Efficiency Considerations of Power to Thrust Conversion in Underwater Thrusters

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Abstract

Propulsion systems are a central element to all underwater vehicles. A wide range of design parameters must be considered to provide the best propulsion for each specific vehicle. In order to properly evaluate different thruster systems, it is important to understand the tradeoffs between size and weight, propeller diameter, power source, power transmission and kinetic energy conversion to thrust produced by each horsepower of input. The necessary data is typically available on most specification sheets from manufacturers to obtain thrust and corresponding input power parameters. In some cases, input power is only provided indirectly by giving Hydraulic Pressure and Flow Rate, or for electrical motors by specifying voltage and current. All of these parameters can provide input power values at corresponding thrust levels. This papers presents the ideal theoretical kinetic jet energy conversion to thrust as a baseline from which to compare the merits and efficiencies of different thrusters.

Introduction

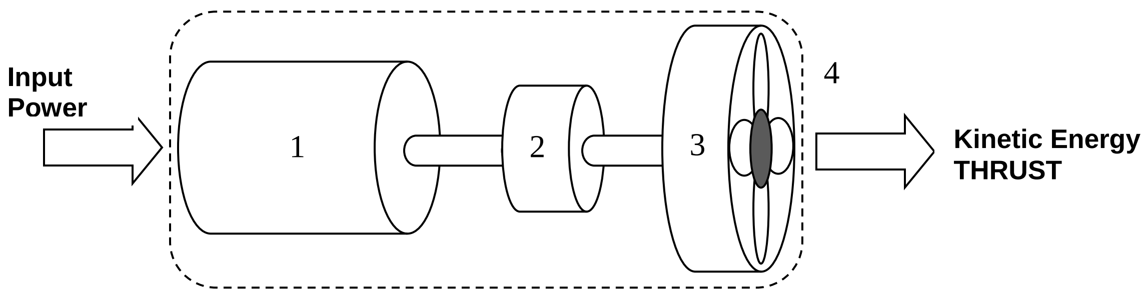
Underwater thruster technology has fascinated humans from the early days that Archimedes invented the screw. Since then all types of systems have been tested and there has been a significant evolution to today's thrusters. Yet, although the propulsion system is a crucial element of every underwater vehicle, its understanding remains shrouded in mystery and its performance evaluation not always easily understood.

The essence of any thruster is to produce a kinetic jet power to produce a movement force given a specified amount of input power. Whether the input power is manual, mechanical or electrical is of little importance. In all cases the objective is to obtain the most kinetic power for every unit of input power. This is the basis if thruster efficiency. The only other parameter that becomes important is the size and weight. A thruster can be very efficient but it very large and heavy. Therefore there is an efficiency of power conversion and an efficiency of space (weight and size). In very general terms, larger propellers and motors will always be more efficient than smaller units operating in the same output range. The compromise, of course, is size and weight. In the process of evaluating a propulsion system, it is incumbent on the engineer to compare thrusters based on equivalent propeller diameter size and establish the level of efficiency through its range of thrust. The choices then lead to the consideration of the physical constraints dictated by the vehicle design. Once a physical envelope is established, the evaluation can then consider whether the motor will be hydraulic or electric, whether the vehicle is surface powered or battery powered. The final stage is the selection of motor according on the HPU pressure and flow capability in the case of a hydraulic unit, or voltage and current in the case of an electric system.

For large surface powered remotely operated systems, the efficiency of the power conversion may be secondary to physical dimensions. The form factor is often a significant consideration pushing thrusters to be as small as possible. In manned underwater vehicles on the other hand, with limited power storage, while form factor is significant, efficiency of power conversion is of primary importance. In all cases, however, establishing the power efficiency of a thruster is an effective way to compare propulsion systems. All data needed for such comparison are easily available from manufacturers which includes Thrust capabilities with their respective Input Power requirements to produce this propulsion force. The efficiency of converting this energy into propulsive force is universal and all propulsion systems can be measured against an ideal Power-to-Thrust conversion formula shown in Equation 1.0 below.

