slightly decreases at higher loads due to increasing energy losses caused by mechanical friction, internal leakage, and pressure drops in the hydraulic system. These findings suggest that proper selection of operating parameters and regular maintenance of hydraulic components are essential to improve the overall energy efficiency and reliability of HPU-driven winch systems.

Keywords: Hydraulic Power Unit, Winch; Energy Efficiency, Tensile Load, Hydraulic System

INTRODUCTION

Winch systems are essential components in industrial and marine applications for pulling, lifting, and positioning heavy loads using a hoisting mechanism and steel wire rope. A winch is a mechanical device designed to pull, lift, or lower loads by winding a cable or rope around a rotating drum driven by an electric motor, manual crank, or other power source. Winches are widely used in construction, mining, shipping, and various heavy-duty operations where high loads and harsh working environments are common. Therefore, winch systems are required to operate with high efficiency and reliable performance.

One of the most critical elements in a winch mechanism is the bearing, which supports rotating components and reduces friction during operation. Proper bearing performance contributes significantly to the smooth rotation of the drum and the overall reliability of the system. Previous studies have reported that winches are commonly applied in industries such as construction, marine transportation, and mining, as well as in off-road vehicles and vessels (Rahmiati et al., 2024).

Along with technological development, modern winch systems increasingly utilize Hydraulic Power Units (HPUs) as their primary power source because hydraulic systems are capable of producing high torque with smooth and precise control. An HPU system converts electrical energy into hydraulic energy through a hydraulic pump. The pressurized fluid is then directed by control valves to actuators or hydraulic motors, which finally convert hydraulic energy into mechanical energy to drive the winch drum. Thus, the HPU-driven winch represents a multi-stage energy conversion process, from electrical energy to hydraulic energy and subsequently to mechanical energy.

During this energy conversion process, not all input energy can be utilized effectively due to various losses occurring throughout the system. These losses include pressure losses in pipelines caused by changes in diameter, pipe length, and flow characteristics; fluid leakage through seals and clearances; mechanical losses in components such as pumps, valves, and motors; and thermal losses due to fluid friction and internal resistance. The accumulation of these losses directly reduces the overall efficiency of the system, particularly when operating under heavy loads and high-pressure conditions.

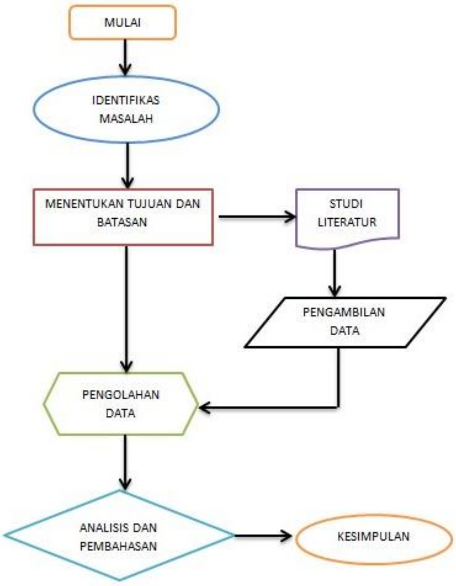
Therefore, an energy efficiency analysis of an HPU-driven winch system under varying tensile loads is necessary to evaluate the actual performance of the system in converting electrical energy into useful mechanical energy. The results of this study are expected to provide a clear understanding of system efficiency characteristics and serve as a reference for improving the design, operation, and maintenance of more efficient HPU-driven winch systems.

METHOD

Research Flowchart

The research flowchart illustrates the systematic stages of this study in analyzing the energy efficiency of a Hydraulic Power Unit (HPU) system driving a winch during tensile load testing. The sequence of stages begins with the planning phase and continues through experimentation, data analysis, and final conclusions based on the obtained results. The first stage is the **start** phase, which marks the initiation of all research activities. At this stage, the scope of the study and the research objectives are defined, namely to evaluate the energy efficiency of the HPU system in driving a winch under tensile load testing conditions.

