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HEMP sea Trial results

Overview

HEMP (Hybrid Electric Marine Propulsion) is an experimental serial hybrid system. With reference to fig1, the vessel is propeller driven using an electric motor. Speed control is effected via a motor controller. The electrical energy required can come from a multitude of sources.

1. An internal combustion engine (ICE) diesel generator.
2. Solar Panels.
3. Wind generators.
4. AC mains supply.
5. Regeneration (When under sail the motor can be used as a generator to charge the batteries)
6. Fuel cell.
7. Other charging sources.

All power sources can buffer their energy in the battery bank for future use. In the case of the ICE generator it can also bypass the battery bank and supply the motor directly. All resources are monitored and controlled via a system of networked microcontrollers (small computers). A central controller is used to supervise the system and analyze real-time performance data.

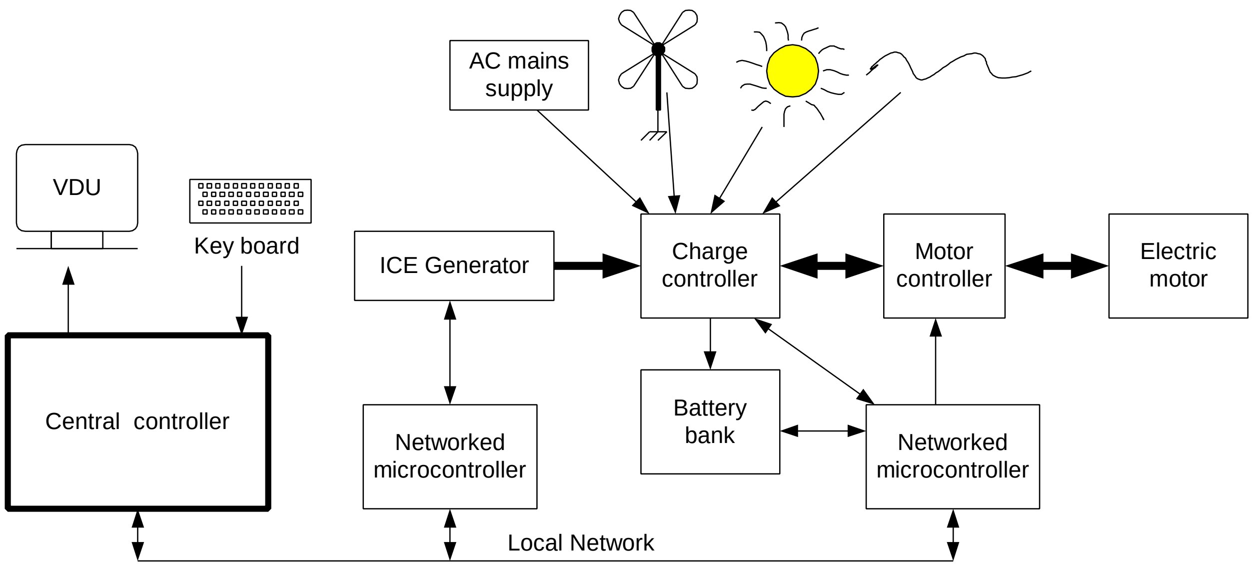

Fig1, Top level block diagram of HEMP

The performance of the generator and charging system has been extensively analyzed (Hawk,2005). The intention of this stage of the sea trials is to determine the complete drive train performance when operating in serial hybrid mode (energy from generator is buffered through the batteries).

The Vessels

Two sister ships have been used to provide a comparative evaluation of technologies. These craft are of the "Wylo" class and are auxiliary powered, gaff rigged cutters with a hull length of 32' (9.754m) and a designed displacement of 6,230kg. See plate1 and table1 for further details.

Plate1, 333.jpg, Three "Wylos" in the river Medina, Left is "Iris", middle is "Apple" and right is "Maud"

Vessel Name	**"Apple"**	**"Maud"**
Propulsion	28hp, Marinised industrial diesel with shaft drive via a reduction gearbox	HEMP Serial hybrid using a 13hp industrial diesel generator and electric motor drive.
Max shaft speed	1,800 RPM	1,030 RPM
Propeller	3 blade, 14" by 9"	3 blade, 18" by 11"

Table 1, a comparison of the two craft used during sea trials.

Calibration of equipment

The following items of test equipment were used during these trials.