Not only do propeller designs have a power conversion ratio (efficiency) but so do the motors and the transmission system between the motor and the propeller. Transmission devices can consists of a wide variety of gear boxes or a hydraulic power unit. In the pursuit of efficiency of power conversion, a direct drive system is the simplest configuration. With the understanding that every phase of power conversion absorbs some energy, the most direct method is always most efficient. It may not be the most compact but in terms of system reliability, dependability and efficiency, it is unmatched.

FIG 1.0 Semantics of Propulsion Systems



1 – Motive Source
- HPU for hydraulic Systems
- AC or DC Motor for electric Systems

2- Power Transmission
- Gear box
- Direct coupling
- Hydraulic motor

3- Thruster
- Ducted Propeller
- Turbine Propeller
- Waterjet or other

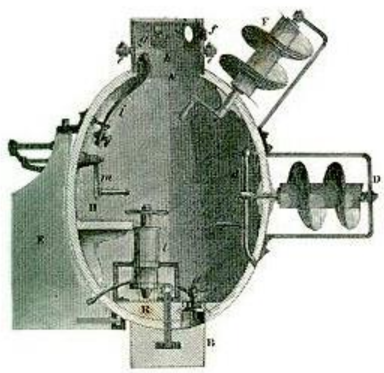
4 – Propulsion System

The propulsion system receives energy and produces the kinetic energy that generates thrust (element No. 4). The thruster (No. 3) consists of a propeller and shroud that is designed to generate thrust through a specific speed range (RPM) and required shaft torque. The propeller will produce a level of thrust at a certain speed and torque, regardless of the method used to produce this motion. This is why a propeller can work equally well with a hydraulic or electric motor, as long as the right amount of speed and torque are delivered to the shaft, the thruster will produce the same amount of kinetic energy.

Thruster shapes and size can vary widely. The diameter of the propeller is a prime determinant while the number of blades and pitch will determine the power profile of the propeller (ie required torque at shaft speed). It is very difficult to say that one propeller is better than another, as each provide some specific advantages for different vehicles.

For underwater vehicles, there are several traits that are more valued than other:

1) Maximum Thrust Capability
2) Efficiency of power conversion
3) Form Factor
4) Bi-Directional Thrust
5) Debris Protection



Turtle Submersible (1776)

Modern Turbine Thruster

Azimuth Drive Thrusters

The question as to which is better is not answered in a single answer. To best establish a baseline against which to evaluate thruster systems, it is useful to return to the very basics of propulsion systems.

Every propulsion system using a propeller of a specified diameter will have a theoretical maximum kinetic power conversion capability to convert energy to rotate the propeller and produce kinetic energy through the water mass that will generate thrust. This universal function is described by:

Equation 1: $$\text{Input POWER} \times n = \text{Kinetic Jet Power} = \frac{(F)^{3/2}}{1100}\sqrt{\frac{g}{W\ A}}$$

Where:

Input POWER = HP in
Kinetic Jet Power = HP Out
n = efficiency
F = Thrust (lbs)
g = acceleration of gravity (32 ft/sec^2)
W = Specific Weight of sea water (64 lb/ft^3)
A = Area of exit (feet^2)

This is of significant value as it provides an "IDEAL" conversion of power to thrust for underwater thrusters given a specified "area of exit" which is based on propeller diameter. The ratio of the Kinetic Power to Input Power establishes the efficiency of the thruster design. If one chooses to set the efficiency at 1.0 (100%) it is possible to graph the theoretical maximum thrust that can be generated by a propeller of a certain diameter given a specific input power. As an example in Figure 1, the graph provides a comparison of Input Power versus Thrust produced for three sizes of propellers: 5.0 inch, 12 inch and 24 inch diameter. It is clearly observed that the larger diameter propeller will produce a specified level of thrust with less input power.

