Sizing Steam Plant

I first started making model steamboats over forty years ago. I had decided to build the MAP *Greta* design and can remember looking around for some sort of guidance on what steam engine to fit. *Greta* was to 1/48 th scale of a Largish Victorian steam yacht. The model was 44” long with a beam of about 5”, and the propeller was 2 ¼” diameter. Very little was forthcoming from the few people I knew who ran steamboats and there was absolutely nothing of value in any of the literature I managed to lay my hands on. Finally I chose to build Westbury’s *Trojan* design. This is a single cylinder, double acting slide valve with bore and stroke equal at **5/8” .** By this time I had obtained a copy of *Model Boilers and Boilermaking* by K.N.Harris and was able to design a centre flue boiler to suit the engine.

Having made the hull, engine and basic boiler, a trial was carried out in the bath to see how much spare buoyancy I had to play with for the superstructure and radio installation. The resulting ¼” freeboard indicated that all was not well! The problem was that the boiler was vastly overweight. So using the same basic design, a much smaller one was made. I knew that it would probably not produce sufficient steam, but at least I would get something on the water. That the engine worked well was in no doubt – on no load and an unlimited supply of air at 50 psi it turned over at around 7000 rpm sounding like an IC engine, and at the other end would even turn over nicely on my puff.

The first outing was something of a revelation. With the gauge showing 50 psi the throttle was adjusted so the engine was just ticking over and the boat released. I then opened the throttle fully. The water churned, the boat shot off, but alarmingly put on a good 30 degrees of list. The pressure quickly dropped to between 5 and 10 psi and everything calmed down and the boat performed quite adequately. The first lesson was learned – steam engines are powerful!

In the intervening years I have built several engines and boilers and a few boats. That original Greta had six engine and three boilers in various combinations. Hopefully something has been learned, and this article is an attempt to summarize my findings. The following information is not claimed to be the ultimate in accuracy, but rather it is intended to provide a basic understanding of what is required and a starting point from which further experience can be gained.

Speed, Propeller size and R.P.M.

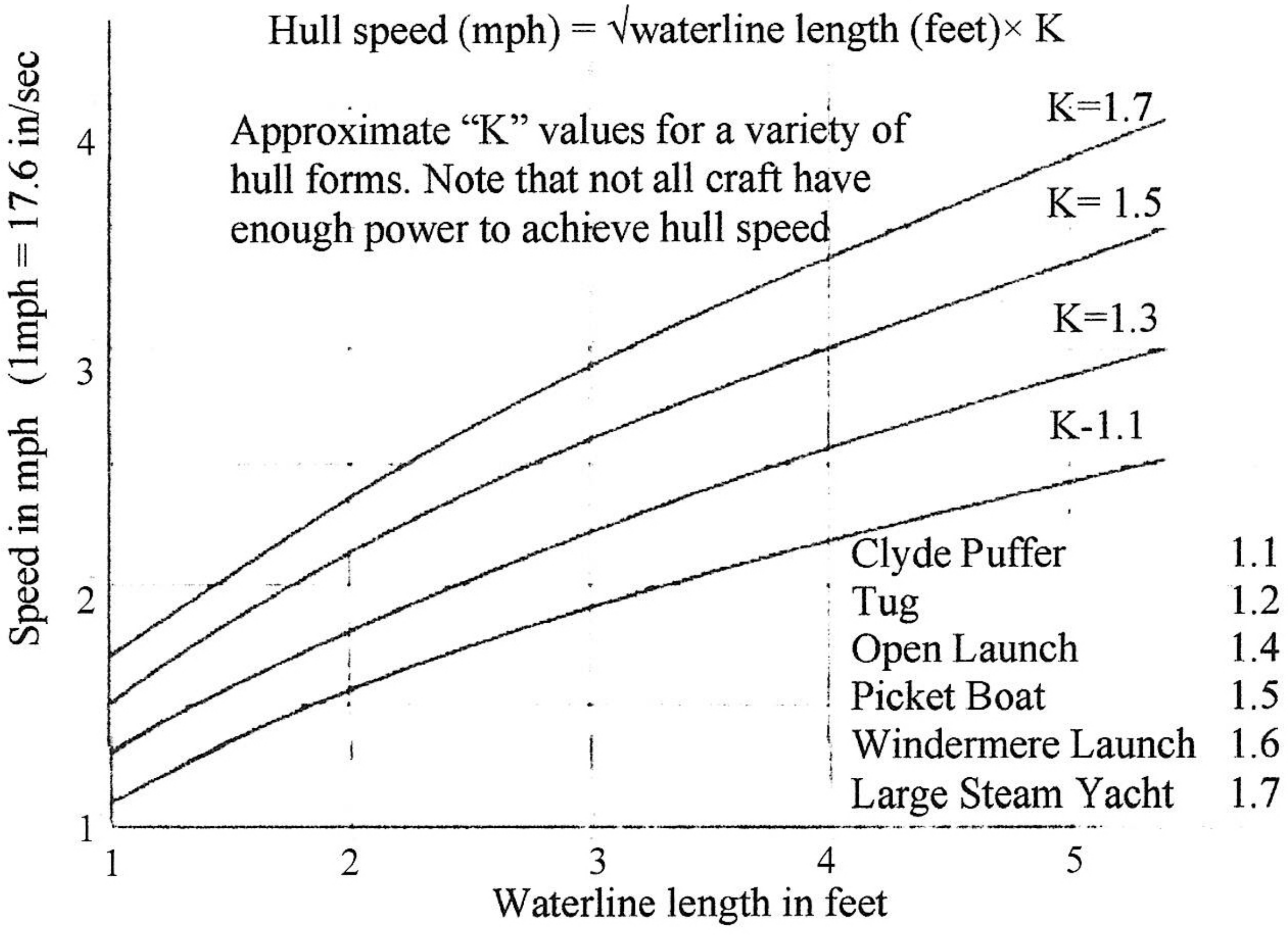
The rpm obviously depends on haw fast the boat is to be driven and the propeller fitted to it. To look right, the hull must be driven at a speed to produce realistic wave patterns. We are of course discussing displacement hull types here. This speed can be generated by a relatively low power source and is known as the Hull Speed. Greater speed can be obtained, but the power required increases at a great rate. The Hull Speed depends on the waterline length – model or full size makes no difference – and is given by the following formula:-