1. Digital balance 0-200kg
2. Fuel flow measuring device comprising of a closed flow/return loop, a calibrated burette and a digital stop watch (Hawk, 2005), see plate2.
3. Digital volt meter (Micronix).
4. Digital clamp current meter (LEM).
5. Electronic trailing log with an analog dial speed indicator.

6. Hand held Garmin GPS.

Spring balance : This is a KERN HCB200 device with a maximum reading of 200kg. The reproducibility is specified as 0.5g with a linearity of 1.0kg. This unit was purchased new, just prior to the test and the accuracy should be better than 1%.

Fuel flow measuring : The burette is specified with an accuracy of 1% and it was assumed that the digital stopwatch provided an accuracy of better than 1%.

Voltage and current meters : Both these instruments are specified to an accuracy better than 1%.jhhghghg

Speed measurement : The trailing log was calibrated against the GPS when in non-tidal waters. A graph of the measured deviation is shown in fig2.

Plate2, measuring fuel consumption on "Apple"

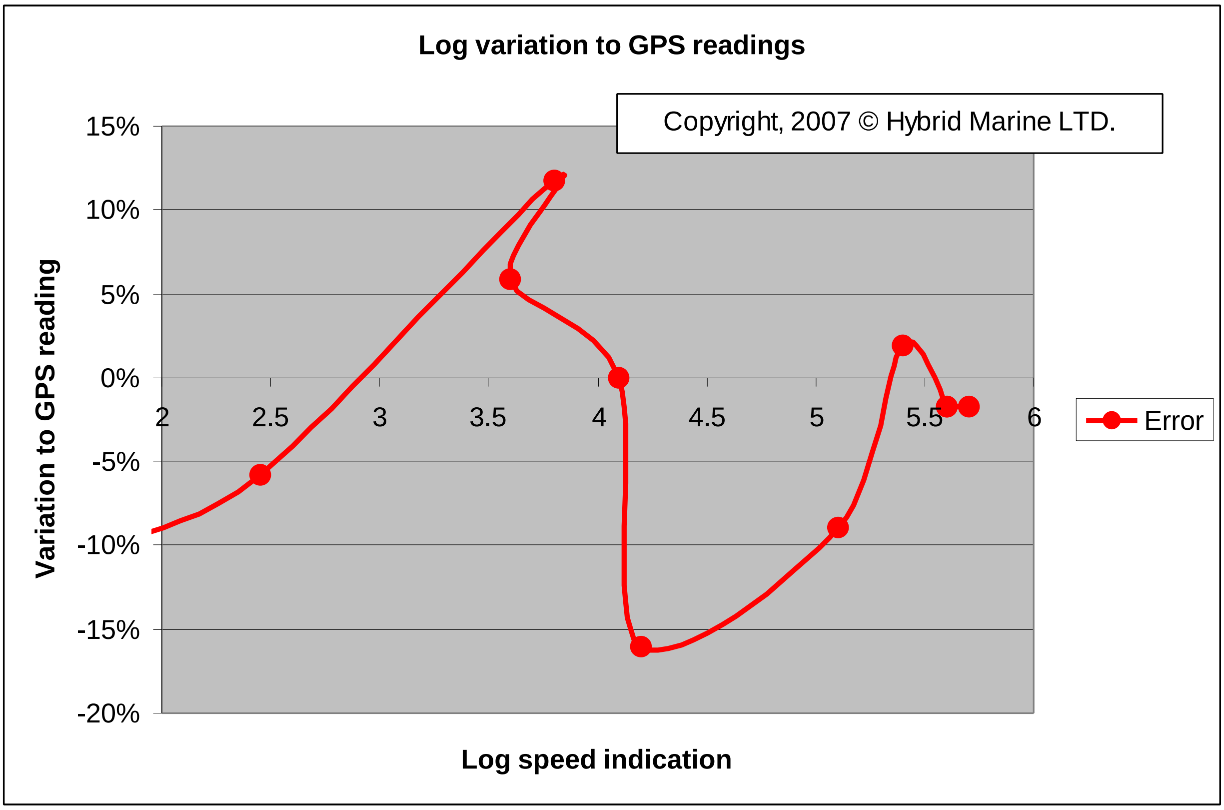

Fig2, Variation between trailing log and GPS.

