

S. C. Misra*, R. P. Gokarn*, O. P. Sha*, Ch. Suryanarayana*, R. V. Suresh*

* PROFESSORS, DEPARTMENT OF OCEAN ENGINEERING AND NAVAL ARCHITECTURE, INDIAN INSTITUTE OF TECHNOLOGY, KHARAGPUR;

*SCIENTISTS, NAVAL SCIENCE AND TECHNOLOGICAL LABORATORY, VISAKHAPATNAM, INDIA

Development of a Four-Bladed Surface Piercing Propeller Series

Introduction

Surface piercing propellers are propellers that are partially immersed in water in operating condition so each blade enters and leaves the surface of the water once in every revolution. The immersion is normally less than 50% of the propeller diameter, and therefore the propeller shaft and the arrangement for holding it to the hull (including shaft bearings) are above water. Each blade entering the water pulls with it an air cavity that moves with the blade, and that separates from the blade when its trailing edge emerges from the water. Surface piercing propellers have many advantages over both conventional propellers and supercavitating propellers, as well as some disadvantages (Allison, 1978; Barr, 1970; Blount et al., 1997; Ghose et al., 2004; Lewis, 1988). Figure 1 shows a typical surface piercing propeller advancing into undisturbed (“open”) water.

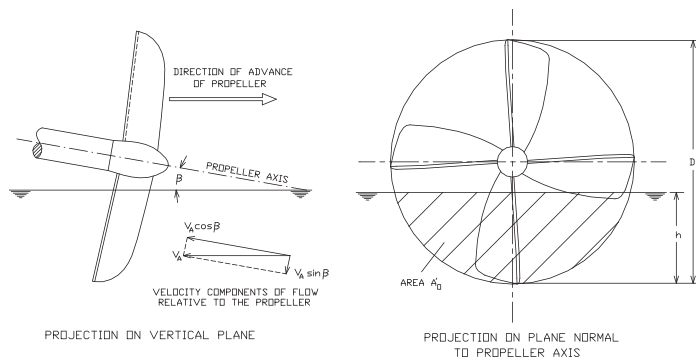


FIGURE 1. A typical surface piercing propeller.

Ferrando (1997) divided the action of a surface piercing propeller into six phases (Figure 2) as follows: Phase 1 – “base vented” phase, Phase 2 – “partially vented” phase, Phase 3 – “transition” phase, Phase 4 – “fully vented” phase, Phase 5 – “cavity blockage” phase and Phase 6 – “cavity choking” phase. For a propeller of diameter D with a thrust T and a torque Q , while advancing with a speed V_A at n revolutions per unit time into “open” (undisturbed) water of density ρ , the thrust, torque, and advance coefficients are usually defined as:

$$K_T = \frac{T}{\rho n^2 D^4} \quad K_Q = \frac{Q}{\rho n^2 D^5} \quad J = \frac{V_A}{n D} \quad \eta_o = \frac{T V_A}{2 \pi n Q} = \frac{K_T}{K_Q} \frac{J}{2 \pi} \quad (1)$$

where η_o is the open water efficiency.

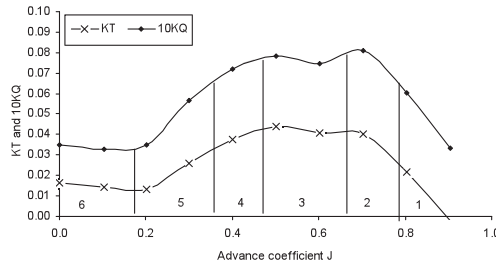
ABSTRACT

■ The intent of this work was to develop a methodical series of four-bladed propellers of the surface piercing type so as to be able to design a surface piercing propeller for a given operating condition. A test rig along with instrumentation was developed at NSTL to determine the open water characteristics of surface piercing propellers experimentally. Initially, four model propellers were designed and manufactured with four different section shapes with the same pitch ratio and blade area ratio. The diameter of all the model propellers was fixed at 250mm. These propellers were of two basic section shapes: wedge and diamond back. To study the effect of trailing edge inclination (cup shape) three different wedge shapes were developed with the trailing edge making angles of 0°, 30°, and 60° to the horizontal respectively. These four propellers were tested extensively in the High Speed Towing Tank of NSTL. Weber number effects were found to be small in the model tests that were carried out at 20rps for the 250mm diameter propellers. The best performance at all immersions was obtained from SPP-3, the propeller having wedge shaped sections with the trailing edge inclined at 60° to the horizontal. The astern performance of this propeller was found to be satisfactory from the limited number of tests that were conducted.

KEYWORDS

Surface Piercing Propeller

FIGURE 2. Variation of K_T with J for different phases of surface piercing propeller action.



For a surface piercing propeller of given geometry, the thrust and torque coefficients are functions not only of the advance coefficient, the Reynolds number, the Froude number, and the cavitation number, but also of the Weber number:

$$K_T, K_Q = f(J, R_n, F_n, \sigma, W_n)$$

where for propellers :

$$\begin{aligned} R_n &= \frac{V_A D}{\nu} \text{ is the Reynolds number,} \\ F_n &= \frac{V_A}{\sqrt{g D}} \text{ is the Froude number,} \\ \sigma &= \frac{p - p_v}{\frac{1}{2} \rho V_A^2} \text{ is the cavitation number, and} \\ W_n &= \frac{V_A^2 D}{\kappa} \text{ is the Weber number.} \end{aligned} \quad (2)$$

ν is the kinematic viscosity, p is the density, p_v is the vapor pressure and κ is the kinematic capillarity (surface tension per unit length/density) of water, g is the acceleration of gravity, and p is the pressure at the center of the propeller. Other definitions of these dimensionless parameters are sometimes used. In addition, the immersion of the propeller as a ratio of its diameter and the angle between the propeller shaft axis and the line of flow, as shown in Figure 1, also affect surface piercing propeller performance significantly. This is explained briefly in the following.

The immersion ratio h/D , where h is the maximum tip immersion, affects the values of K_T and K_Q since the thrust and torque depend on how much of the propeller blade is in water during each revolution, and this depends upon the immersion of the propeller. The thrust and torque coefficients can be defined in a modified form, taking h/D into account, as:

$$K_T = \frac{T}{\rho n^2 D^2 A'_o} \quad K_Q = \frac{Q}{\rho n^2 D^3 A'_o} \quad (3)$$

where A'_o is the area of the immersed segment of the propeller disc. K_T and K_Q have been defined as given in Eq. (3). The effect of h/D (as separate from the effect of A'_o) should therefore be negligible, particularly in the base vented and partially vented phases (Phases 1 and 2 in Figure 2).

If the flow of water to the propeller in open water is directed at an angle β to the propeller axis, the velocity of advance V_A can be resolved into an axial component $V_A \cos \beta$ and a component $V_A \sin \beta$ in a plane normal to the axis. This second component gets either added to or subtracted from the tangential velocity $2\pi nr$ of the blade section at radius r . The relative tangential velocity of the blade section with respect to water (resultant of $2\pi nr$ and $V_A \sin \beta$) then varies with the angular position of the blade during its revolution about the axis. This causes the thrust and torque of each blade to vary during its revolution, and also gives rise to a varying unbalanced force in a plane normal to the propeller axis.

Since the propeller blades pierce the water surface in every revolution, surface tension is obviously an important factor in the behavior of surface propellers. The Weber number is related to surface tension effects. Experience has shown that the critical value of J , at which transition to full ventilation results in a sharp drop in K_T and K_Q and depends on the value of the Weber number W_n .

The Froude number influences surface piercing propeller behavior because such propellers operate on the surface of the water, and give rise to surface waves. However, model experiments seem to indicate that at sufficiently high values the effect of Froude number vanishes, i.e., for a Froude number (defined as $F_n = nD/\sqrt{gD}$) greater than 4, there is no effect. Care should be taken to see that this is the case in both model experiments and full-scale operation if predictions are to be reasonably accurate.

Surface piercing propellers rarely suffer from cavitation. Only if high values of J , at which the air-filled cavities are small and confined to the trailing edge, are combined with very low values of the cavitation number σ is there a possibility of cavitation. Otherwise, the air-filled cavities prevent the formation of cavities filled with water vapor that characterize cavitation.

For a surface piercing propeller, the hydrodynamic forces on a blade commence when the

blade touches water while immersing. These hydrodynamic forces are maximized when the propeller blade is fully immersed in water, and start reducing as the blade is lifted from the water, reaching a zero value when the blade is completely raised. Thus, the thrust and torque fluctuate in each revolution from zero to a maximum, and there are unsteady forces on the blade. These unsteady forces on a single blade have a component (thrust) along the propeller axis, and vertical and horizontal components in a plane normal to the axis (Nozawa et al., 2002; Vorus, 1991). Unsteady forces also occur if the propeller shaft is inclined to the flow, as indicated earlier. Thus, the blade is subjected to unsteady forces at times and must have the strength to withstand bending and torsional stresses, fatigue, and vibration. Since the propeller has a number of blades, the resulting forces on the whole propeller exhibit less unsteady behavior compared to the forces on a single blade because the maximum force on each blade occurs at different times.

It is difficult to develop a theoretical/numerical model of a surface piercing propeller because it involves the flow of both a liquid and a vapor. The nature of the flow around a surface piercing propeller changes according to the phase (i.e., base vented, partially vented, transition, fully vented, cavity blockage, and cavity choking) depending on the advance coefficient J , for which the limiting values for each phase are not known. Young et al. (2004) used a low-order, three-dimensional boundary element method for the performance prediction of surface piercing propellers. Nevertheless, reliable methods of estimating the performance of surface piercing propellers by theoretical means for design purposes do not appear to be currently available, and model experiments still remain the best way to determine the performance of such propellers. However, experiments must be carried out taking into account the actual shaft inclination, and with instrumentation capable of measuring not only the thrust and torque of the propeller but also the components of the force in a plane normal to the propeller axis. Furthermore, the effects of the Froude number and the Reynolds number can be disregarded only if the Froude number is sufficiently large and if the flow is in the fully turbulent range. Disregarding the effect of the Weber number is more difficult since no firm guidelines are currently available.