Hull speed in mph = $\sqrt{\text{waterline length in feet}} \times K$

Where K varies between about 1.1 and 1.7 depending on the hull form The finer the lines the higher, the value of K

Figure 1 shows the variation of hull speed with waterline length for a variety of different K values.

Figure 1 Variation of hull speed with Waterline length



Let’s take an example – one that I know works – a 50 foot steam picket boat to a 1/12 scale. The waterline length is 48” and the hull lines are fairly fine so we will take K as 1.5

Hull speed = $\sqrt{4} \times 1.5$ = 3 mph = 4.4 ft/sec = 52.8 inches/sec

Now to the propeller. Assuming a scale type of craft is being considered, use a scale diameter or slightly larger propeller. Props for steam craft tend to have a fairly course pitch – a reasonable figure would be 1.5 x diameter.

But the prop slips in the water, so for one revolution it will travel a distance somewhat less than it’s pitch. For the sizes and speeds we use, an efficiency of about 67% seems to be right. So the effective pitch works out at 1.5 x .67 x diameter = 1 x diameter (near enough) How convenient!

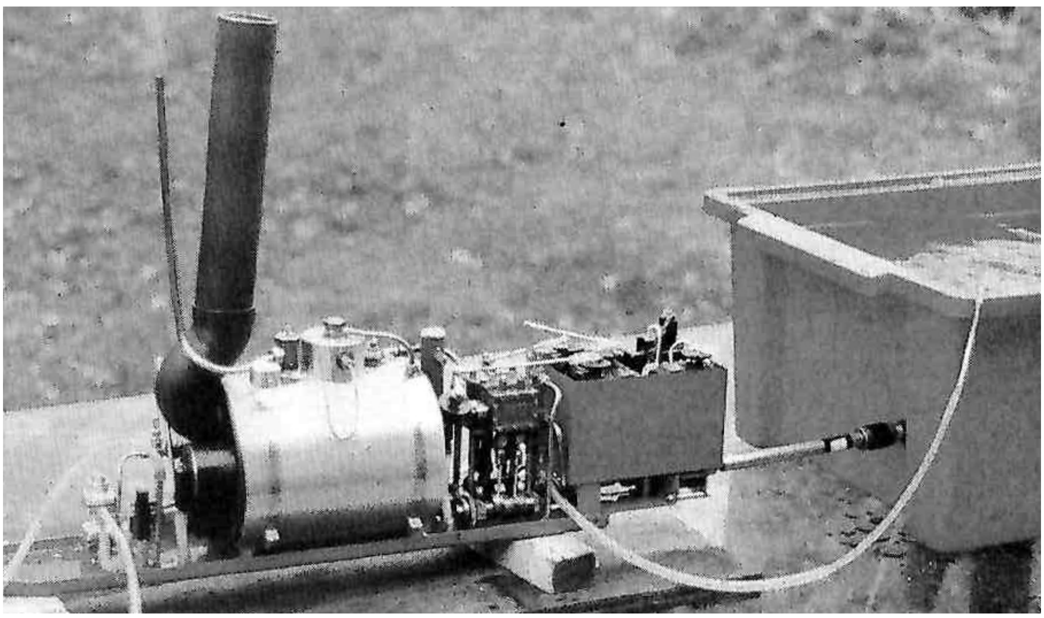
To continue with the example. Propeller is 3” diameter x 4.5” pitch. Allowing for slip, the effective pitch = 3”

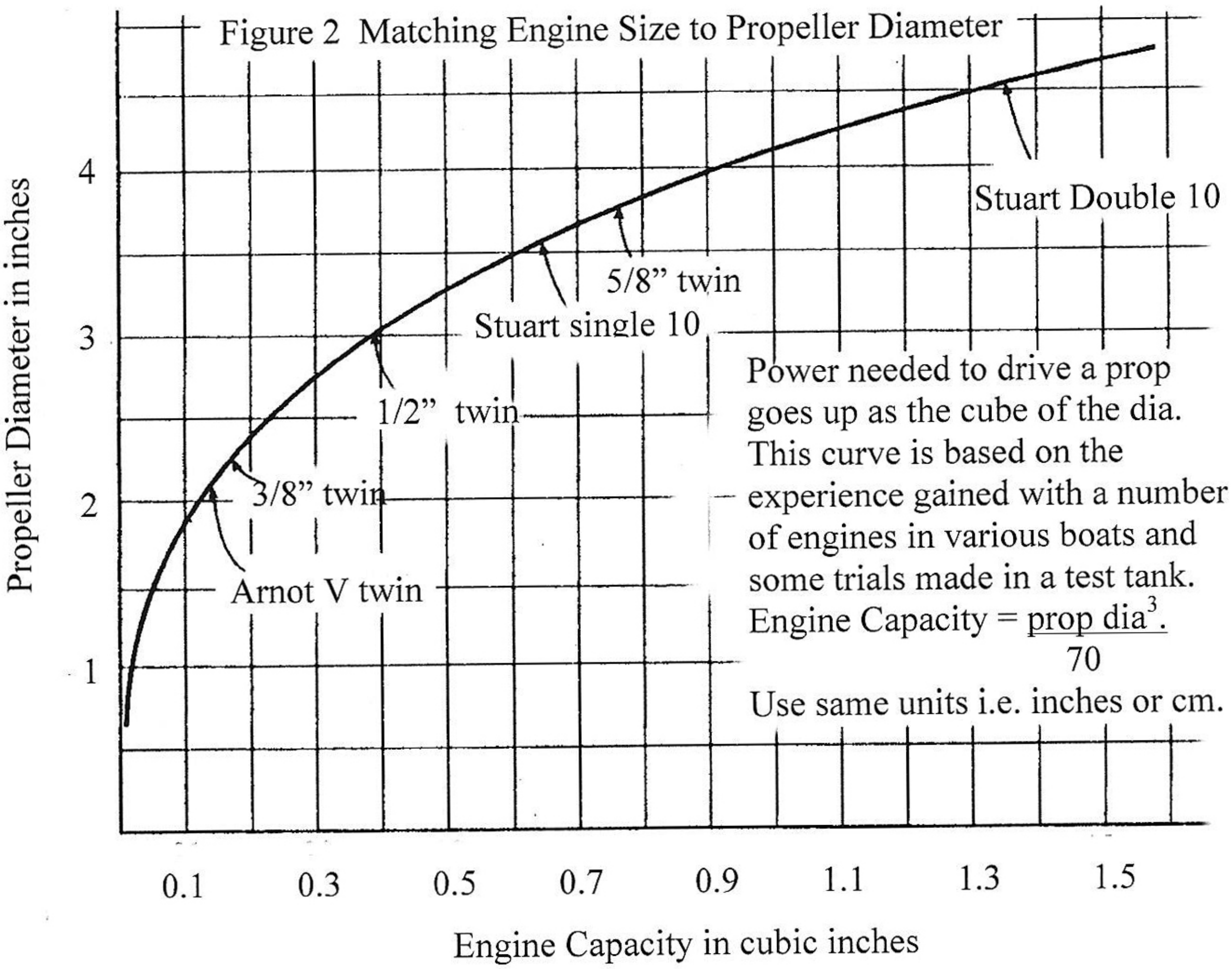
To propel the hull 52.8” in one second the prop needs to turn at