It is assumed that the GPS has an intrinsic high accuracy of speed measurement. However the response to speed changes appeared very long indicating a long integration time (perhaps 60 seconds). Readings appeared to fluctuate during an apparently constant speed of the vessel. The trailing log responded to variations faster but the small analog dial made readings prone to error (+- 0.2kts)

Most of the testing was performed in tidal waters and the trailing log was relied upon to provide all speed data. The same error applies to each vessel and since this was a comparative test then the accuracy was deemed sufficient for this purpose.

Drag testing

The drag of both hulls was measured by tow testing. Each craft was towed at various speeds using a tow rope connected to a digital spring balance. Vessel speed was measured using the trailing log.

Raw data is provided in tables 2&3 and this is displayed in graphical form in fig 3,

Maud				
Speed kts	**Speed m/s**	**Pull kg**	**Drag Newtons**	**Power kW**
1	0.51	6.25	61.31	0.03
2.6	1.34	17.25	169.22	0.23
3.1	1.59	24	235.44	0.38
3.5	1.80	27.5	269.78	0.49
3.8	1.95	34	333.54	0.65
4.4	2.26	39.5	387.50	0.88
5.8	2.98	71.25	698.96	2.08

Table2, Drag testing data for Maud

Apple				
Speed kts	Speed m/s	Pull kg	Drag Newtons	Power kW
0.5	0.26	7	68.67	0.02
1.9	0.98	14.5	142.25	0.14
2.4	1.23	19.5	191.30	0.24
3	1.54	27.5	269.78	0.42
3.4	1.75	37.5	367.88	0.64
3.7	1.90	44	431.64	0.82
4	2.06	51	500.31	1.03
4.5	2.31	64	627.84	1.45
5	2.57	77	755.37	1.94