This paper describes some work on surface piercing propellers carried out at the Naval Science and Technological Laboratory (NSTL), Visakhapatnam, India. The work included the selection of a parent propeller blade section out of four typical sections, and the development of a four-bladed surface piercing propeller series consisting of twelve propellers. The model test results have been presented, the analysis method used is described, and a design method is proposed.

Test Set Up and Model Manufacture

A number of propeller models were manufactured and tested in the facilities at NSTL. To reduce scale effect, it was decided to manufacture the propeller models of the largest diameter (viz. 250mm) taking into account the limitations of the equipment at NSTL. The model propellers were manufactured from defect-free aluminum alloy forged blanks (24345 to IS:734 WP condition). The blades and the external surface of the hub were modeled on a computer-aided manufacturing (CAM) software system, part programmed and machined on 4- or 5-axis computer numerical control (CNC) machines to the final blade form. The internal details of the hub were machined on conventional or CNC lathes. The blade profiles were inspected on an automatic computer measuring machine (CMM) using surface normals. The finished propeller models were statically balanced and anodized. Tolerances on propeller geometry were maintained in accordance with the recommendations of the International Towing Tank Conference (ITTC).

The NSTL towing tank facility (500m x 8m x 8m) was utilized for the surface piercing propeller open water tests. The towing tank has a forward carriage speed between 2-20m/sec and an astern speed up to 4m/sec with an accuracy of 0.1%. The propeller dynamometer used for the open water tests was the *K&R R-33* dynamometer manufactured by Cussons Technology Ltd., U.K. This is based on the original Kempf and Remmers design, and has a high reputation for reliability and accuracy, measuring thrust up to 400N and torque up to 15Nm.

An extension shafting piece was manufactured and attached to the shafting of the dynamometer through a universal coupling such that the extension piece could be inclined in the vertical or horizontal planes to a desired angle between 0 and

10 degrees. The shaft could then be locked in the desired inclined position. The propeller was then attached at the end of the inclined shaft. Thus, the propeller could be immersed in water while the propeller dynamometer was housed inside the test rig above water. Since a large number of propeller models were required to be tested, it was determined that the angle of inclination of the propeller shaft would not be a variable in the experimental program. The propeller shaft inclination was fixed at 5° in the vertical plane with zero inclination in the horizontal plane (i.e., to the tank center line). The immersion of the propeller was adjusted by raising or lowering it, while keeping the shaft alignment unaltered. In all the experiments, the towing speed, propeller revolutions, thrust, and torque were measured and recorded through a robust data acquisition system on the carriage with a sampling rate of 500 per second. The measurement of the forces normal to the propeller shaft axis could not be undertaken for the full range of experiments due to practical reasons and has not been reported in this paper.

Parent Propeller Selection

There are basically two types of sections used in surface piercing propellers — wedge-shaped sections and diamond-backed sections, the former of which can have a cup at the trailing edge. To choose the parent propeller, four alternatives were considered. A right handed propeller of pitch ratio 0.83 and a blade area ratio 0.76 was chosen as the parent propeller. The model propeller diameter was fixed at 250mm. Four blade sections were considered. They were as follows: SPP-1— wedge shape with a cup at the trailing edge, the cup edge being horizontal, SPP-2— a modified version of SPP-1 obtained by chamfering the cup edge at an angle of 30 degrees, SPP-3— a modified version of SPP-1 obtained by chamfering the cup edge at an angle of 60 degrees, and SPP-4— diamond back profile. The drawings of the propellers are given in Figures 3(a) and 3(b).

Experiments were conducted with all four model propellers for the following values of the various experimental variables:

- Shaft inclination in the vertical plane: 5° to horizontal, fixed for all tests.
- Shaft inclination in the horizontal plane: zero.
- Carriage speed: 0 to 3.0m/s at 0.5m/s intervals and above 3m/sec, at 0.25m/sec intervals.

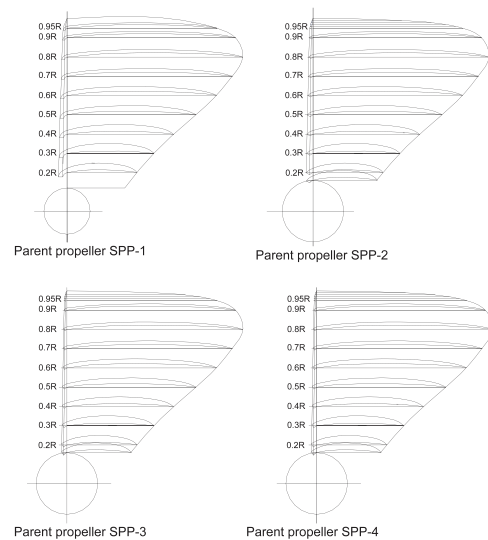


FIGURE 3(A). Expanded blade outlines and sections of parent propellers.

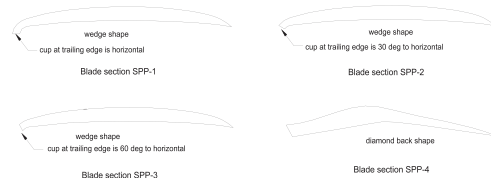


FIG. 3(B). Blade section shapes of parent propellers.

- Propeller revolutions: 10, 15, and 20 revolutions per second (rps).
- Propeller immersion: 30%, 40%, 50%, and 70% of the diameter.

The quantities measured during each run of the open water testing were the carriage speed, propeller revolutions, thrust, and torque. The propeller revolutions and carriage speed ranges were chosen so that the complete range of the advance coefficient J , from zero to the value at which thrust just becomes negative, could be obtained. Test runs could not be carried out and measurements could not be taken in some cases of the test matrix due to constraints and limitations of the tank or the instrumentation. The instantaneous data recorded by the data acquisition system were checked at random to see that the data were following the right trends and there was no “impulsive” error. The experimental instantaneous data were averaged to get the thrust T and torque Q . The propeller rps n and carriage speed (speed of advance) V_A

were also recorded. Non-dimensional quantities $J = V_A/nD$, $K_T = T/\rho n^2 D^2 A'_0$ and $K_Q = Q/\rho n^2 D^3 A'_0$ were then calculated.

In these experiments, the values of the area of the immersed segment of the propeller disc for the different immersion ratios h/D were:

h/D (%)	30	40	50	70
A'_0 (cm ²)	167.6	206.4	245.4	323.3

As has been explained earlier, the effects of F_n , R_n , and σ have been ignored since the effects due to the variation of these quantities have been found to be negligible. To study the effect of the Weber number W_n , κ has been taken as $0.000072\text{m}^3/\text{sec}^2$ and the Weber number has been defined as $W_n = V^2 D / \kappa$, where

$$V = \sqrt{V_A^2 + (\pi n D)^2}$$

Figures 4, 5, and 6 give K_T and $10K_Q$ as functions of J for three of the four parent propellers, SPP-1, SPP-2, and SPP-3, at three immersion ratios, 30%, 40%, and 70%. Figure 7 gives similar data for the fourth propeller, SPP-4, at 30% and 40% immersion. For propellers of a fixed diameter, the Weber number is a function of V , which is almost directly proportional to n since V_A is small compared to $\pi n D$. Thus, the Weber number for the three values of propeller revolutions for which experiments have been carried out is nearly constant at different speeds of advance. The Weber numbers for the three values of propeller revolutions are approximately 2.0×10^5 (for $n = 10\text{rps}$), 4.5×10^5 (for $n = 15$), and 8.0×10^5 (for $n = 20$).

The following conclusions may be drawn from Figures 4, 5, and 6:

- At 30% immersion, the effect of W_n on K_T and K_Q is significant only at low values of J ; for J greater than 0.4, the effect is comparatively small.
- At 40% and 70% immersions, K_T and K_Q vary with W_n over a wider range of J .
- The effect of W_n on K_T and K_Q decreases as W_n (or n) increases — i.e., the change in K_T and K_Q when n increases from 10rps to 15rps is much greater than the change in K_T and K_Q when n increases from 15rps to 20rps.
- However, in the case of propeller SPP-4, which has diamond-back blade sections, K_T and K_Q vary in Weber number in a manner different from that of the other three propellers.

Ferrando et al. (2001) performed some work on the effects of Weber number on the working of surface piercing propellers. They have also referred to the work of Shiba (1953) on the same subject. A simplified Weber number defined by Shiba is:

$$W'_n = \sqrt{\frac{n^2 D^3}{\kappa}} \quad (4)$$

Ferrando et al. (2001) have defined the Weber number in a different manner to include the depth of immersion:

$$W''_n = \sqrt{\frac{n^2 D^3 \left(\frac{h}{D}\right)}{\kappa}} \quad (5)$$

Table 1 gives the approximate mean values of Weber number defined in a different manner for each of the four propellers. J_{cr} is defined later.

n	h/D	W_n	W'_n	W''_n	J_{cr}
10	0.3	2.0×10^5	150	82	0.447
	0.4	2.0×10^5	150	95	0.497
	0.7	2.0×10^5	150	125	0.576
15	0.3	4.5×10^5	220	120	0.565
	0.4	4.5×10^5	220	139	0.600
	0.7	4.5×10^5	220	184	0.647
20	0.3	8.0×10^5	295	162	0.629
	0.4	8.0×10^5	295	187	0.650
	0.7	8.0×10^5	295	247	0.673

TABLE 1. Weber number for various operating conditions.