$\frac{52.8}{3}$ =17.6 revs / sec = 1050 rpm

Engine Size and Steam Consumption

All the above is based on theory and the results of well proven experimentation and any assumptions made are not far off. However, in matching engine and propeller sizes the variables and hence the assumptions are rather larger. What follows is based on what a number of successful craft use and some experimental work carried out in a small test tank. The results are summarized in Figure 2 which is a graph showing the relationship between propeller size and engine capacity. The photo shows a complete plant under test. This plant is fitted with automatic water level control and gas supply. When photographed it was undergoing an extended test running for over three hours continuously apart from changing propellers and occasionally checking reverse.





Any engine will obviously drive a range of propeller sizes and the line shown probably represents the lower size of the useful range. A steam plant similar to that shown in the above photo was used to carry out trials using a range of propeller sizes. The engine is a ½" bore and stroke double acting twin and the tests were carried out at full throttle with steam at 50 psi. The results are shown below. In all cases the pitches of the props was 1.5 x the diameter.

Prop Diameter inches	R.P.M.	Nominal speed M.P.H.
2.2	1500	3.20
3	1250	3.55
3.5	750	2.84
5	400	1.89

It is realized that these are quasi-static tests, and if carried out in a hull capable of moving through the water the R.P.M. and hence the speed would be somewhat higher. However, if the test is regarded as a straightforward comparison it should be perfectly valid.

A test has been carried out on the water. A tachometer was mounted in a hull, and the boat run at a constant throttle setting. Three passes were made, and on each occasion a reading of 750rpm was observed. On the fourth run the boat was stopped by hand and the rpm dropped to 650. Two repeats produced the same result. Thus the dynamic condition shows an increase of approximately 15% over the quasi-static state. This is only the result of a single test, but at least gives an indication of the figure to expect.

Continuing with the example of the Steam Picket Boat, the scale size propeller is about 3” diameter which requires an engine of about 0.39 cubic inches capacity. Engine capacity can be worked out quite easily by using the following formula:-

$$\frac{\pi \text{ x bore}^2 \text{ x stroke x number of power strokes per revolution}}{4}$$

In this case a double acting twin (4 power strokes/rev) with1/2” bore and stroke gives the capacity needed:-

$$\frac{3.142 \text{ x } 0.5^2 \text{ x } 0.5 \text{ x}4}{4} = 0.393 \text{ cubic inches (pretty close)}$$

As the desired engine speed is 1056 rpm the steam consumption should be 1056 x 0.393 = 413 cubic inches/minute

Note that this figure makes no allowance for any cut off which would result in a smaller steam requirement. This is probably compensated for by the fact that most small engines leak steam to some extent.

Boiler Size

For the small sized steam plant we are concerned with it is convenient to express the rate of evaporation in terms of cubic inches of water per 100 square inches of heating surface per minute.

The evaporation rate will obviously depend on the design of the boiler and the method of firing. A simple pot boiler fired with a meths burner may well have a rate of only 0.5 cu. in. / 100 sq.in. / min. whereas a water tube boiler of the Yarrow or Lune Valley type, fired with gas could have a rate nearer 5. For the sort of boilers usually found in model steam plant a figure of 1.5 to 2 cu.in./100 sq. in. / min. seems to be about right.