Table3, Drag testing data for Apple

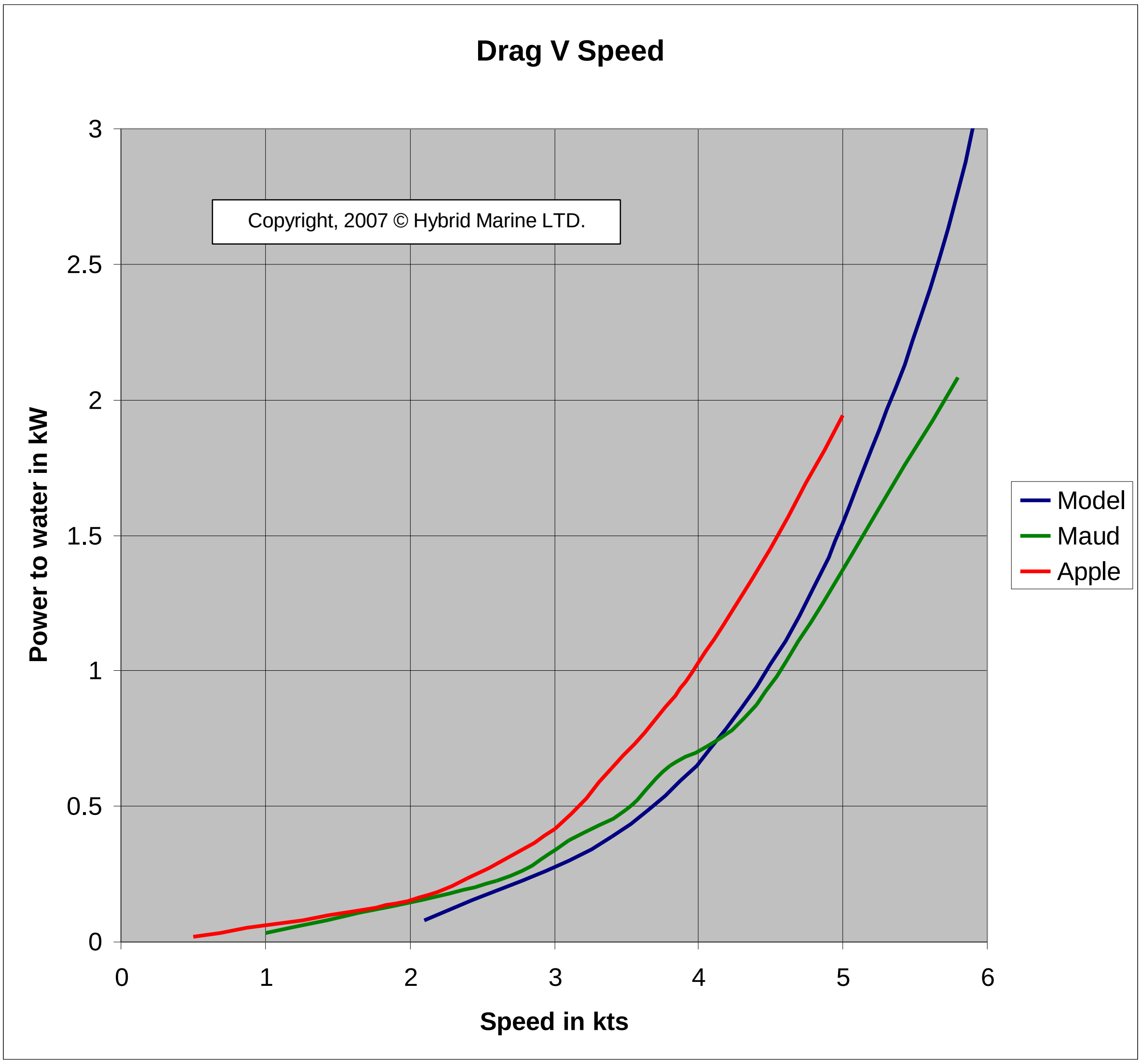

Fig 3, Comparison of measured drag to the software model.

A number of observations can be made :-

Maud has not been completely fitted out, has no spars or sails, the tanks are empty and she is high on her waterline. Her weight is probably at present below the designed weight. These factors combine to make her drag lower than expected at speeds above 4kts.

Apple is in full cruising trim with a considerable amount of gear. Her displacement is probably 1-2 tons above designed weight. She also has a seasons fowling on her hull. These factors combine to make her drag higher than the model and higher than Maud.

When presenting comparative data in this report, the measured performance for Maud has been modified. This adjustment is to account for the difference in drag performance and indicates how the Serial Hybrid is expected to perform in Apple's hull.

Note: Drag testing was not performed above 5.8kts. This is due to the limited power of the towing vessels. When determining the difference in drag at higher speeds, extrapolations were made from the available data.

Plate3, 364.jpg "Maud", showing herself high on her marks

Maud performance measurements

Maud was tested in calm conditions with no tidal flow. She was run at varying speeds (measured by trailing log) while system voltages & currents were measured. Table 4 provides the measured data.

Speed LOG	Bat Volts	Current Amps	Power kW	Motor Volts	Current Amps	Power kW	Motor Controller efficiency	Estimated Motor efficiency	Estimated shaft power kW
2.0	50.10	8.3	0.416	13.40	21.0	0.281	67.7%	**78.0%**	0.219
2.4	50.00	11	0.550	15.50	25.7	0.398	72.4%	**80.0%**	0.319
2.8	49.80	14	0.697	17.40	31.5	0.548	78.6%	**82.0%**	0.449
3.1	49.70	17	0.845	18.95	36.2	0.686	81.2%	**83.0%**	0.569
3.8	49.40	23.5	1.161	21.80	45.0	0.981	84.5%	**87.0%**	0.853
4.5	48.90	40	1.956	26.80	66.0	1.769	90.4%	**88.0%**	1.557
5.0	48.60	51	2.479	29.50	79.0	2.331	94.0%	**88.0%**	2.051
5.5	48.30	64	3.091	31.80	90.0	2.862	92.6%	**89.0%**	2.547
6.2	47.30	100	4.730	37.00	120.0	4.440	93.9%	**88.0%**	3.907
6.6	45.70	163	7.449	44.50	164.0	7.298	98.0%	**88.0%**	6.422

Table4, speed V power measurements for Maud

Motor efficiency was estimated (from manufactures data) and the shaft power derived at each speed. Fig 4 displays this data compared to the model's prediction. This power profile correlates well with the measured drag for apple (fig3).

The fuel consumption performance for the generator and battery charging combination is 0.43L/kWh. This has been measured in previous project stages (Hawk,2005) and is defined at the output of the batteries. This performance has the potential for improvement (to 0.36L/kWh) with better component selections. For the purpose of this evaluation the measured performance of 0.43L/kWh has been used.