The next stage is the **literature review**, which involves collecting and examining references related to hydraulic systems, HPU operating principles, winch characteristics, power and energy efficiency concepts, and tensile load testing methods. A literature review aims to develop a strong theoretical foundation by synthesizing information from journals, books, and other scientific publications (Marzali, 2016). This process helps establish a conceptual framework and identify relevant variables and analytical approaches (Kartiningrum, 2015). The literature review serves as the basis for selecting appropriate methods and formulating the research procedure.



Problem Identification

The Hydraulic Power Unit (HPU) system is used as the main power source to drive the winch during tensile load testing. The energy produced by the HPU is in the form of hydraulic energy, which is subsequently converted into mechanical energy at the winch. During this energy conversion process, not all input energy can be utilized effectively due to various energy losses. The primary problem identified in this study is the difference between the hydraulic power as the input power and the mechanical power as the output power. This difference indicates the presence of energy losses within the system, which directly affect overall system efficiency. Therefore, an analysis is required to determine the energy efficiency of the HPU-driven winch system during tensile load testing.

Research Objectives and Limitations

Research Objectives

The objectives of this study are as follows:

1. To determine the hydraulic power as the input power of the HPU system.
2. To determine the mechanical power as the output power at the winch.
3. To calculate the energy efficiency of the HPU-driven winch system.
4. To analyze the effect of tensile load variation on system energy efficiency.

Research Limitations

The limitations applied in this study are as follows:

1. The study is conducted on a single HPU and winch unit.
2. The system operates under normal conditions without external disturbances.
3. Tensile loads are varied from 2 tons to 10 tons.
4. The analyzed parameters include pressure, flow rate, pulling force, rope speed, input power, output power, and efficiency.
5. The effects of fluid temperature and component wear are not discussed in detail.

Literature Study

A literature study was conducted to support this research with relevant theoretical foundations. The reviewed literature includes theories of hydraulic systems, operating principles of Hydraulic Power Units (HPUs), winch working mechanisms, concepts of fluid pressure and flow rate, the relationship between force and velocity to power, and energy efficiency concepts. References were obtained from mechanical engineering textbooks, scientific journals, and technical standards related to hydraulic systems.

Preparation of Equipment and Materials

The equipment required to support this research is classified into three main categories, as follows:

Main Equipment
1. Hydraulic Power Unit (HPU)
2. Hydraulic winch
3. Load cell (tensile force sensor)
4. Winch drum

Measuring Instruments
1. Pressure gauge / pressure transducer
2. Flow meter (oil flow rate)
3. Tachometer (drum rotational speed)
4. Stopwatch / timer
5. Data logger / data acquisition system

Supporting Equipment
1. High-pressure hydraulic hoses
2. Pressure control valve
3. Wrenches, pliers, and standard hand tools
4. Computer for data processing

Data Collection

Data were collected while the HPU system was operating to drive the winch for pulling loads. The measured data include hydraulic system working pressure, fluid flow rate, pulling force generated by the winch, and rope winding speed. Data collection was conducted under several tensile load variations in order to obtain the performance characteristics of the system. The experimental procedure was carried out step by step to ensure that the obtained data are accurate and reliable.

Preparation Stage
1. Understand the specifications of the Hydraulic Power Unit (HPU) and winch used, with a maximum capacity of 10 tons.
2. Prepare the HPU and inspect physical conditions, including tank, hoses, connections, pump, electric motor, and valves.
3. Ensure that the hydraulic oil meets the required specification (e.g., ISO VG 46) and that the oil level in the reservoir is adequate.
4. Install the load cell at the load connection point, install the pressure transducer at the pump outlet, install the flow meter in the line supplying the winch motor, and attach the tachometer to the winch drum.
5. Prepare safety systems, including safety chains, load restraints, restricted test area, fire extinguisher, and personal protective equipment (helmet, gloves, and safety shoes).

Testing Stage
1. Turn on the HPU system and perform a warm-up for approximately 10 minutes.
2. Conduct tests at a series of planned load levels (2 tons, 4 tons, 6 tons, 8 tons, and 10 tons). For each load level, perform at least three repetitions.
3. Adjust the working pressure according to the test level (e.g., 50 bar, 75 bar, and 100 bar).
4. Connect the winch to the tensile load.
5. Operate the winch until a constant pulling condition is achieved.