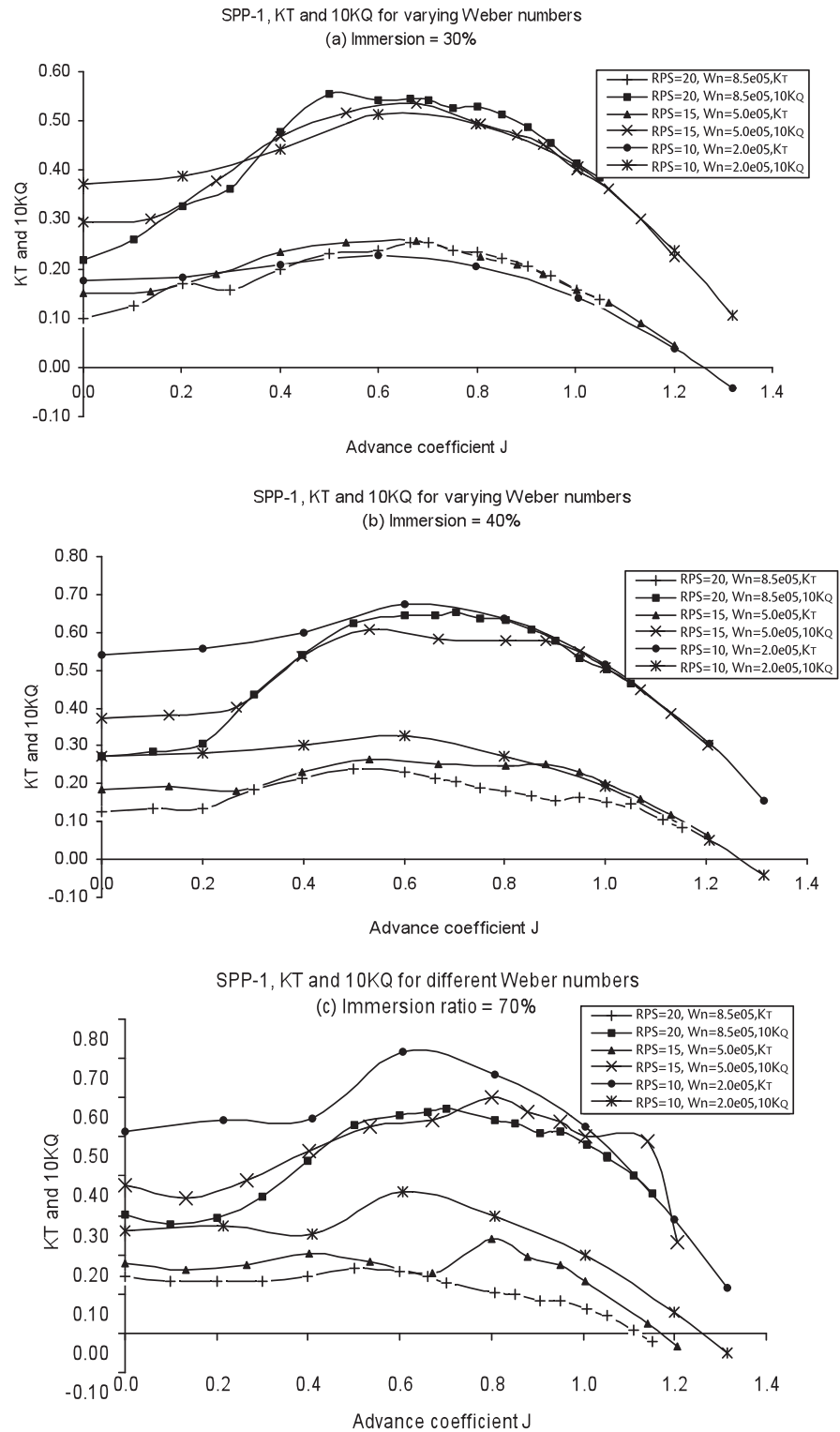


FIGURE 4. K_T and $10K_Q$ variation with Weber number for SPP-1.

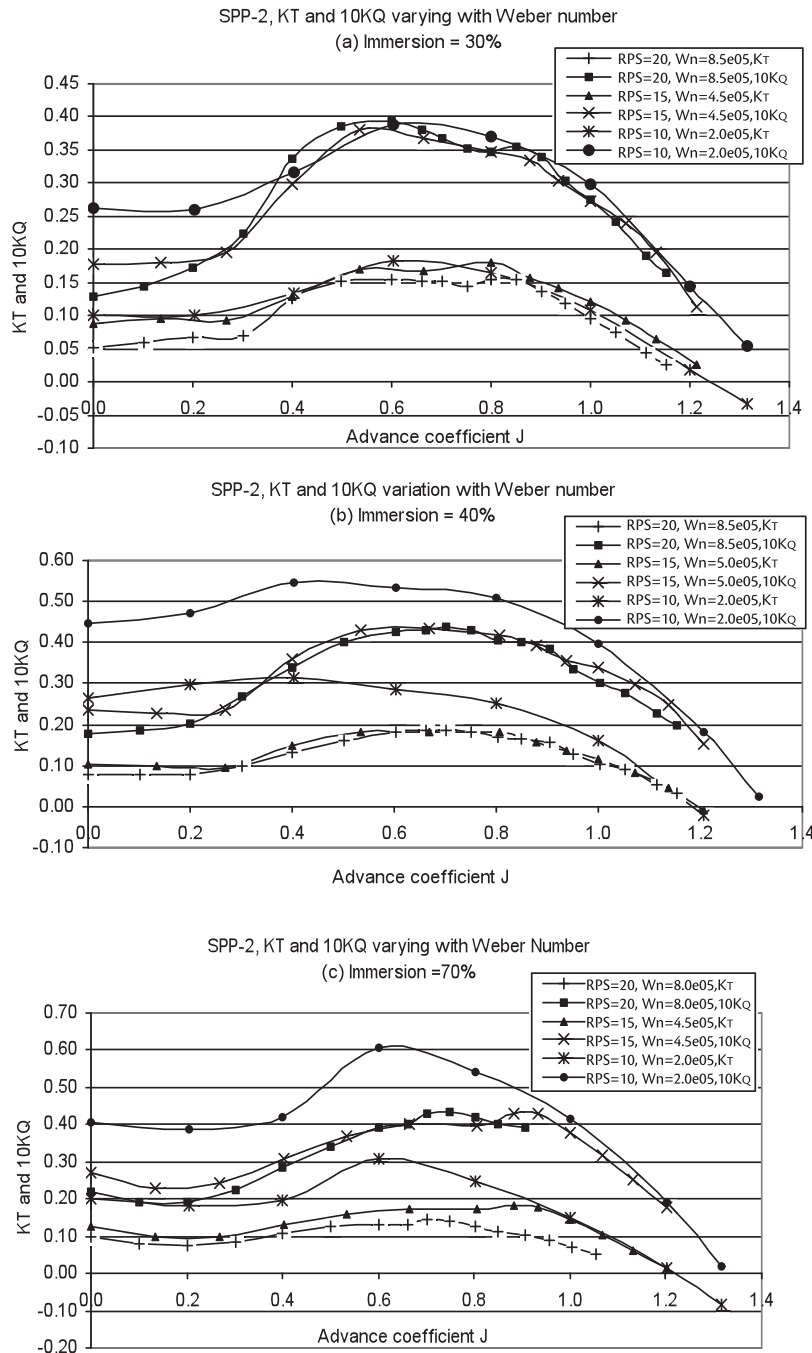


FIGURE 5. K_T and $10K_Q$ variation with Weber number for SPP-2.

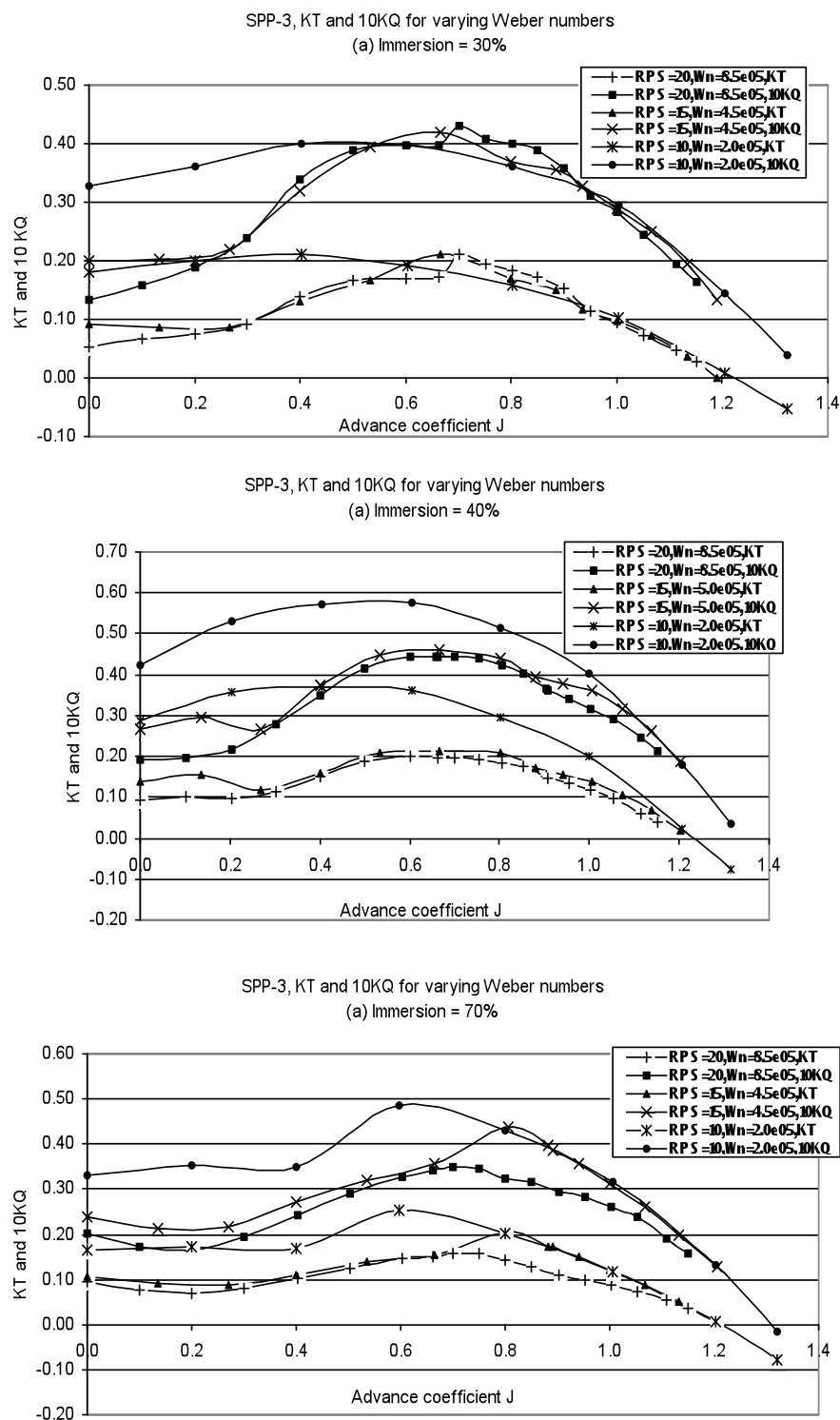


FIGURE 6. K_T and $10K_Q$ variation with Weber number for SPP-3.