Using these measured parameters the Miles/Liter performance was derived, this is displayed in fig5. Adjustments were made to this data to account for the difference in drag between Maud and Apple. The lower line in fig5 (blue) shows the predicted hybrid performance in a hull with the same drag as Apple.

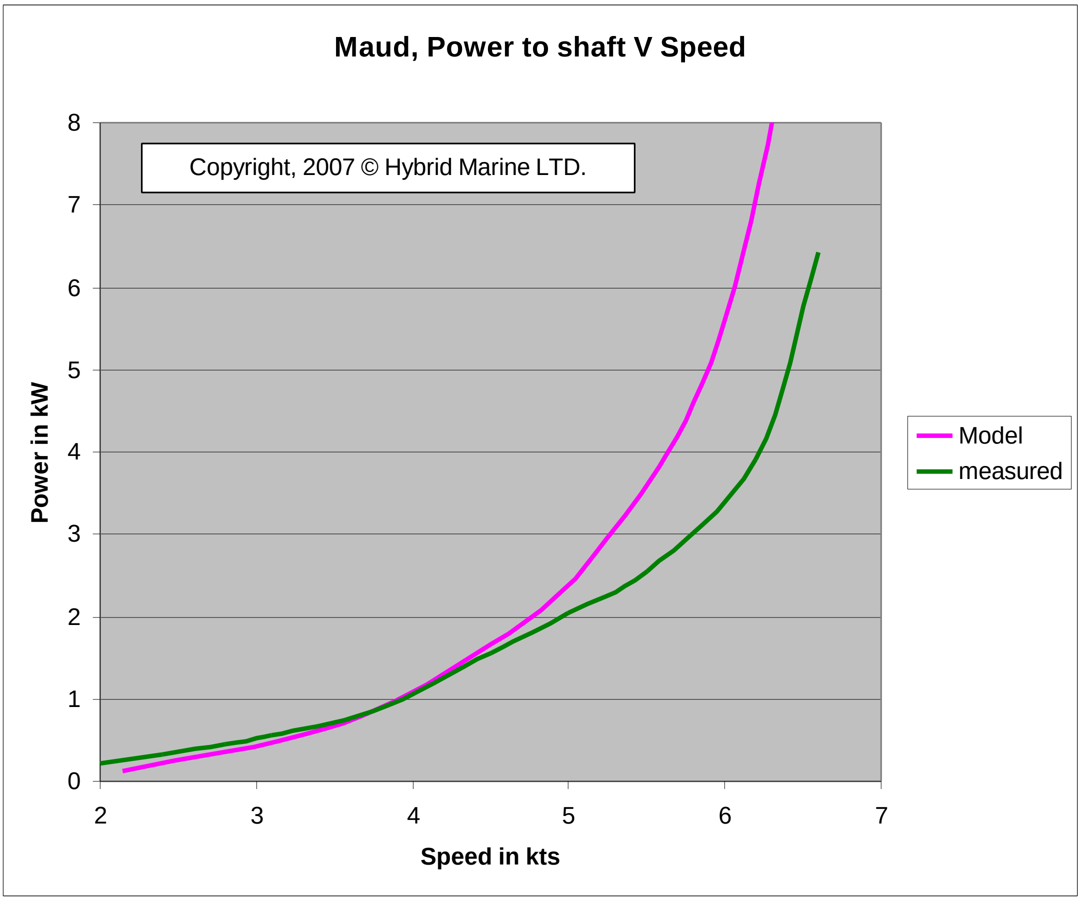

Fig4, Power to shaft (estimated) for Maud displayed against the software model.