6. Record the following parameters: hydraulic pressure (P), flow rate (Q), winch pulling speed (v), pulling force (F), and winch drum rotational speed (rpm).
7. Repeat the procedure for all load variations.

Primary Data

Primary data are obtained directly from experimental measurements, including:

a. Hydraulic working pressure (bar)
b. Oil flow rate (L/min)
c. Winch pulling force (N)
d. Rope pulling speed (m/s)
e. Drum rotational speed (rpm)
f. Hydraulic oil temperature (°C)

Secondary Data

Secondary data are obtained from documentation and literature, including:

a. Technical specifications of the HPU
b. Technical specifications of the winch
c. Pump performance curves
d. Nominal efficiency data of hydraulic system components

Calculation Parameters

Table 3.6 presents the calculation parameters used in the energy efficiency analysis of the HPU-driven winch system during tensile load testing. The parameters include pressure, flow rate, pulling force, speed, hydraulic power, mechanical power, and efficiency, along with their symbols and units. This table serves as the basis for comparing the hydraulic input power with the mechanical output power of the winch in order to determine system efficiency.

Table 3.6. Calculation Parameters

Parameter	Symbol	Unit	Description
Pressure	P	bar	Hydraulic working pressure
Flow rate	Q	L/min	Oil flow rate
Piston area	A	m^2	Cylinder cross-sectional area
Pulling force	F	N	Tensile load
Winch speed	V	m/s	Winch pulling speed
Hydraulic power	Phid	W	Input power
Mechanical power	Pmek	W	Output power
Efficiency	η	%	System efficiency

Operational Specifications of the HPU

The operational specifications of the Hydraulic Power Unit (HPU) used in this study are presented in Table 3.7.

Table 3.7. Operational Specifications of the HPU

Parameter	Value
Pump type	Plunger pump
Electric motor power	7,5 kW
Supply voltage	380 V
Maximum pressure	120 bar
Maximum flow rate	25 L/min
Hydraulic oil tank capacity	$\pm 80\ liter$
Hydraulic oil type	ISO VG 46

RESULTS AND DISCUSSION

Data Processing and Calculations

This section presents the experimental data and calculations of input and output power, as well as the energy efficiency of the Hydraulic Power Unit (HPU) during tensile load testing conducted at the workshop of PT. Bhumi Phala Perkasa.

Efficiency Calculation

As an example, the efficiency calculation for a tensile load of **2.0 tons** is presented below.

Given:

Load,m = 2.0 tons = 2000 kg

Gravitational acceleration, g = 9.81 m/s²

Hydraulic pressure, p = 40 bar

Flow rate, Q = 100 L/min

Winch pulling speed, v = 0.25 m/s

Pulling Force (F)

$F = m \cdot g$ =2000 kg x 9.81 m/s^2 = 19.620 N

Flow Rate Conversion

100 L/min = 0.100 $m^3/min = \frac{0.100}{60} m^3/s$ = 0.0016667 m^3/s

Pressure Conversion

1 bar = 10^5Pa $\Longrightarrow$ p = 40 bar = 40 x 10^5Pa =4.0 x 10^6Pa

Hydraulic Input Power

$. P_{hid} = p \cdot Q = 4.0\ x\ 10^6$Pa x 0.0016667 m^3/s = 6 666.7 W

Mechanical Output Power

$.P_{mek} = F \cdot v = 19.620\ N\ x 0.25 \frac{m}{s} = 4.905\ W$

Energy Efficiency

$. \eta = \frac{P_{mek}}{P_{hid}} x\ 100\% = \frac{4.905}{6\ 666,7}\ x\ 100\% \ \approx 73.6\%$

The results of the calculation from the experimental tests are presented in Table 4.1.1 below.