It should be obvious that the volume of steam produced by 1 cu. in. of water will decrease as its pressure is increased. Table 1 shows the volume of steam produced from a cubic inch of water over a range of pressures. Also shown is the boiling point of water at those pressures.

The evaporation rate of a boiler can be ascertained quite simply by timing how long it takes to evaporate the water between two levels of the sight glass, and then measuring how much water is needed to fill between the same two marks. The test should be carried out at the working pressure by adjusting the steam valve to give a constant pressure.

Getting back to our example. We know that we need 415 cubic inches of steam each minute. We will aim for a working pressure of 50 psi and assume that our boiler has an evaporation rate of 1.5 cu.in. /100 sq. in. / min. Looking at the table we see that at 50 psi, one cu. in. of water gives 405 cu. in. of steam.

Therefore we need to evaporate $\frac{415}{405} = 1.025$ cu. in. / min.

Heating area required is $1.025 \times \frac{100}{1.5} = 68.3$ sq. in.

The choice of working pressure is rather difficult to quantify. Most model steam boats seem to operate between 30 and 50 psi. If the above calculations were made for 30 psi, we would need 0.728 cu. in. of water each minute and a heating surface of 48.3 sq. in. It is always better to have too much steam than too little, so aim to make the boiler on the large size if possible.

When designing fire tube boilers it is easy to fall into the trap of cramming in as many tubes as possible. There are two problems here. First, don’t make them too small as the burnt gasses do not like travelling through small tubes. A minimum of 3/8” dia. is suggested. Second, don’t put them too close to each other. Remember that water has to be able to get between them at the same time as steam is boiling off the surface. A bunch of closely packed tubes will probably only boil the water around its periphery rather than round each tube. A minimum gap of 1/8” is suggested.

Gas Consumption

Having managed to build a boiler the right size, it would be a pity if insufficient heat were applied for it to do its work properly.

To calculate the fuel consumption we need to know the calorific value of the fuel and the total heat of the steam. Calorific values of common fuels are given in Table 3. The total heat of the steam is given in tables, but for our purposes it is sufficiently accurate to take it as 1170 BThU/lb of steam over the range of pressures we use. This heat is the total needed to raise one lb of cold water to boiling point and convert it to steam at a given pressure.

So back to the example yet again. We need to evaporate 1.025 cubic inches of water each minute at 50 psi. One pound of water occupies 27.7 cu ins and at 50 psi the total heat of the steam is 1170 BThU/lb. Thus we need to supply heat at the rate of:

Heat required = $\frac{1.025}{27.7} \times 1170 = 43$ BThU/min

If we use Butane at 21,300 BThU/lb we must burn:

$$\text{Butane used} = \frac{43}{21{,}300} \times 16 = 0.033 \text{ ozs/min}$$

This is the theoretical heat input, but as we all know, quite a lot of heat goes up the funnel. K.N. Harris suggests that a good model boiler should reach 60% efficiency, but I would imagine that our rather smaller boilers are likely to be less – say 50%.

So we will need 2 x 0.033 = 0.066 ozs/min of butane.

This apparently very small amount actually equates to nearly 2 gm/min. Using a reasonably good set of kitchen scales it should be possible to measure how much you are burning over say a ten minute period. So if you find your boiler does not appear to steam your engine fast enough, do not assume the boiler to be the only culprit – it could be the burner!

Table 1

Gauge pressure psi	Cu.in.steam from 1 cu.in. water	Boiling temp. deg. C
15	838	121
20	726	126
25	640	131
30	572	134
35	518	138
40	474	142
45	437	145
50	405	148
55	378	151
60	354	153
65	333	156
70	318	158
75	298	160
80	283	162
85	270	164
90	257	166
95	247	168
100	237	170

Table 2

Showing the blade angle at a number of diameter stations to produce a propeller with a pitch of 1.5 x dia.

Proportion dia.	Blade angle Deg.
0.2 dia.	67.2
0.4 dia.	50.0
0.6 dia.	38.4
0.8 dia.	30.9
1.0 dia.	25.6

Table 3

Calorific values of common fuels

Fuel	BThU/lb
Propane	21660
Butane	21300
Meths	11000
Petrol	19500
Paraffin	19000
Coal	13 - 15000