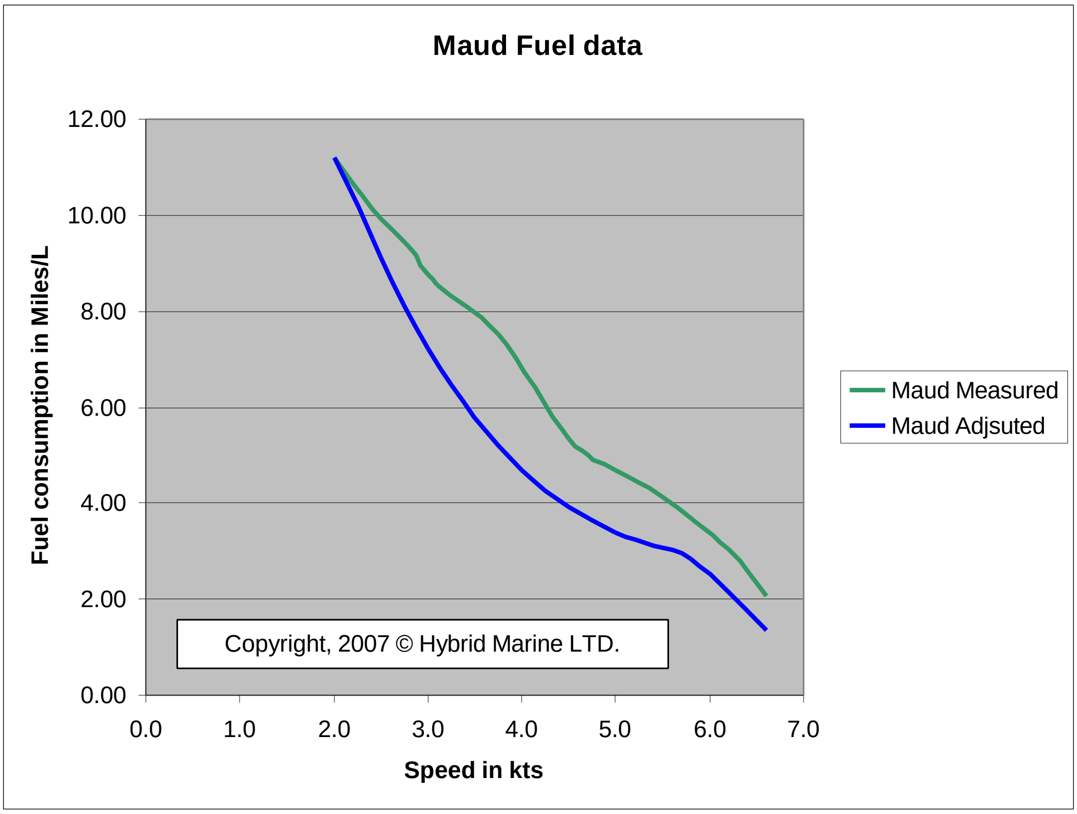

Fig 5, Measured fuel data for Maud and adjusted data to represent predicted performance in Apple's hull

Apple performance measurements

During testing of Apple there was a slight breeze from the NE direction. Test runs were performed while travelling due North then due South. The average of the two runs was then taken.

One problem encountered was the calibration of the vessels engine RPM gauge. When at full throttle the gauge registered 3,200RPM while the engine is rated to 3,600RPM. An investigation showed the governor was in it's maximum position against the factory set stop screw. All indications from the model show the vessel is slightly under proped and the engine should be allowed to come up to full speed. It was concluded therefore that the RPM gauge was indicating low and all readings were adjusted by a factor of 3600/3200.

For each measurement point the engine was set at a constant RPM and the craft was allowed to settle to it's steady speed. Fuel consumption measurements were taken using a closed loop apparatus (Hawk,2005). The burette was used to measure a calibrated quantity of fuel consumed while being timed with the stopwatch. The compiled data is provided in table 5.

RPM	**Log**	**Fuel**	**Time**	**Consump**	**Consump**
		qty in mL	**in secs**	**L/h**	**M/L**
1350	2.375	10	68.39	0.53	4.51
1575	2.95	10	50.115	0.72	4.11
1800	3.525	20	74.155	0.97	3.63
2025	3.875	20	57.235	1.26	3.08
2250	4.25	20	46.75	1.54	2.76
2486	4.75	20	37.375	1.93	2.47
2925	5.225	20	25.67	2.80	1.86
3375	6.325	19	15.33	4.46	1.42
3600	6.95	18	12.03	5.39	1.29

Table5, Fuel consumption data for Apple

Trial Results

Fig 6 shows a graph of the combined fuel consumption results and table 6 provides a short summary of the findings.