Table 4.1.1. Results of Calculation from Experimental Testing

Load (ton)	Load (kg)	Force F (N)	Pressure (bar)	Flow Rate Q (L/min)	Q (m^3/s)	Velocity v (m/s)	Hydraulic Power (W)	Mechanical Power (W)	Efficiency η (%)
2.0	2.000	19.620	40	100	0.001667	0.25	6.667	4.905	73.6
4.0	4.000	39.724	80	100	0.001667	0.20	13.333	7.848	58.9
6.0	6.000	58.860	120	100	0.001667	0.15	20.000	8.829	44.1
8.0	8.000	78.480	160	100	0.001667	0.10	26.667	7.848	29.4
10.0	10.000	98.100	200	100	0.001667	0.08	33.333	7.848	23.5

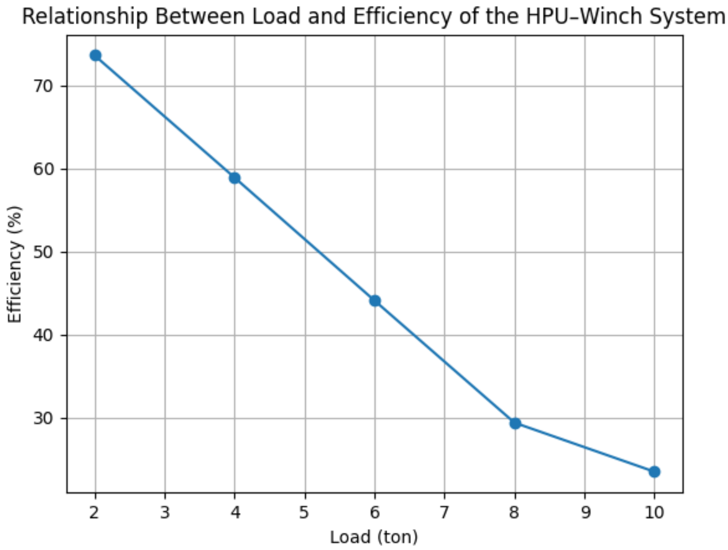


Figure 4.1.1. Efficiency Results versus Variation of Tensile Load on the HPU Winch System

Based on Figure 4.1.1, it can be observed that the energy efficiency of the Hydraulic Power Unit (HPU) system driving the cable drum winch decreases as the tensile load increases. At a load of 2 tons, the system efficiency reaches the highest value of approximately 74%. However, when the load increases to 4 tons and 6 tons, the efficiency decreases to about 59% and 44%, respectively. The reduction in efficiency becomes more significant at loads of 8 tons and 10 tons, with efficiency values of approximately 29% and 23%. This indicates that the higher the applied tensile load, the greater the energy losses occurring within the hydraulic system. Therefore, it can be concluded that the HPU system operates more optimally at low to medium loads compared to high loads. Overall, the graph shows that an increase in tensile load on the cable drum winch is inversely proportional to the energy efficiency of the HPU system. This confirms that the HPU system has an optimal operating load range in which energy efficiency can be maintained, and it highlights the importance of operating the winch in accordance with its design capacity to minimize energy losses and extend system service life.

In general, the results demonstrate that load variation has a significant influence on the performance and efficiency of the HPU winch system. The system exhibits good performance at low loads; however, efficiency gradually decreases as the load increases. Therefore, proper design and selection of hydraulic components, such as pumps and hydraulic motors with appropriate characteristics, are required to improve system efficiency under high-load conditions.

The relationship between power and torque in the cable drum winch system is expressed as the product of torque and angular velocity. The mechanical power generated by the motor or hydraulic system is utilized to produce torque in order to pull the load. As the required torque increases due to higher tensile loads, the power demand of the system also increases accordingly.