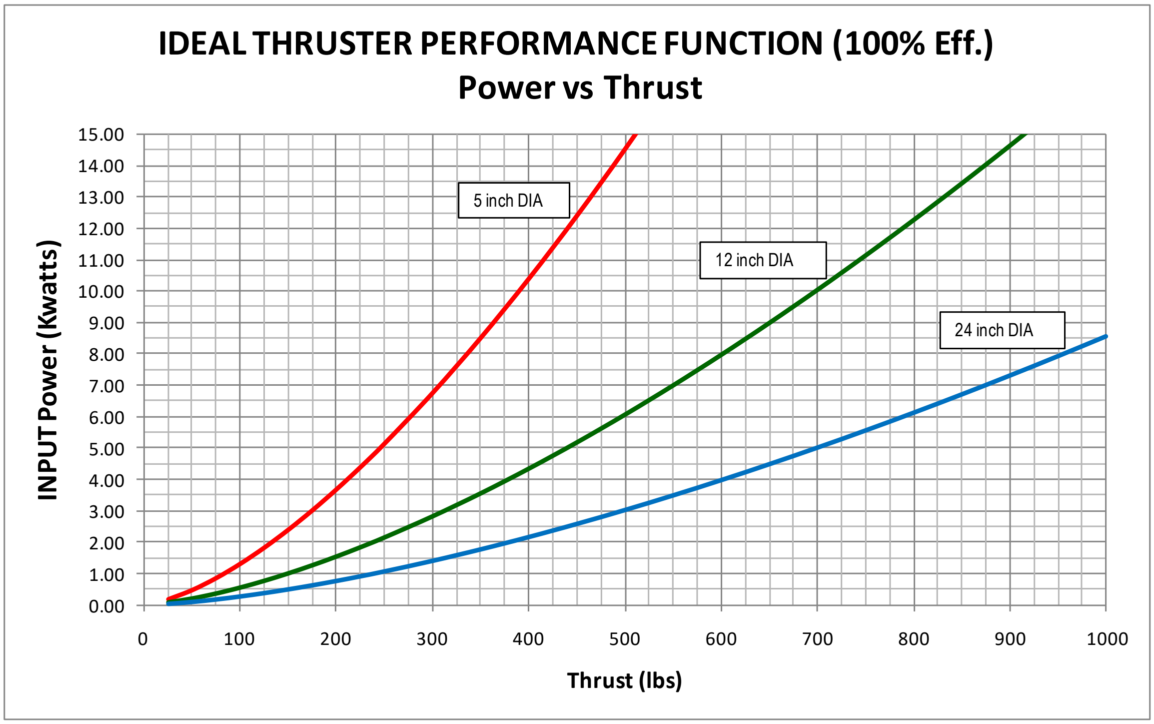


Figure 2. Ideal Power conversion to Thrust by three size propellers

From such a graph it can be found that in order to obtain a thrust of 500 lbs, a propeller of 24 inch diameter would require a minimum of 3.0 Kwatts input power under ideal conversion function. A 12 inch diameter propeller would require 6.0 Kwatts and a 5 inch diameter propeller would require nearly 15Kw. This disparity is even before any engineer has applied the art of thruster design. In reality it is rather difficult to achieve efficiency levels above 50% from this ideal condition and although this graph has little practical meaning, it does provide a useful universal backdrop against which various thruster systems can be compared.

EVALUATING THRUSTER PERFORMANCE

It is easy to see from the graph above that there is a wide range of choices given a specified thrust range desired. In addition, since the graph uses Input Power to the entire Thruster System (Fig 1.0 item 4), the energy needed for the motor and the energy expended in the transmission are all additional to this input power level. Consequently, it does become of significant importance which type of energy source is used, how efficient this first level of energy conversion is created (rotary motion from motor) and then how efficient the coupling/transmission is to the actual propeller shaft.

As an example, if a motor with 80% efficiency is coupled to a gear box which itself is 80% efficient then only 64% of the energy is actually reaching the propeller to convert into Kinetic energy and thrust. Such a case is easy to demonstrate the benefits of a direct drive between the motor and propeller. Eliminating the transmission would immediately raise the efficiency from 64% to 80%. Direct drive systems are simple, and reliable, whether for hydraulic or electric motor drives.

Why does anyone use a transmission?
The main reason is for form factor control. A specific thruster will require a minimum torque at a particular RPM. It is easy to imagine that smaller motors are always better at producing high speed and less torque. Transmissions are perfect tools to reduce speed to the level needed while also multiplying its torque. Consequently, given any random motor specification, a transmission gearbox can be produced to match the perfect speed/torque profile needed by the propeller. Similarly, one could use a very small motor and couple it to a 10:1 gearbox to produce a very compact thruster system. The tradeoff for such a thruster system, however, is the reduced system efficiency and the dynamic response of the thruster. It is easy to picture that if the motor must spin at 6000RPM for rated thrust, it would take some time to reverse this thrust and spin 6000RPM in reverse. There is nothing fundamentally bad about it but a tradeoff of dynamic power control for the benefit of a smaller size. A direct drive motor would have to be bigger to produce 10x more torque (in order to eliminate the transmission), but it would provide very quick thrust response as demanded by the user.