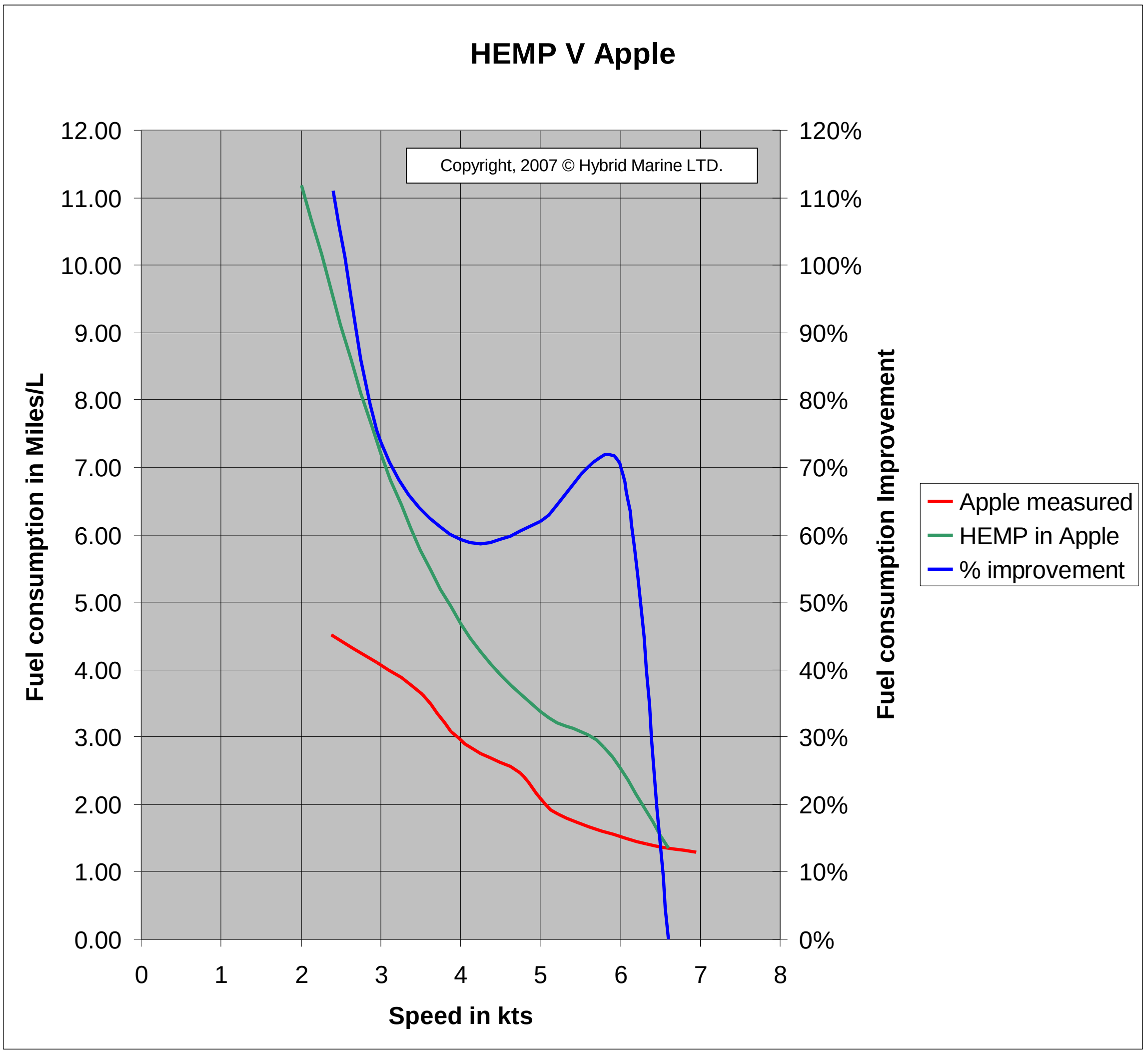

Fig 6 Combined fuel economy results.