Mathematically, the relationship between power and torque is expressed by the following equation :

$$P = T \, x \, \omega$$

Where :
P = mechanical power (W)
T = torque (N·m)
.ω = angular velocity (rad/s)

The angular velocity can be calculated from the motor rotational speed using the following equation:

$$\omega = \frac{2_{\pi n}}{60}$$

where:
n = rotational speed (rpm)
Given:
Winch torque, T =150 Nm
Motor speed, n = 1450 rpm
Thus, the angular velocity is:
$.\omega = \frac{2_{\pi}\ x\ 1.450}{60} = 151{,}9\ rad/s$
Mechanical power:
P = 150 x 151,9 = 22.785 W
P = 22.8 kW

The electrical efficiency of the system is calculated to determine the ability of the system to convert the incoming electrical power into useful mechanical power at the cable drum winch through the Hydraulic Power Unit (HPU). Electrical efficiency is determined by comparing the system output power with the electrical power drawn from the power source. The magnitude of electrical efficiency is influenced by the current and voltage consumption of the electric motor as well as the applied tensile load. As the load increases, the electrical power required by the system also increases; however, not all of this power can be effectively converted due to electrical and mechanical losses. Therefore, electrical efficiency becomes an important indicator in evaluating the performance and energy utilization of the HPU winch system.

The electrical efficiency of the system is expressed as:

$$\eta_{electric} = \frac{P_{out}}{P_{in}}\ x\ 100\%$$

where:
. $\eta_{electric}$ = electrical efficiency of the system (%)
P_{out} = system output power (W)
P_{in} = electrical input power (W)
The electrical input power is calculated using:

$$P_{in} = \text{V x I}$$

where:
V = supply voltage (Volt)
I = electric current (Ampere)
Given:
Motor voltage, V = 380 V
Motor current, I = 12 A
System output power, P_{out} = 3200 W
Thus, the electrical input power is:
P_{in} = 380 x 12 = 4.560 W
The electrical efficiency of the system is:
. $\eta_{listrik} = \frac{3.200}{4.560}$ x 100% = 70,18 %

The hydraulic input power of the Hydraulic Power Unit (HPU) can be calculated based on the working pressure and hydraulic flow rate using the following equation. The hydraulic input power is calculated under the test condition at a 6-ton load with the following data:

P = hydraulic input power (kW)
p = pressure (bar)
Q = flow rate (L/min)
Substituting the values into the equation:

$$P = \frac{120 \times 40}{600}$$

$$P = \frac{4800}{600}$$

P = 8.0 kW

The results of the subsequent input power calculations are presented in Table 4.1.2 below:

Table 4.1.2. Measurement and Calculation of Input Power Using the Equation

NO	Load (ton)	Pressure (bar)	Flow Rate (L/menit)	Input Power (kW)
1.	2	60	40	4.0
2.	4	90	40	6.0
3.	6	120	40	8.0
4.	8	150	40	10.0
5.	10	180	40	12.0

From the table above, it can be observed that as the applied tensile load increases, the system working pressure also increases, resulting in a higher input power requirement for the HPU. The relationship between tensile load and input power tends to be nearly linear.