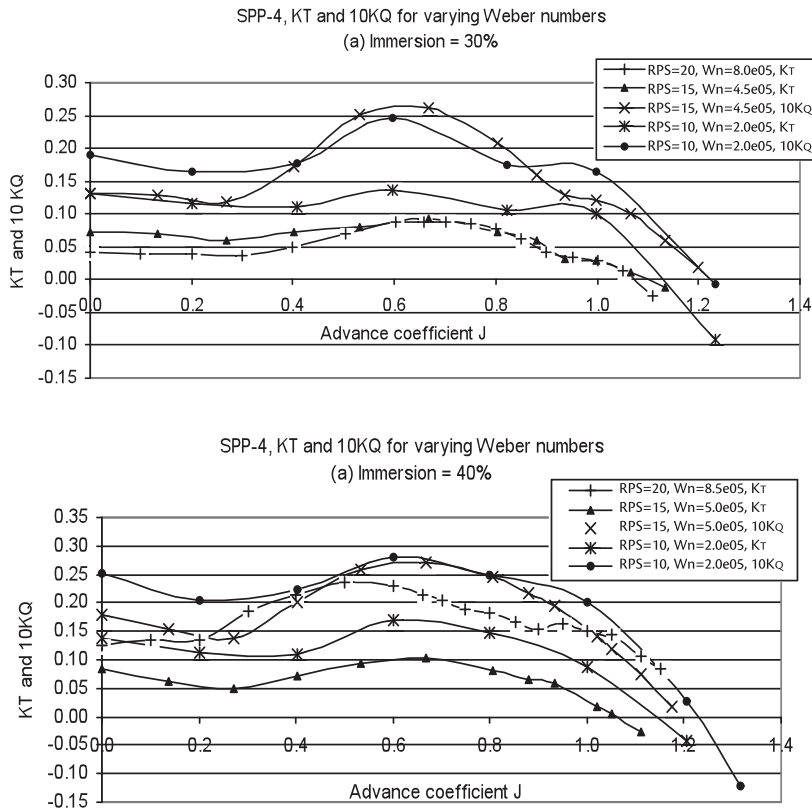


FIGURE 7. K_T and $10K_Q$ variation with Weber number for SPP-4.

The effect of the Weber number can be seen during the fully vented operation of the propeller. Phases 4, 5, and 6 of propeller action shown in Figure 2 correspond to fully vented operation. The value of J , at which the fully vented phase starts, is called the critical advance coefficient and is denoted by J_{cr} . Phase 3 is the transition phase between partially vented and fully vented operation, and is unsteady. It has been suggested that J_{cr} can be taken as the value of J at the mid-point of the range of the transition phase, and this may be regarded as the start of the fully vented phase. (J_{cr} is marked on Figure 2). J_{cr} depends markedly upon the Weber number up to some value which may be determined experimentally. At Weber numbers higher than this critical value, J_{cr} is not greatly affected by the Weber number. Therefore, if model experiments are conducted at Weber numbers greater than this critical value, the extrapolation to full scale will not be affected by the difference in

Propeller series number	Blade Area Ratio	Pitch Ratio
SPP-S1	0.70	0.80
SPP-S2	0.70	1.00
SPP-S3	0.70	1.20
SPP-S4	0.70	1.40
SPP-S5	0.60	0.80
SPP-S6	0.60	1.00
SPP-S7	0.60	1.20
SPP-S8	0.60	1.40
SPP-S9	0.45	0.80
SPP-S10	0.45	1.00
SPP-S11	0.45	1.20
SPP-S12	0.45	1.40

TABLE 2. Surface piercing propeller series.

the Weber numbers of the model and the full scale propellers. Shiba (1953) suggested that this critical Weber number is $W'_n = 180$, as reported in Ferrando et al. (2001). For the current experiment, this condition of W'_n greater than 180 is satisfied for $n=15$ and 20rps (Table 1). It may be noted from Figures 4, 5, and 6 that the K_T and K_Q values for $n=15$ rps are significantly different from the corresponding values at $n=20$ rps only at very low values of J (i.e., in the cavity blocking and choking phases).

In the present experiments, J_{cr} has been determined for the four parent propellers (SPP1, SPP2, SPP3 and SPP4), all of which have the same pitch ratio $P/D = 0.83$. The values of J_{cr} are given in Table 1 and are plotted as a function of Weber number W'_n in Figure 8. It appears from this figure that the effect of Weber number on J_{cr} wanes only after $W'_n = 200$ or so. W'_n lies between 162 and 247 for $n=20$ rps. The experimental results show some dependence on Weber number only at low values of J . This small variation has been ignored and it has been assumed that if all the experiments are conducted at 20rps when the Weber number is sufficiently high, the scale effect due to Weber number will be small for the entire range of J .

Figure 9(a) and Figure 9(b) show the values of K_T and η_o efficiency of all four propellers at 30% immersion. Figures 10 and 11 show the corresponding values for 40% and 50% immersion respectively.

In these three figures, it can be seen that the efficiency of propeller SPP-3 is generally high over the entire speed range and at all immersion ratios. The maximum efficiency has been obtained for each propeller at each immersion ratio. The variation of maximum efficiency with

immersion ratio has been plotted for all the propellers and is shown in Figure 12.

As can be observed from the figure, in the case of propeller SPP-1, the maximum efficiency drops steadily from about 60% to 27% as immersion increases from 30% to 70%. For SPP-2, the efficiency is nearly constant with a value of about 60% up to an immersion ratio of 50%, but drops sharply after that. In the case of SPP-3, the efficiency is nearly constant with a value of around 60% over the complete range of immersion ratios considered. Propeller SPP-4, on the other hand, shows an almost constant maximum efficiency over the whole range of immersion ratios but with a much smaller value of around 47%. Thus, propeller SPP-3 appears to have the best efficiency characteristics at all immersion ratios among the four parent propellers.

The behavior of the propellers discussed in the foregoing is for the propeller operating in the first quadrant (i.e., with a positive forward speed and propeller revolutions in the direction corresponding to forward thrust). The astern behavior of surface piercing propellers is generally poor. It has therefore been thought necessary to observe the behavior of the propellers in at least another quadrant. Propeller SPP-3 has been tested with positive forward speed of carriage with the propeller rotating in the reversed direction. Thrust and torque are also reversed in this condition. This is the third quadrant experiment with J negative. Figure 13 shows the variation of K_T and K_Q with J in this quadrant for the three values of $n = 10, 15$, and 20rps. It can be observed that there is almost no variation of K_T and K_Q with n or Weber number except at values of J near zero.

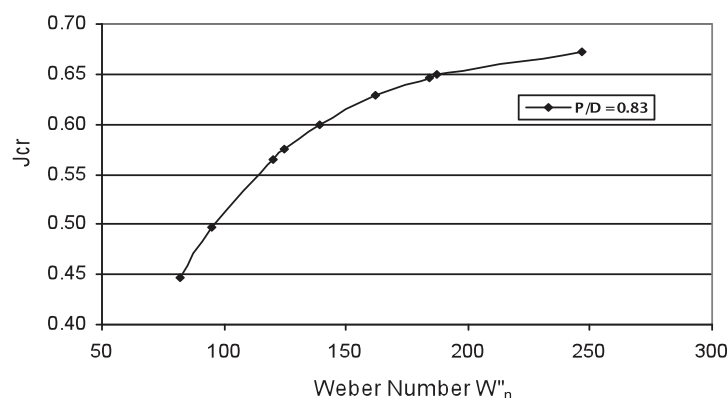


FIGURE 8. Variation of J_{cr} with Weber number W'_n .

This is how it should be, since in this condition, the trailing edge goes into water first and the propeller is perhaps either never fully vented or is fully vented only for a very small range of J near zero. Figure 14 shows a composite diagram of propeller performance in two of the four quadrants. The nature of performance is normal.

Therefore, propeller SPP-3 seems to have the best performance characteristics amongst all the four propellers considered. Therefore, the section shape of SPP-3 has been adopted for propeller series design, manufacture and testing.

Four-Bladed Surface Piercing Propeller Series

Taking the section shape of propeller SPP-3 as the basic shape, the non-dimensional geometry of the propeller blades has been defined. With this

shape, a series of twelve propeller designs has been developed for four pitch ratios and three blade area ratios. All the model propellers have a diameter of 250mm and have been manufactured with an accuracy conforming to ITTC standards. The particulars of the model propellers are given in Table 2.

Open water experiments have been conducted with all the twelve model propellers in the High Speed Towing Tank facility at NSTL with the shaft inclined at 5° to the horizontal and 0° to the tank center line. All the experiments have been conducted with constant shaft revolutions $n=20\text{rps}$ and different carriage speeds so as to get values of J at reasonably small intervals. Tests have been conducted with 30%, 40%, 50%, and 70% propeller immersion. The range of tests has been constrained in some cases by the limitations

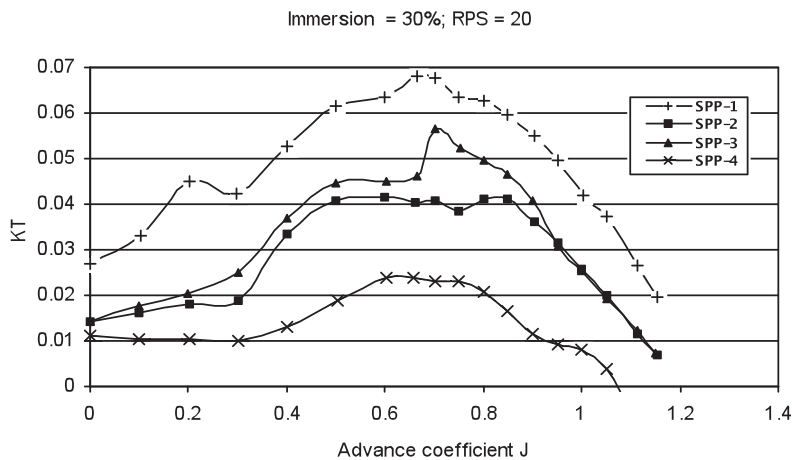


FIGURE 9(A). Variation of K_T with J for the four parent propellers at 30% immersion and 20rps.