Some other reliability issues with transmissions are maintenance requirements. In addition, the benefit of the gear ratio can also be a liability if the propellers are locked/jammed. Various coupling techniques have been devised, including magnetic couplings, but these generally only add complexity to the system that also affect efficiency. In a direct drive system, no coupling is really needed to protect the mechanical items because the propeller and motor shaft are already protected by a magnetic coupling inside the motor between the rotor and the stator. The principal draw back of a static magnetic shaft coupling is that if it dis-engages under operation, the motor must come to a standstill before the coupling can reset. These couplings can also loose coupling if a large torque moment is applied. In all cases, these failure mechanisms occur under severe operation, but that is exactly when the response of the thruster is most critical to the safety of the vehicle.

Hydraulic Motors vs Electric Motors
Hydraulic motors provide some of the most compact power densities possible. However, this generally does not take into account the power and space required by the hydraulic Power Unit (HPU). There are many reasons why hydraulic motors are useful in underwater vehicle designs, especially in large power units of 100HP and more. These vehicles are large and the hydraulic piping required to each motor becomes very practical for the power levels that are transmitted. These vehicles are typically remotely controlled and surface powered, where power efficiency is not the leading design parameter.

Electric motors have the distinction that they are self contained elements and only require adequate cabling to each motor for operation. The issue of motor control electronics is a significant element in the design, but beyond the scope of this paper. The unique feature of an electric motor is that they can be designed and fabricated to provide any torque level at any speed, given a specific source voltage, by simply customizing the motor windings and the internal magnets. This makes it possible to design an electric motor that can perfectly match the torque/speed requirements of a thruster to operate at it optimum level. This can increase efficiency, eliminate the need for a transmission or both. If a motor is not properly matched to the thruster/propeller, the output performance will be diminished and consequently, so will the efficiency.

Symmetric Efficiency
One of the features that is highly valued and sought in all underwater thruster systems is their ability to provide bi-directional thrust. This means the thruster operates in forward and reverse. Since there are no brakes on an underwater vehicle, the ability to reverse thrust for stopping can be very important.

Most propellers are designed to go in only one direction. The asymmetry of the blade design is usually a good indicator. This allows an engineer to optimize the thrust generated by the propeller in one direction, at the expense of the reverse direction. The ratios of forward to reverse thrust can be as much as 2:1 or sometimes more. In the case of underwater vehicle thrusters, one would prefer this ratio to be 1:1. In evaluating the performance of a thruster, one is best to evaluate the performance based on the average thrust between forward and reverse, or add the forward & reverse thrust to determine its maximum capability.

Evaluating Thruster System Performance
Evaluating a thruster system will ideally provide the efficiency of the thruster/propeller, the efficiency of the transmission (if present) and the efficiency of the motor (if electric) or motor + HPU (if hydraulic). However, this is usually more than can be determined by standard commercial thruster systems on the market. Typically, the data available is limited to thrust and power levels, with many occasions where the input power levels are not provided, but they can be determined. Even if only the overall efficiency is determined along with its maximum total and average thrust, this can provide a good basis for relative evaluation of the thruster system.

To compare the performance of two thrusters, it is only proper if one compares two thrusters of comparable propeller diameter. This example will look at the Innerspace 1002-1.23 turbine thruster which offers a propeller diameter of 11.2 inches, and the Sub-Atlantic Thruster SA-300 which offers a slightly larger diameter of 11.8 inches. This is essentially close enough for a reasonable comparison although the SA-300 is slightly larger. From published performance data of thrust and input power available from the manufacturers, a comparison table is produced as shown in Table 1.0 using the published thrust performance and input power parameters. Then using the Kinetic Jet power of Equation 1, it is possible to calculate the overall propulsion efficiency of the thruster system. This can then be compared to the ideal Power-Thrust conversion ratio from Eq. 1 assuming 100% efficiency.