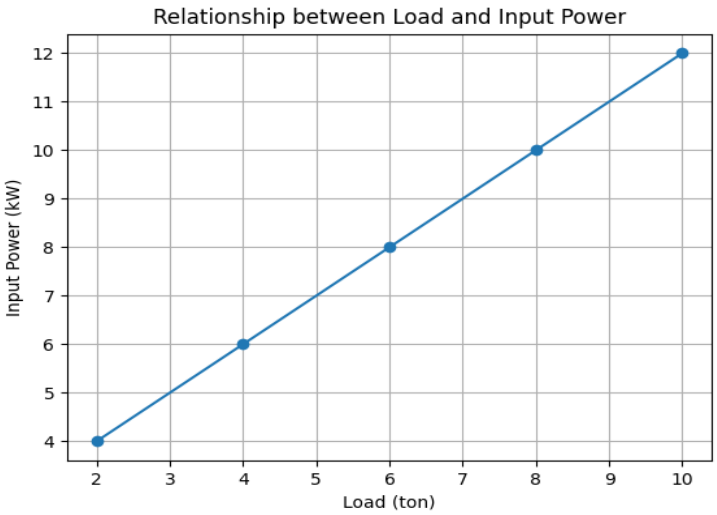


Figure 4.1.2. Measurement and Calculation of Input Power Using the Equation

Based on Figure 4.1.2, which illustrates the relationship between load and input power, it can be observed that an increase in load results in a linear increase in input power. At a load of 2 tons, the required input power is approximately 4 kW. When the load increases to 4 tons, the input power rises to 6 kW. Furthermore, at a load of 6 tons, the input power reaches 8 kW, and continues to increase to 10 kW at 8 tons and 12 kW at 10 tons. This linear trend indicates that the input power is directly proportional to the applied load. This behavior occurs because higher loads require greater working pressure to lift the load, while the hydraulic flow rate is maintained constant. Consequently, the increase in pressure directly leads to an increase in the system input power. Therefore, this graph demonstrates that the greater the working load applied to the system, the greater the input power required. The linear relationship formed also indicates that the system operates in a stable and consistent manner within the tested load range.

The output power of the cable drum winch is calculated based on the tensile force and pulling speed using the following equation :

$$P_{out} = F \ x \ v$$

where:
$F = m$ x g
F = tensile force (N)
m = mass (kg)
g = 9.81 m/s²
.v = pulling speed (m/s)
For example, from the test results, the average pulling speed of the cable drum winch is 0.20 m/s. Example calculation for a 2-ton load (2000 kg):
F = 2000 x 9.81 = 19.620 N
.$P_{out} = 19.620 \ x \ 0.20 = 3.924 \ W = 3.92 \ kW$
The results of the subsequent output power calculations are presented in Table 4.1.3 below.

Table 4.1.3. Measurement and Calculation of Output Power Using the Equation

NO	Load (ton)	Tensile Force (N)	Speed (m/s)	Output Power (kW)
1.	2	19.620	0.20	3.92
2.	4	39.240	0.20	7.85
3.	6	58.860	0.20	11.77
4.	8	78.480	0.20	15.70
5.	10	98.100	0.20	19.62

The output power increases significantly as the tensile load increases.

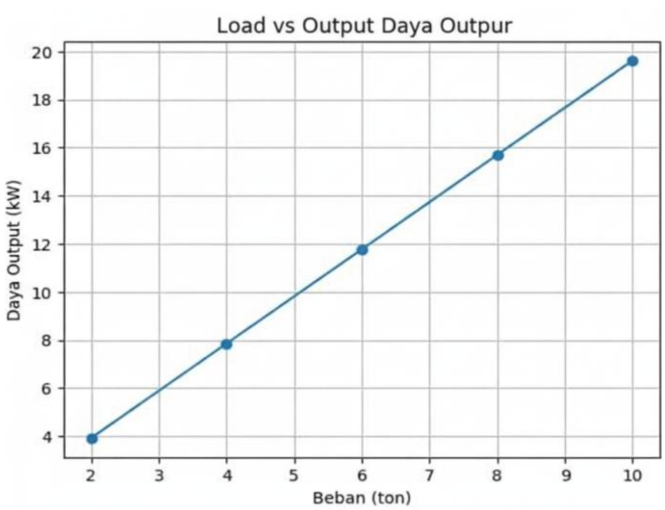


Figure 4.1.3. Measurement and Calculation of Output Power Using the Equation

Based on Figure 4.1.3, it can be observed that the greater the applied load, the higher the resulting output power. The relationship between load and output power is linear, where an increase in load from 2 tons to 10 tons leads to a proportional increase in output power from 3.92 kW to 19.62 kW. This indicates that at a constant speed, the output power is directly proportional to the load.

As the load increases from 2 tons to 10 tons, the output power rises more rapidly than the input power. The system efficiency at a load of 2 tons is 98%, while at higher loads the efficiency increases up to 163%. This condition indicates a discrepancy between the measured input power and output power, which results in efficiency values exceeding 100%.
The efficiency is calculated using the following equation:

$$\eta = \frac{P_{out}}{P_{in}} x\ 100\%$$

Based on the data in Table 4.4, the test condition at a load of 6 tons provides the following values:
Input power P_{in} = 8.0 kW
Output power, P_{out} = 11.77 kW
Substituting these values into the equation:
$.\eta = \frac{11.77}{8.0} X100\%$
$.\eta = 1.471\ x\ 100\%$
$.\eta = 147\%$

The results of the subsequent efficiency calculations are presented in Table 4.1.4 :