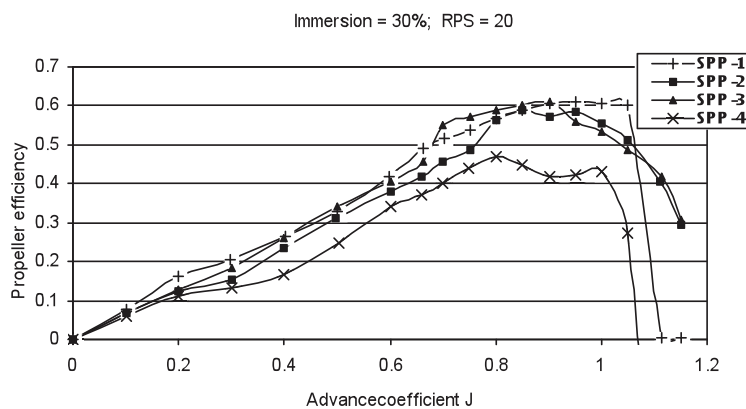


FIGURE 9(B). Variation of efficiency with J for the four parent propellers at 30% immersion and 20rps.

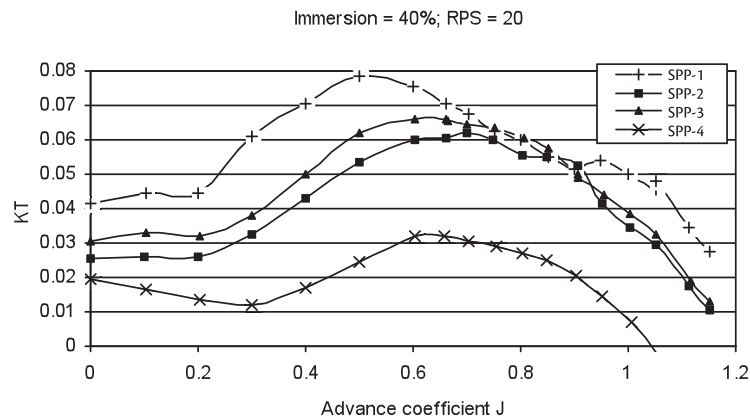


FIGURE 10(A). Variation of K_T with J for the four parent propellers at 40% immersion and 20rps.

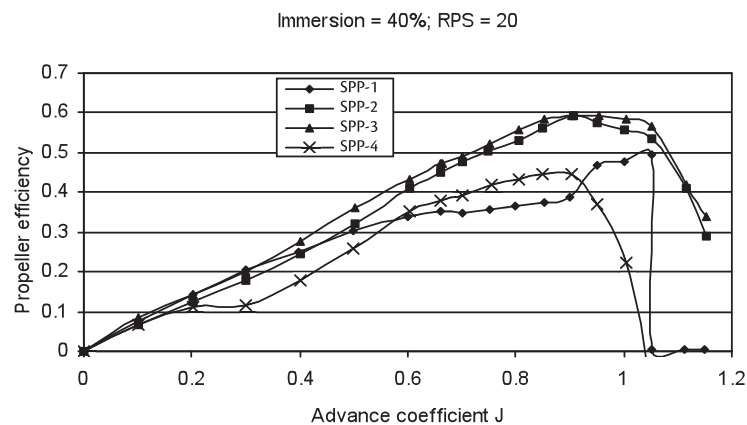


FIGURE 10(B). Variation of efficiency with J for the four parent propellers at 40% immersion and 20rps.

of the propeller dynamometer. The open water test results of the twelve propellers are presented in Figures 15 through 26. Each figure gives the values of K_T , $10K_Q$, and η_o obtained experimentally for one propeller at 30%, 40%, 50%, or 70% immersion ratios. There are also other curves labeled $K_T(\text{ANN})$, $10K_Q(\text{ANN})$, and Efficiency (ANN) that are explained later.

There are a number of sources of error during the experiments and data acquisition, the effects of which are not precisely known. The extension to the shaft of the dynamometer for holding the surface piercing propeller partly above water and the holding device could have introduced bias error, but this has been taken care of in the form of zero error and precision error in the measurement of thrust and torque. The hydrodynamic forces acting on the propeller being unsteady may have caused vibration to affect the measured quantities. Even though the

Weber number effects have been minimized by taking $n=20\text{rps}$, the effects have not been completely eliminated since W_n'' could not be maintained above 200 in all cases. Neglecting the effect of Weber number can lead to errors at low J values. Adequate care and caution have been taken during the experiments, and data acquisition and the experimental uncertainties have been minimized. However, no formal uncertainty analysis has been done.

The following observations can be made from Figures 15 through 26:

- The variation of K_T and K_Q with J is oscillatory. This is because of the various phases of operation of the surface piercing propellers as discussed in the Introduction. Oscillations in efficiency are, however, much lower.
- The transition of the propeller from the wet zone to the fully vented zone is not well defined in most of the cases.

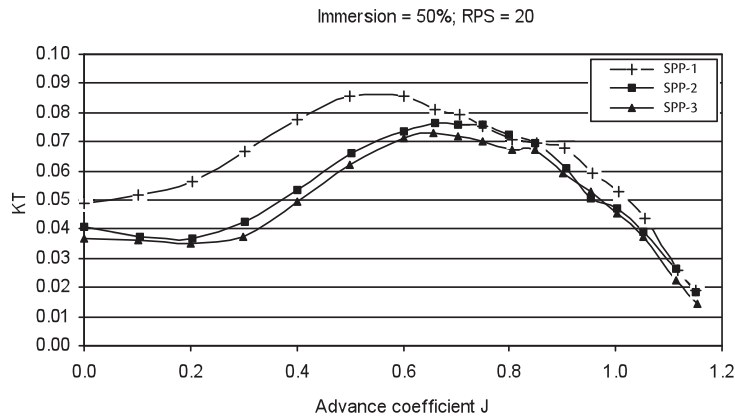


FIGURE 11(A). Variation of K_T with J for three parent propellers at 50% immersion and 20rps.

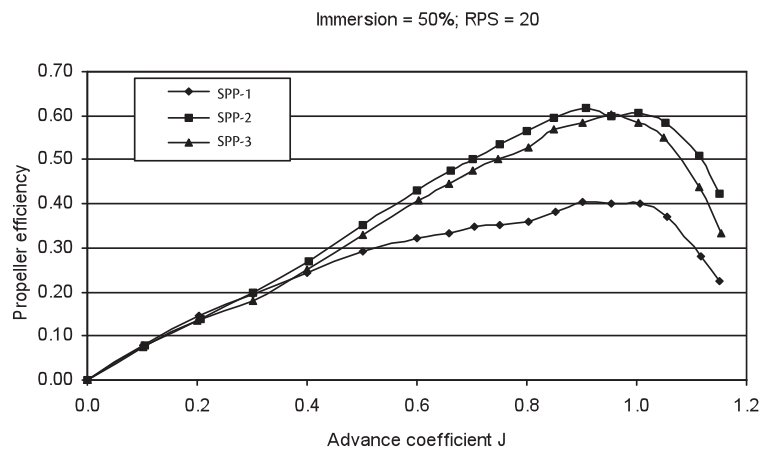


FIGURE 11(B). Variation of J efficiency with J for three parent propellers at 50% immersion and 20rps.

- It is, in general, difficult to demarcate clearly the various phases of propeller operation from the K_T and K_Q diagrams, and therefore to determine J_{cr} .
- Even if J_{cr} can be identified in each case, it does not seem to follow any systematic variation with immersion ratio, pitch ratio or blade area ratio.

The data generated with this series of propellers is to be used to (i) design a propeller with similar geometrical properties as the series and (ii) predict the performance characteristics of the design propeller. For this purpose, it is necessary to have a method for predicting the open water characteristics, i.e., K_T , K_Q , and η_o as functions of J for different values of P/D , blade area ratio and h/D . The techniques that have been considered for developing such a method are regression analysis, interpolation techniques and Artificial Neural Networks (ANN). With the oscillation of the data seen in the

figures, it is difficult to fit regression equations for prediction. Even if one desires to fit a regression equation to only the partially vented zone for $J > J_{cr}$, the fitted curve is not satisfactory. Interpolation can be attempted graphically or by using a computer. Since the data oscillates very much, any interpolation has to be done using small patches of data. Manually this process is very laborious and prone to error. Numerically, the accuracy of interpolation depends on the oscillation of data over the selected patch and fitting the right equation for interpolation. The nature of the equation changes with the variable range considered. Interpolation in such a case will not be easy and guaranteeing a reasonable accuracy level may be difficult. Therefore, an artificial neural network has been developed for determining the open water characteristics of this surface piercing propeller series. A brief description of this method is given in the next section.

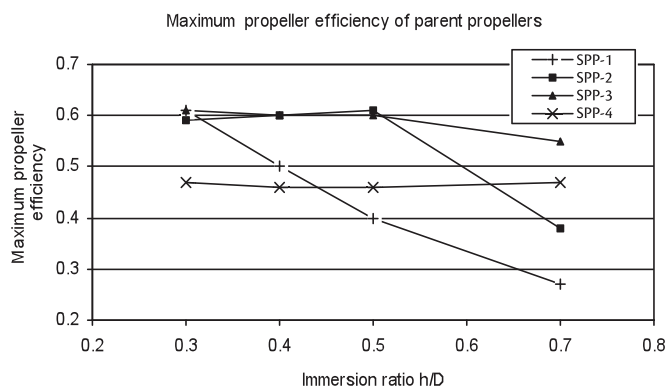


FIGURE 12. Variation of maximum propeller efficiency of parent propellers with immersion.