	Conventional Diesel drive	Serial Hybrid
Propulsion	28hp, Marinised industrial diesel with shaft drive via a reduction gearbox	Serial hybrid using a 13hp industrial diesel generator and electric motor drive.
Max speed in calm conditions	6.9kts	6.6kts
Fuel consumption @ 2.5kts	4.5 Miles / Liter	9.2 Miles / Liter
Fuel consumption @ 3kts	4.2 Miles / Liter	7.3 Miles / Liter
Fuel consumption @ 5kts	2.1 Miles / Liter	3.4 Miles / Liter
Fuel consumption @ 6.0kts	1.5 Miles / Liter	2.55 Miles / Liter
Fuel consumption @ 6.6kts	1.35 Miles / Liter	1.35 Miles / Liter
Max speed, rough conditions (estimated)	5.7kts	3.5kts
Max shaft speed	1,800 RPM	1,000 RPM
Propeller size	14"/9"	18"/11"
Prop efficiency at 5kts	57.6%	61.5%

Table 6, sea trial results for a 32' moderate displacement auxiliary sailing craft

Comments on results

At a speed of 2.5kts the hybrid shows a massive 105% improvement in fuel consumption. This can be understood as follows. At 2.5kts Apple has the engine running at approximately 1,400RPM and it is consuming fuel at a measured rate of 0.53L/hour. If the gearbox is put into neutral and the engine allowed to idle, then the measured fuel consumption is 0.49L/h. So it can be seen that the vast majority of the fuel is being used to turn the engine over and most of the energy is being lost as heat. The Hybrid system generates and stores it's energy with the engine running at high load and high efficiency. Despite the extra transmission loss the hybrid is able to return this power to the propeller shaft with much higher efficiency than the standard system.

Characterization of engine fuel performance indicated the potential for a hybrid to double the M/L @ 5kts. The extra losses in the hybrid drive chain together with the increased propeller efficiency has resulted in a 62% increase in fuel economy. The conventional diesel could use higher gearing and a larger prop and this would narrow this gap.

Smooth water top speed performance is similar but rough water speed is much lower for the Hybrid. This is mainly due to the smaller engine plant employed .

The hybrid uses a much smaller engine than the conventional craft. It should therefore be expected that better fuel economy will be seen regardless of the technology used to get power from the crankshaft to the propeller. For a detailed analysis of how different technologies can be expected to effect the efficiency of identical engine plants then refer to Hawk2 (2007).

Conclusion.

The purpose of this research program is to investigate the feasibility of using Hybrid technology in small ocean going craft. Hybrids, under certain conditions, can offer improvements in fuel economy but this is not the only factor to consider in evaluating the technology. The average leisure yacht uses its engine for only 60 hours a year (BMF). Regardless of the fuel savings provided the economic or environmental benefits of the Hybrid will be very small for this market. It is the other advantages a hybrid can provide that will define it's market acceptance.

This program has developed a flexible serial hybrid drive train. Many unique methods have been employed. The system provides sophisticated control of power sources and this has resulted in a very usable system (Hawk,2005). The sea trials have taken this technology into it's intended environment and proven that Hybrid technology is a feasible option. Apart from giving sufficient power for propulsion , with good fuel economy, many other powerful features are provided.

The considerable amount of stored energy in the batteries can be used for more than propulsion. Powerful electric appliance can now be used in a craft usually considered too small for this luxury. Maud has a 3.5kW inverter driving an standard ring main circuit. On board you will find :

1. An electric kettle
2. A microwave oven
3. Computers.
4. A powerful ark-welder
5. The ability to drive any domestic appliance.

With the large battery bank then energy can be accumulated from solar panels and wind generators. In the next stage of the project a 200W solar array and two 400W wind generators will be installed. This is expected to provide approximately 3.5kWh a day of energy. This energy can be used for propelling the vessel for two hours at just below 5kts or for powering the appliances. In this way environmentally friendly resources can be allowed to drastically reduce the use of the engine. The hybrid is a technology that enables this to happen.

Taken as a whole hybrids have a great deal to offer. There are many Hybrid configurations and each one has it's own unique benefits for any individual application. In the next stage of this development the cost/ feature trade off of each possible implementation will be analyzed with the view to developing commercial products.

Acknowledgments

Grateful thanks go to Roma and Martin Morris, the intrepid owners of Apple. They turned sheets of steel and standing trees into a magnificent vessel. This was done through the sweet of their own brows, their intellectual powers and their supreme enthusiasm. Over the years they have been an immense inspiration for me. Their contribution to this project goes far beyond help with the sea trials and I own them an enormous debt of gratitude.

My wife Jane and daughters Alice and Rosie, have been alongside me throughout this project. They have endured my tendency to be a nutty professor and suffered through the financial constraints my obsession has brought about. They have understood why I have been pursuing this project even at times when I haven't. I hope to be able to take you sailing sometime in the near future and show that boats can also be fun!

References

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