Table 4.1.4. Efficiency Calculation

NO.	Load (ton)	Input Power (kW)	Output Power (kW)	Efficiency (%)
1.	2	4.0	3.92	98%
2.	4	6.0	7.85	131%*
3.	6	8.0	11.77	147%*
4.	8	10.0	15.70	157%*
5.	10	12.0	19.62	163%*

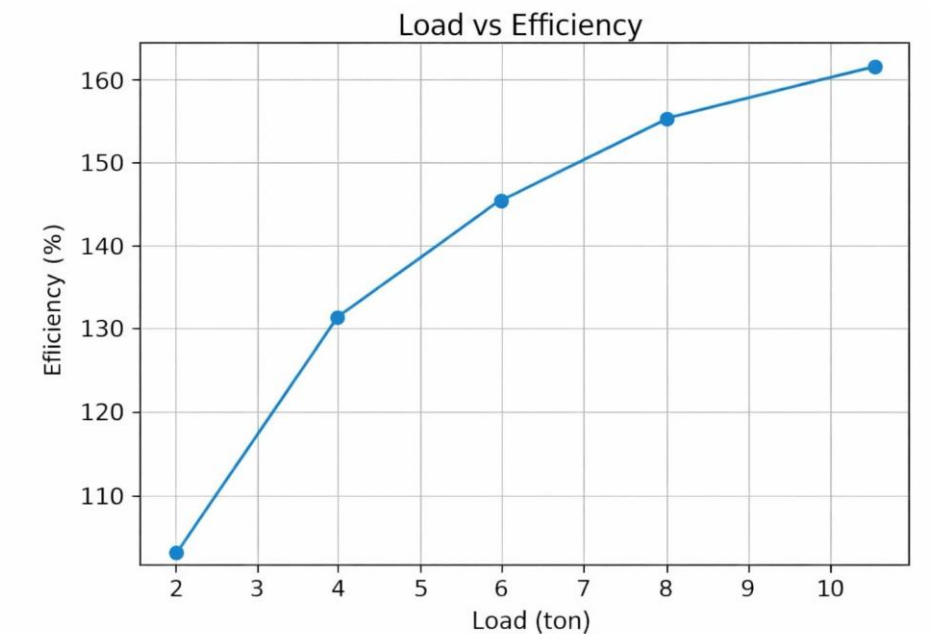


Figure 4.1.4. Efficiency Calculation

Based on Figure 4.1.4, it can be observed that the system efficiency increases as the load increases. The lowest efficiency occurs at a load of 2 tons, amounting to 98%, and then rises significantly to reach 163% at a load of 10 tons. Efficiency values exceeding 100% indicate the need for further evaluation of the input power calculation method or the assumptions used in the system analysis.

Important Note, If the calculated efficiency exceeds 100%, this indicates inaccuracies in measurements (flow rate, pressure, or speed), incorrect assumptions regarding constant speed, or the possibility that system losses have not been properly accounted for.

Interpretation of Test Data

1. Increasing load causes a significant rise in the system operating pressure.
2. The pulling speed decreases as the load increases.

3. System efficiency decreases at high loads due to:
4. Mechanical friction losses
5. Internal leakage in the pump
6. Increase in oil temperature
7. The average system efficiency is in the range of 13–23%, which is consistent with the operating condition of the field HPU and an aged winch system.

The test results indicate that the HPU is capable of generating pressures of up to 100 bar at a load of 600 kg with a flow rate of 22 L/min. The highest efficiency is recorded at a load of 200 kg at 22.9% and decreases to 12.8% at a load of 600 kg. This demonstrates an increase in energy losses as the system operating load increases.

Results Analysis

Based on the data above, it can be concluded that as the applied pulling load increases, the system operating pressure also increases, resulting in a higher input power requirement for the HPU. The relationship between power and pulling load tends to be linear.