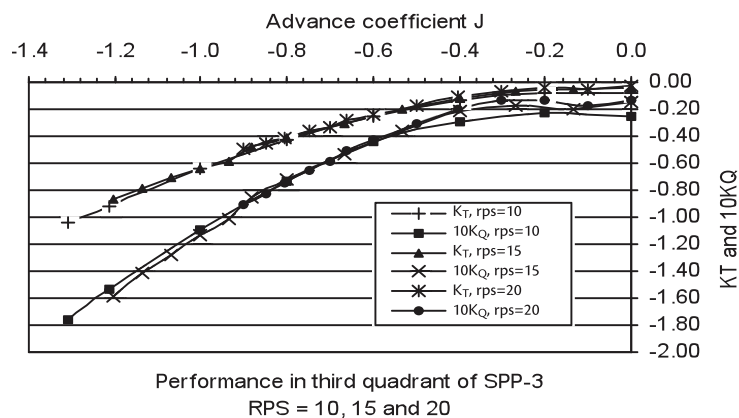


FIGURE 13. Performance of SPP-3 with positive forward speed and reversed rotation.

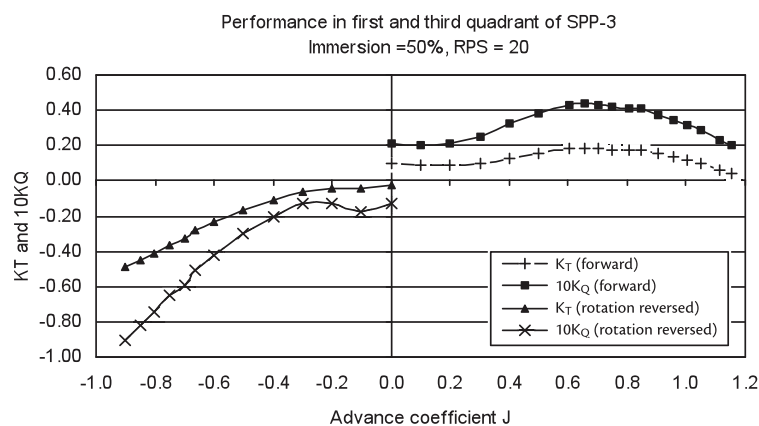


FIGURE 14. Performance of SPP-3 in the first and third quadrants.

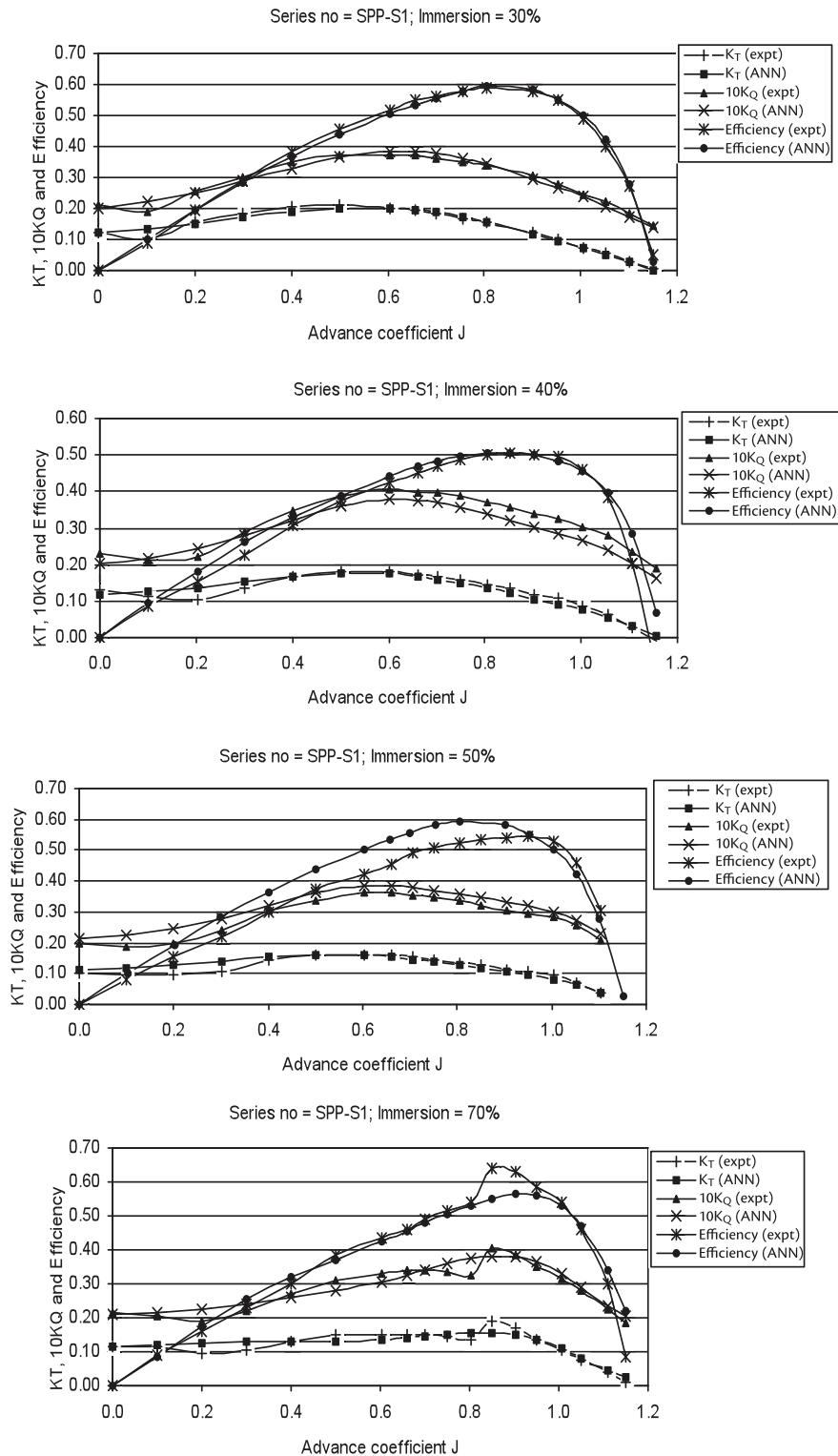


FIGURE 15. Open water characteristics of SPP-S1 for varying immersions.

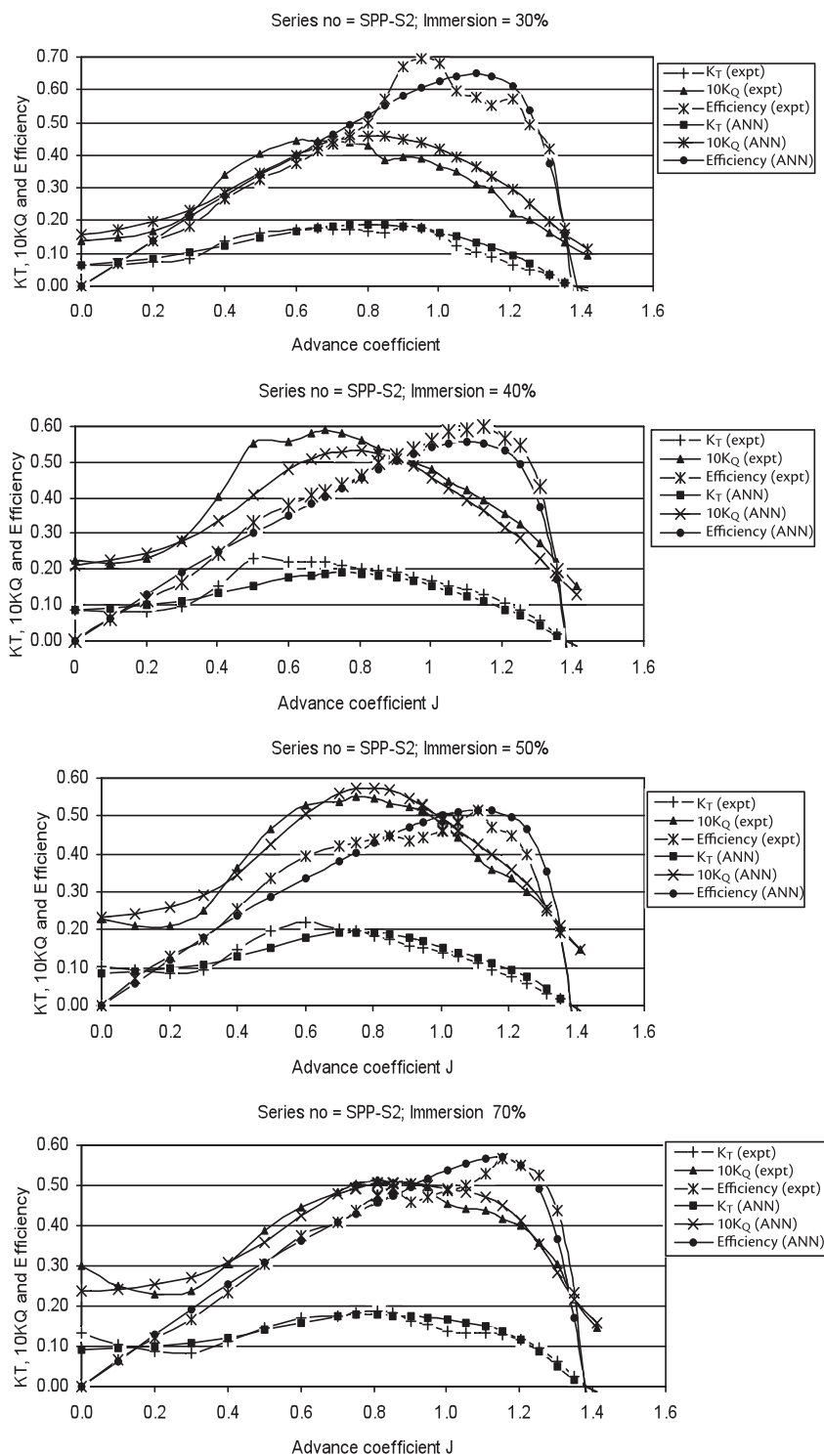


FIGURE 16. Open water characteristics of SPP-S2 for varying immersions.