Fig 3.0 below shows the system efficiencies of two electric thrusters on a single graph. The green line shows the thrust conversion curve for a 12inch dia thruster at 100% efficiency. The Black line shows the efficiency of the complete Innerspace 1002-1.23 thruster system while the Red line shows the efficiencies of a Sub-Atlantic SA-300-30 thruster system.

The blue line illustrates the efficiency of the innerspace 1002-1.23 thruster propeller unit alone, while the Black line shows the effects of adding the direct drive motor. This type of data is not always available from manufacturers but is provided by Innerspace for all their thruster propellers. Only the total system efficiency can be determined from the specification data provided with the Sub-Atlantic thruster.

10HP 460V motor with 1.23 Thruster			
Thrust lbs	Input Power Kwatts	Calc. Kinetic Power (Kw)	Efficiency %
36	0.20	0.12	59.7%
82	0.61	0.40	65.7%
145	1.41	0.95	67.1%
227	2.8	1.9	66.8%
327	4.9	3.2	65.9%
445	7.9	5.1	64.7%
582	12.0	7.6	63.5%
736	17.4	10.8	62.1%
909	24.4	14.8	60.8%
1100	33.2	19.7	59.5%
1309	44.0	25.6	58.2%
1536	57.2	32.6	57.0%
1782	73.0	40.7	55.8%
2045	91.6	50.1	54.6%
2327	113.5	60.8	53.5%

SP300-30 (11.8 inch DIA Prop.)			
Bollard Thrust (lbs)	Input Power (Kwatt)	Calc. Kinetic Power (Kw)	Efficiency %
220	4.0	1.8	44.1%
330	6.5	3.2	49.9%
440	9.5	5.0	52.6%
550	13.0	7.0	53.7%
660	16.8	9.2	54.6%
770	21.0	11.6	55.1%

Table 1.0 Comparison of Power versus Thrust performance data

Figure 2 below illustrates the efficiency of the two thruster systems compared against the ideal performance of a 12inch propeller thruster. The Blue curve represents the

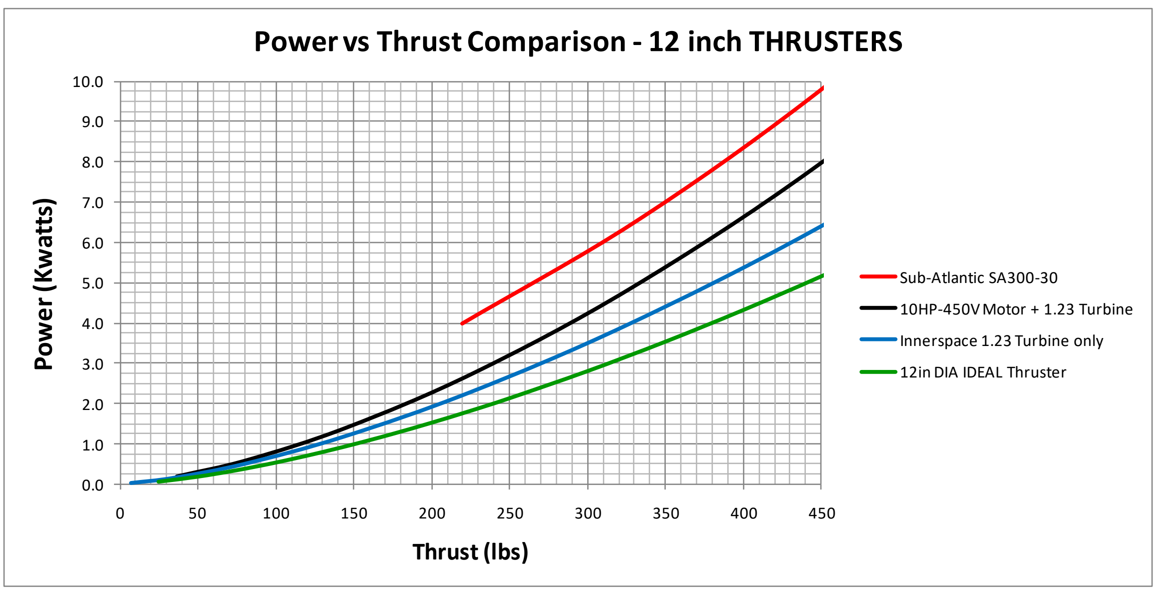


Figure 3.0 Performance Comparison of Innerspace 1002-1.23 Thruster System

performance of the Innerspace1002-1.23 turbine propeller system alone, which achieves an efficiency in the range of 80%. The Black curve represents the total power input combining the 1.23 turbine with a 10HP, 460VDC brushless DC motor.