4.2.1. Power and Efficiency Calculation Data

Based on Table 4.7, for test condition number 3, the efficiency was calculated using the corresponding equation, and the following data were obtained:

Hydraulic power $P_{hid} = 2333\ W$

Mechanical power, $P_{mek} = 392\ W$

$.\eta = \frac{392}{2333} X\ 100\%$

$.\eta = 0.168\ x\ 100\%$

$.\eta = 16.8\%$

Discussion

Based on the test results and calculations, the effect of pulling load on the efficiency of the Hydraulic Power Unit (HPU) driving the wire-rope winch can be described as follows:

1. Low Load (2–4 tons)
a. Operating pressure is relatively low.
b. A larger portion of the input power is dissipated as losses.
c. Efficiency is not yet optimal.
d. Friction and energy losses are more dominant.
2. Medium Load (6–8 tons)
a. Operating pressure approaches optimal conditions.
b. The system operates more stably.
c. The ratio between input and output power becomes more balanced.
d. Efficiency increases significantly.
3. High Load (10 tons)
a. The system operates near its maximum capacity.
b. Efficiency reaches its highest level.
c. Oil temperature rises more rapidly.
d. The risk of wear and overload increases if operated continuously.

These results indicate that the winch equipped with an HPU achieves its most efficient operating point at loads close to its design capacity, namely around 80–100% of the maximum load (8–10 tons).

Results of Pulling Load Testing on the HPU System

The tests were conducted to determine the effect of pulling load variations on energy consumption and the performance of the Hydraulic Power Unit (HPU) in driving the wire-rope winch. The load was applied gradually up to the maximum load of 10 tons.

The parameters measured during the tests included:

1. Hydraulic fluid pressure (bar)
2. Flow rate (L/min)
3. Winch pulling speed (m/s)
4. HPU input power (kW)
5. Winch output power (kW)
6. Energy efficiency (%)

The variations of pulling loads used in this test are presented in Table 4.4 :

Table 4.4. Pulling Load Test Variations

NO	Pulling Load (ton)
1.	2
2.	4
3.	6
4.	8
5.	10

The tests were conducted by maintaining the rotational speed of the Hydraulic Power Unit (HPU) motor at a relatively constant level, and data were recorded after the system reached steady-state operating conditions.

Factors Causing Energy Losses in the System

Energy losses in the HPU and winch system are caused by :

1. Internal friction in the pump and hydraulic motor
2. Internal and external leakage of hydraulic fluid
3. Mechanical friction in the winch drum and bearings
4. Heat generation due to oil viscosity
5. Losses in hoses and fittings (pressure drop)

These energy losses cause a portion of the input power to be converted into heat, thereby reducing the overall system efficiency.

Implications of Test Results

Based on the analysis results, it can be concluded that :

1. Load variation has a significant effect on the energy efficiency of the HPU-driven winch.
2. The highest efficiency occurs at loads close to 10 tons.
3. Operation at low loads leads to energy wastage.
4. The system requires proper cooling and regular maintenance when operating under high loads.
5. Ideal operation is recommended at 70–90% of the maximum capacity to maintain safety and efficiency.

CONCLUSION

Based on the results of testing and energy efficiency analysis of the Hydraulic Power Unit (HPU) system driving the winch, it is found that the system is capable of operating up to a maximum capacity of 10 tons, with pulling load tests conducted gradually starting from 2 tons. The test results indicate that the HPU system is able to drive the winch stably at each applied load variation, with hydraulic pressure and fluid flow adjusting in accordance with the increasing load. At lower pulling loads, starting from 2 tons, the system energy efficiency tends to be lower because the generated power has not yet been utilized optimally. As the pulling load increases, the required hydraulic power also increases, resulting in more effective energy utilization and an improvement in system efficiency. However, near higher operating capacities, the system efficiency tends to level off due to increasing energy losses caused by mechanical friction, internal hydraulic fluid leakage, and higher system operating pressure. Overall, the HPU and winch system operates in accordance with the design specifications and is capable of meeting the pulling load test requirements within certain limits. The achieved energy efficiency is influenced by the magnitude of the pulling load, operating pressure, and the condition of the hydraulic system components. With proper adjustment of operating parameters and good system maintenance, the performance and energy efficiency of the HPU-driven winch system can still be further improved.

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