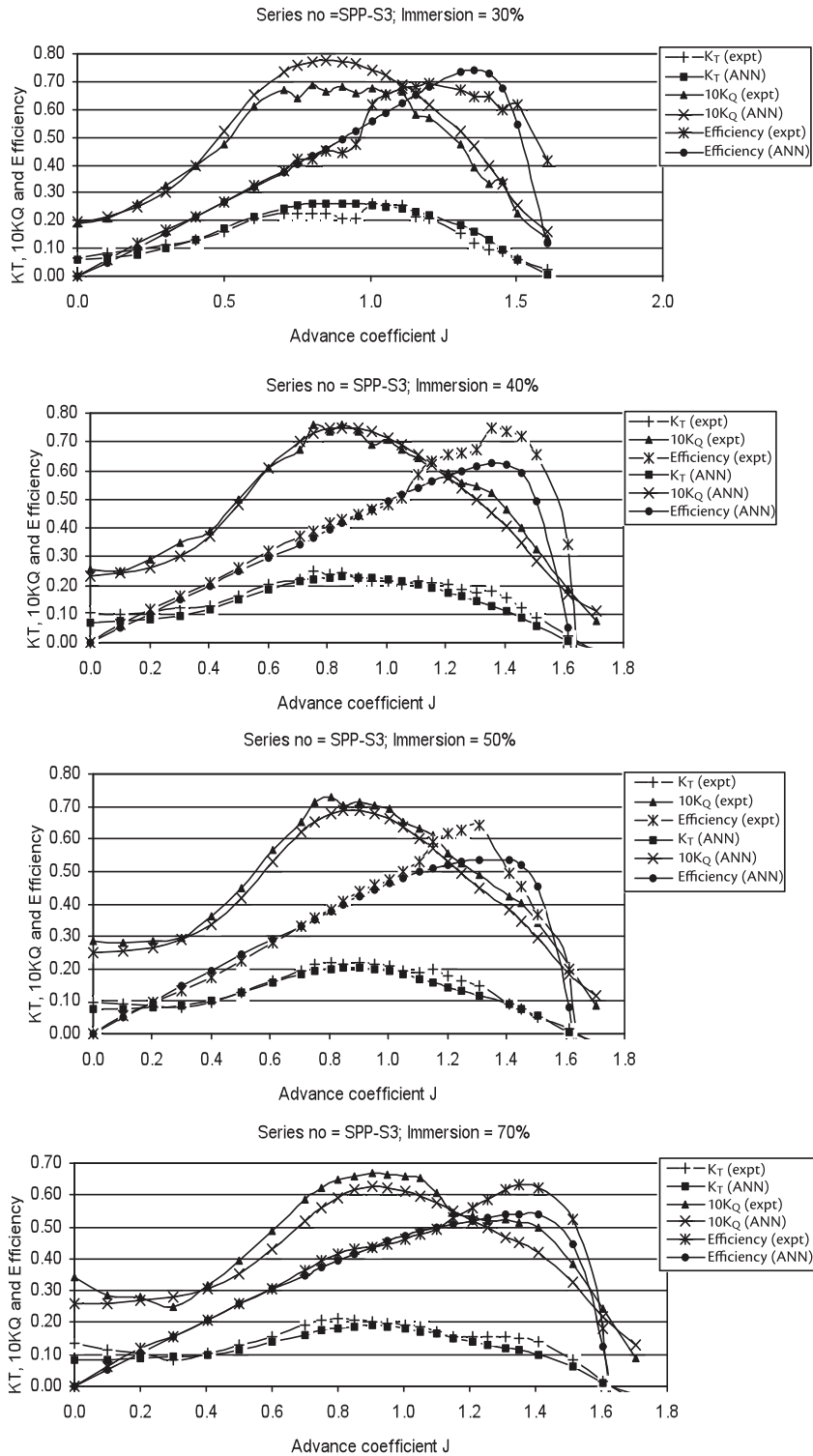


FIGURE 17. Open water characteristics of SPP-S3 for varying immersions.

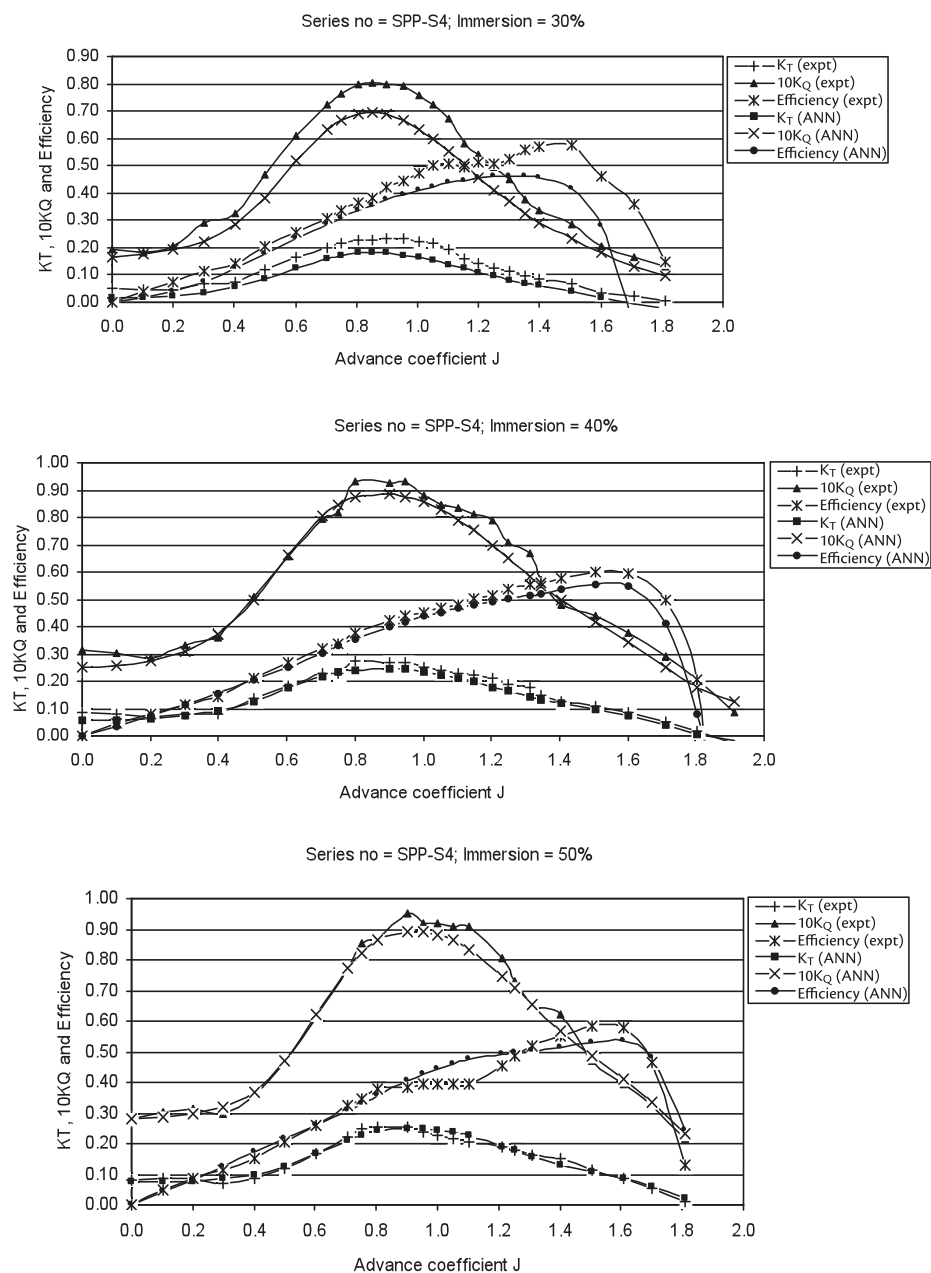


FIGURE 18. Open water characteristics of SPP-S4 for varying immersions.