The same type of comparison can be made with a different 12 inch propeller system, such as the Tecnadyne 2020 which offers two choices of electric motors: a 150V and a 300V system. Both have different performance characteristics and based on published thrust data along with corresponding current and voltage, the input power is easily obtained.

Input Power (watts) = Current * Voltage

Based on this simple equation, the diameter of the propeller (12 inch) and using the earlier formula for Kinetic Power, the data is easily presented in a comparison chart that clearly demonstrates the efficiency comparison of all components.

Tecnadyne 2020-150V (12.0 inch DIA Prop.)			
Bollard Thrust (lbs)	Input Power (Kwatt)	Calc. Kinetic Power (Kw)	Efficiency %
50	0.5	0.2	42.5%
100	1.2	0.5	45.1%
150	2.3	1.0	44.2%
200	3.8	1.5	40.8%
250	5.7	2.1	37.5%

Tecnadyne 2020-300V (12.0 inch DIA Prop.)			
Bollard Thrust (lbs)	Input Power (Kwatt)	Calc. Kinetic Power (Kw)	Efficiency %
100	0.9	0.5	60.1%
200	2.7	1.5	56.7%
300	5.4	2.8	52.1%
400	8.4	4.3	51.5%
500	12.6	6.0	48.0%

Table 2.0 Performance data for 12 inch Tecnadyne Thruster using 150Vdc and 300Vdc motor

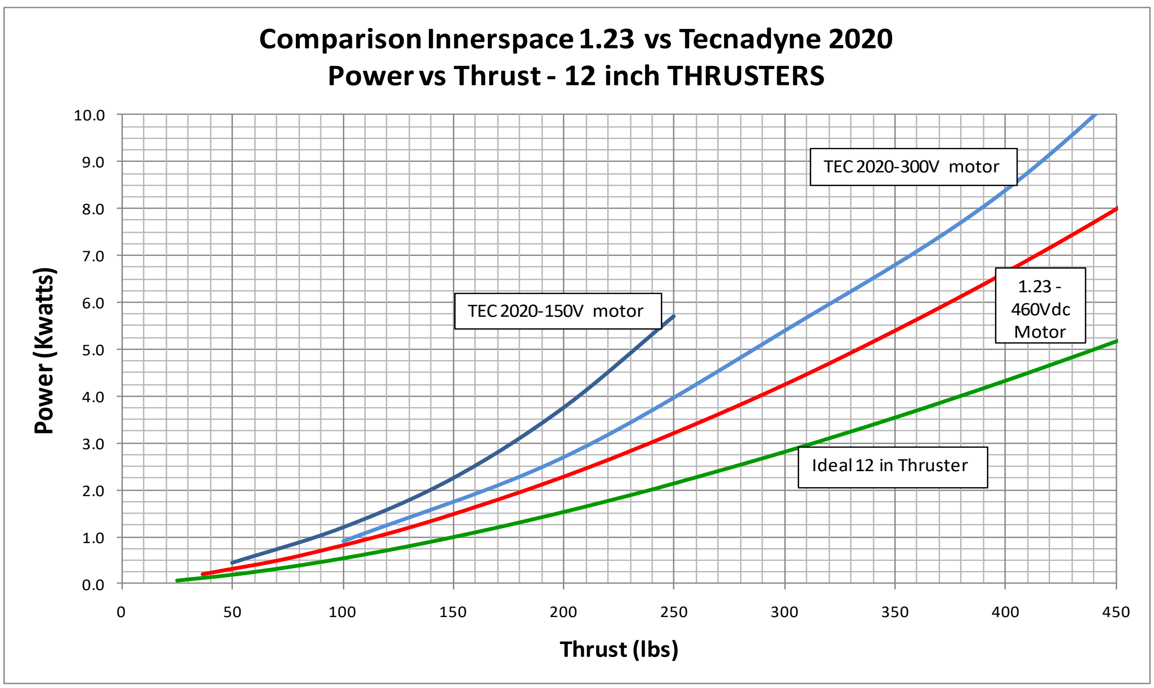


Figure 3.0 Performance Comparison of Innerspace 1.23 and Tecnadyne 2020 Thruster

Figure 4.0 below illustrates the performance efficiency of the same three thruster systems. Although it is not possible to separate the efficiencies of the motors and of the propellers in other systems, the Innerspace 1.23 turbine assembly shows an 80% efficiency in converting its input power into jet kinetic power.

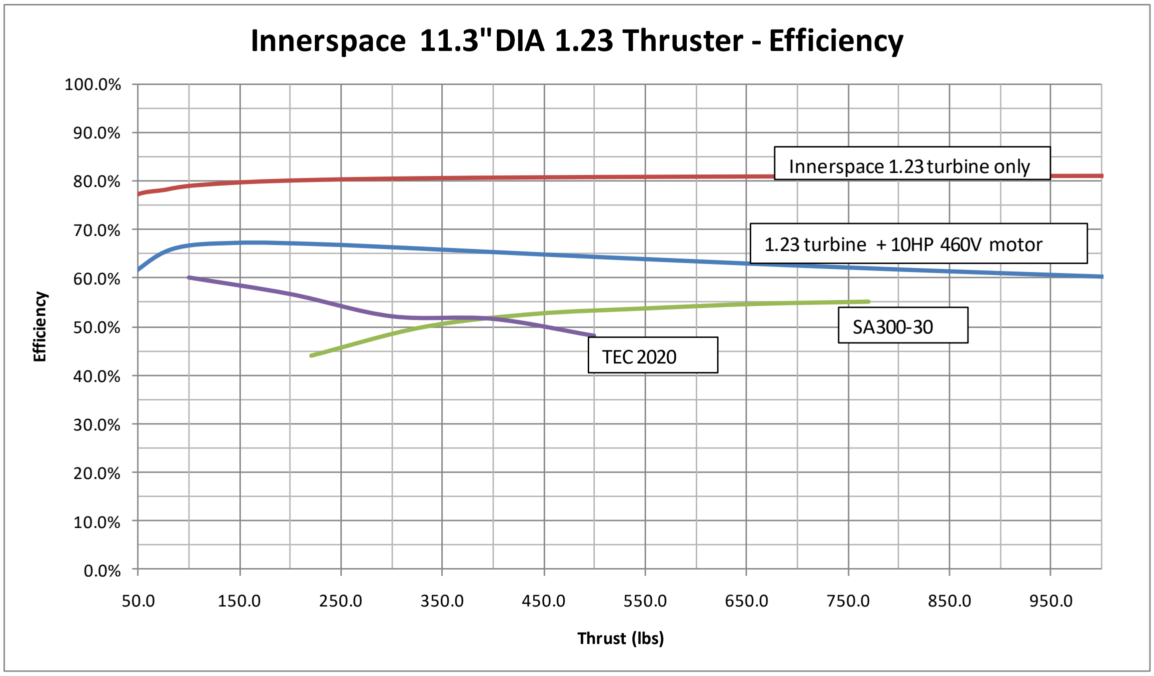
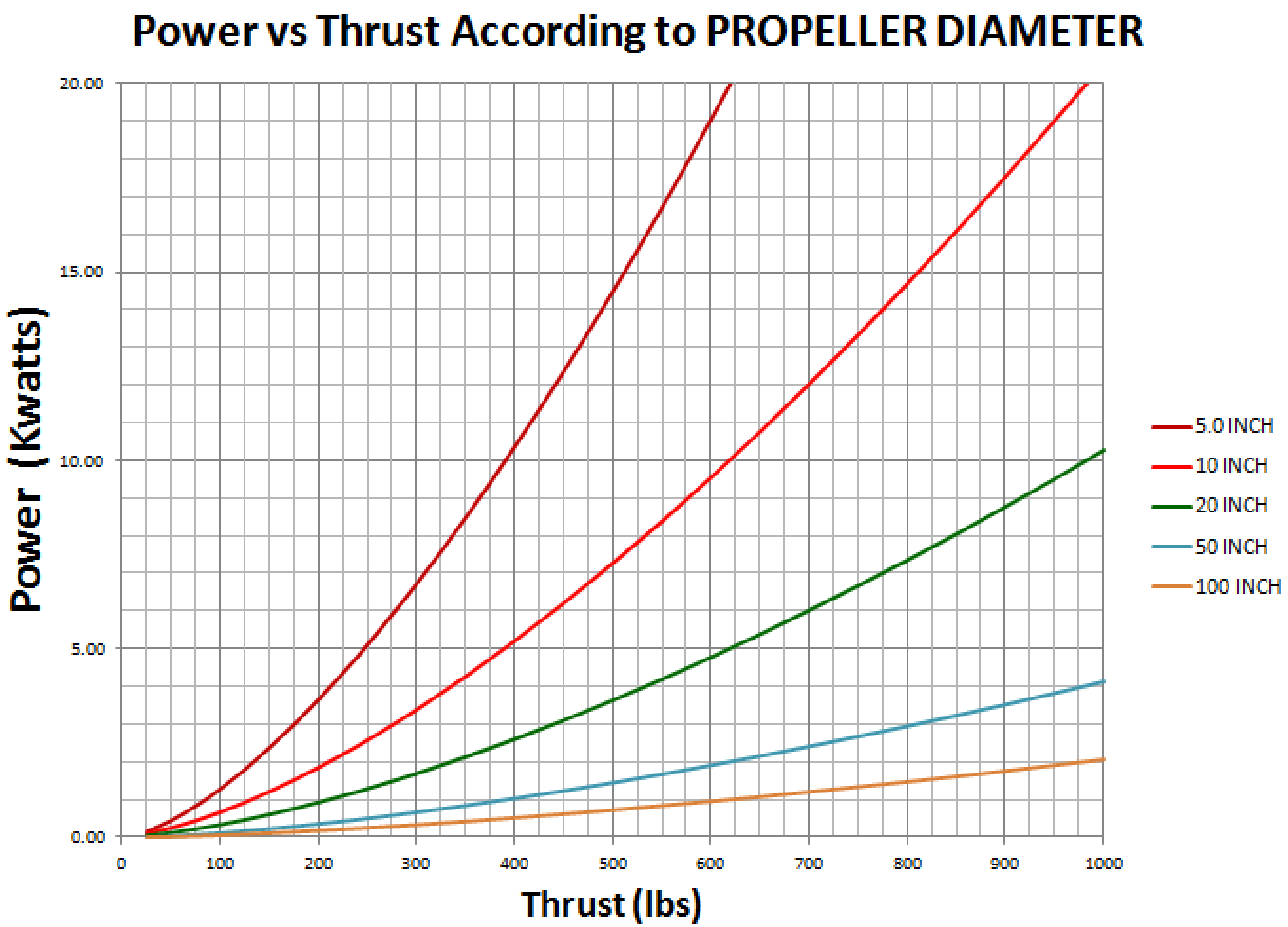


Figure 4.0 Efficiency Comparison of Innerspace 1002-1.23 Thruster System

Conclusion –

In order to properly evaluate different thruster systems, it is important to understand and consider the size of the units, as the propeller diameter has a big impact on the theoretical level of thrust produced by each horsepower of input. The necessary data is easily available on most specification sheets from each manufacturer to obtain different values of thrust with corresponding input power. In some cases, input power is only provided indirectly by giving Hydraulic Pressure and Flow Rate, or for electrical motors by giving voltage and current. All of these parameters will provide values of input power at that thrust level. The kinetic jet energy can be calculated by the equation given earlier and efficiencies can be determined for each device.


Power vs Thrust According to PROPELLER DIAMETER
Power (Kwatts)
20.00
15.00
10.00
5.00
0.00
0
100
200
300
400
500
600
700
800
900
1000
Thrust (lbs)
5.0 INCH
10 INCH
20 INCH
50 INCH
100 INCH