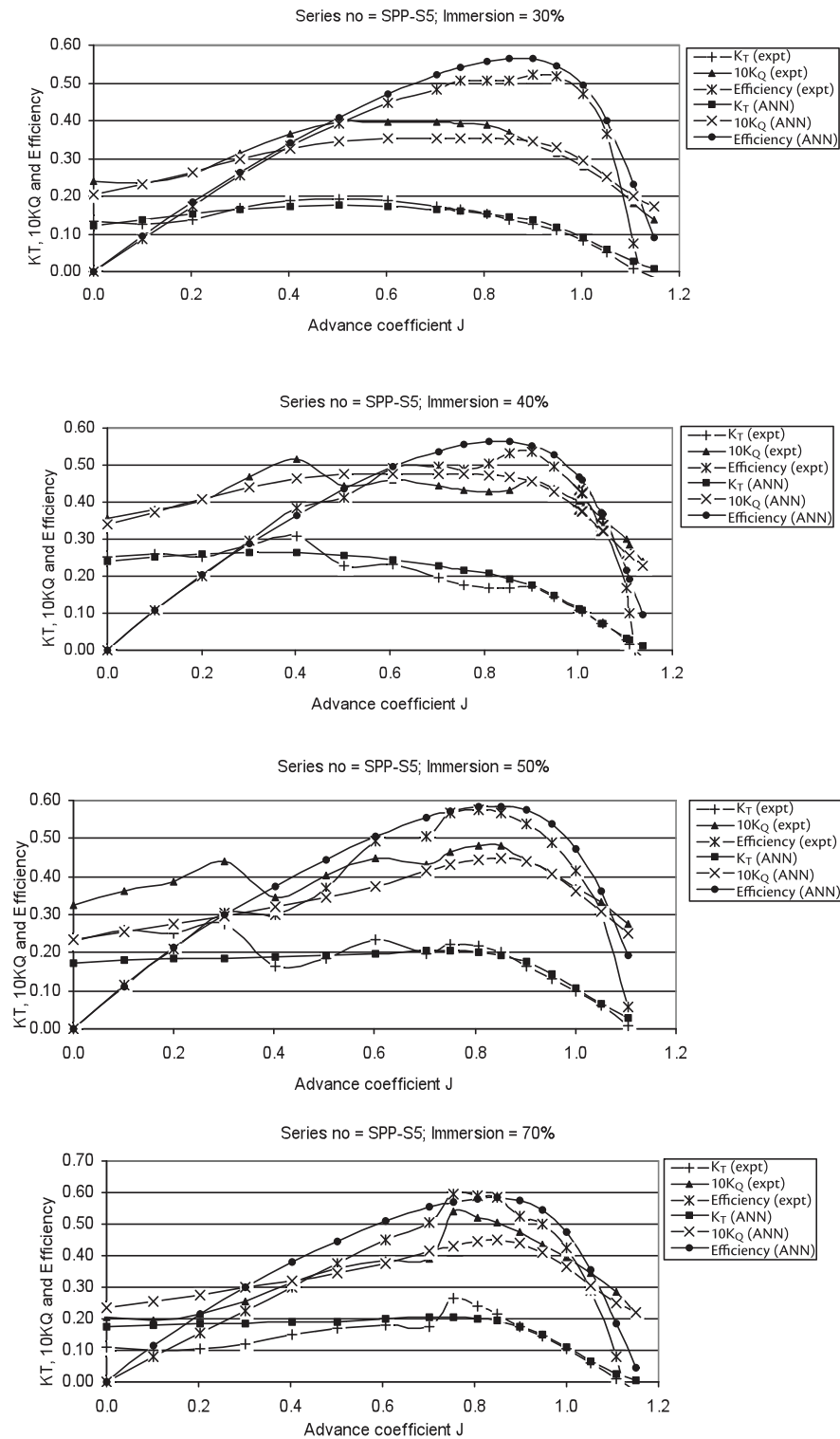


FIGURE 19. Open water characteristics of SPP-S5 for varying immersions.

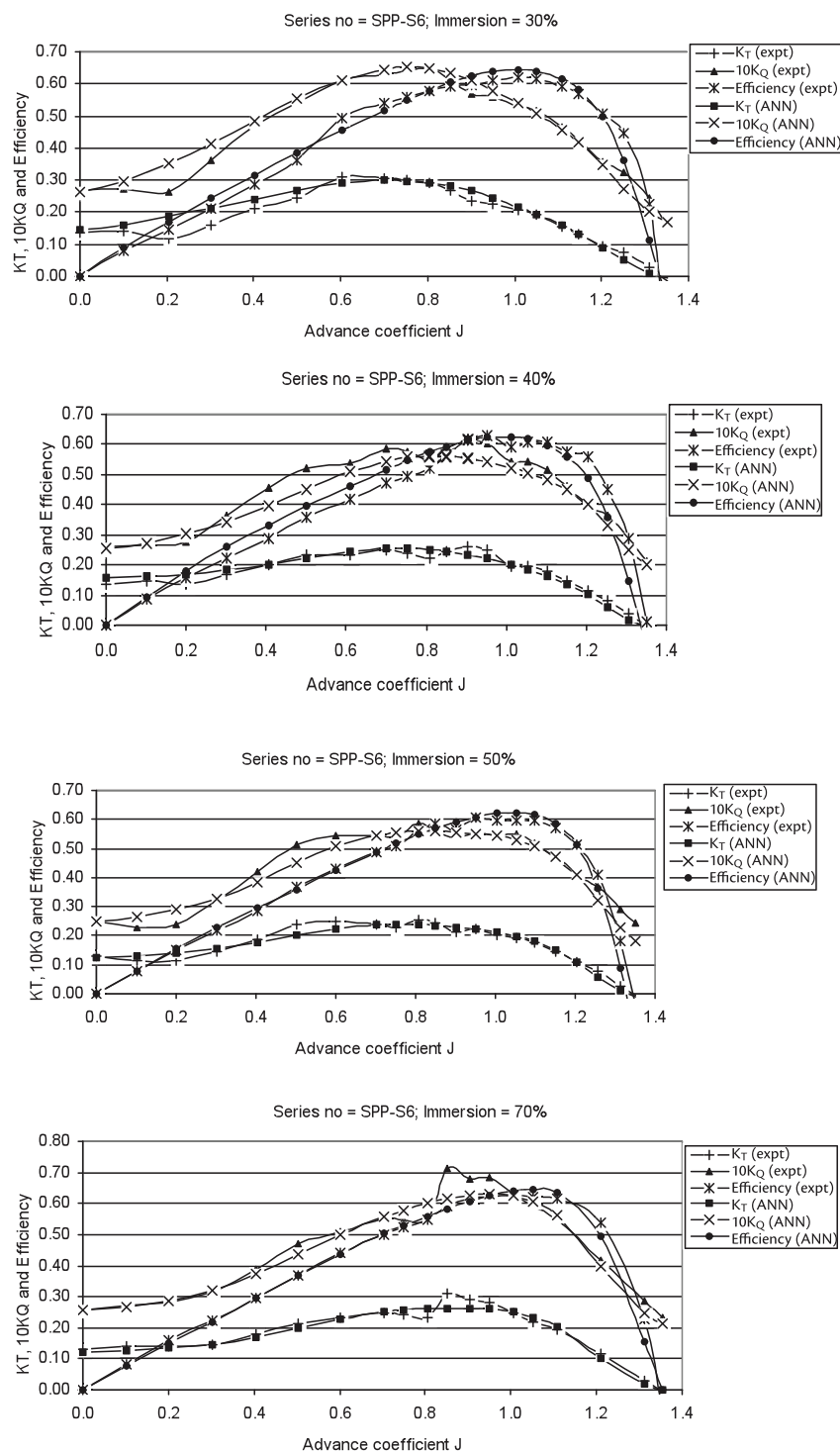


FIGURE 20. Open water characteristics of SPP-S6 for varying immersions.

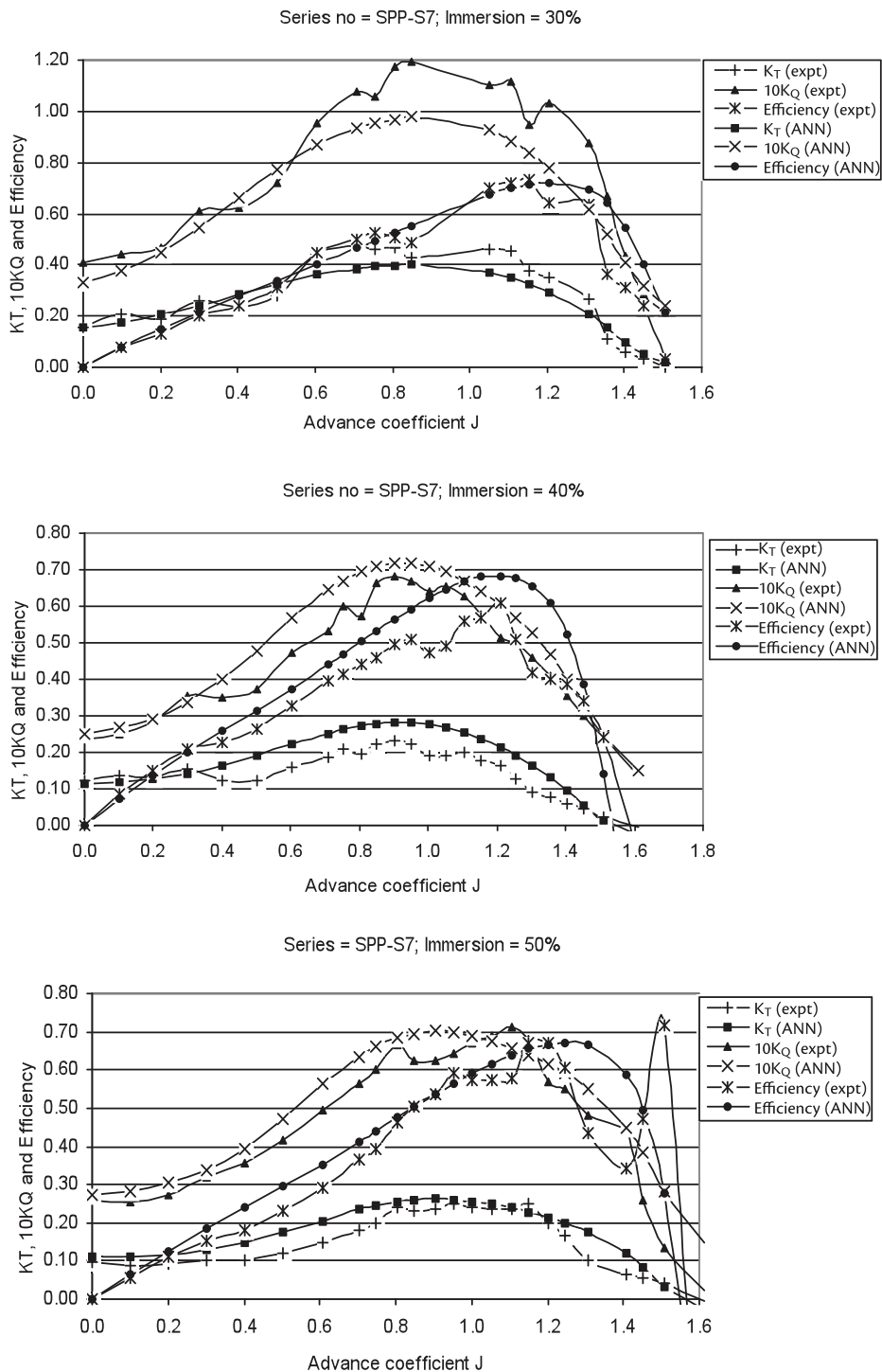


FIGURE 21. Open water characteristics of SPP-S7 for varying immersions.

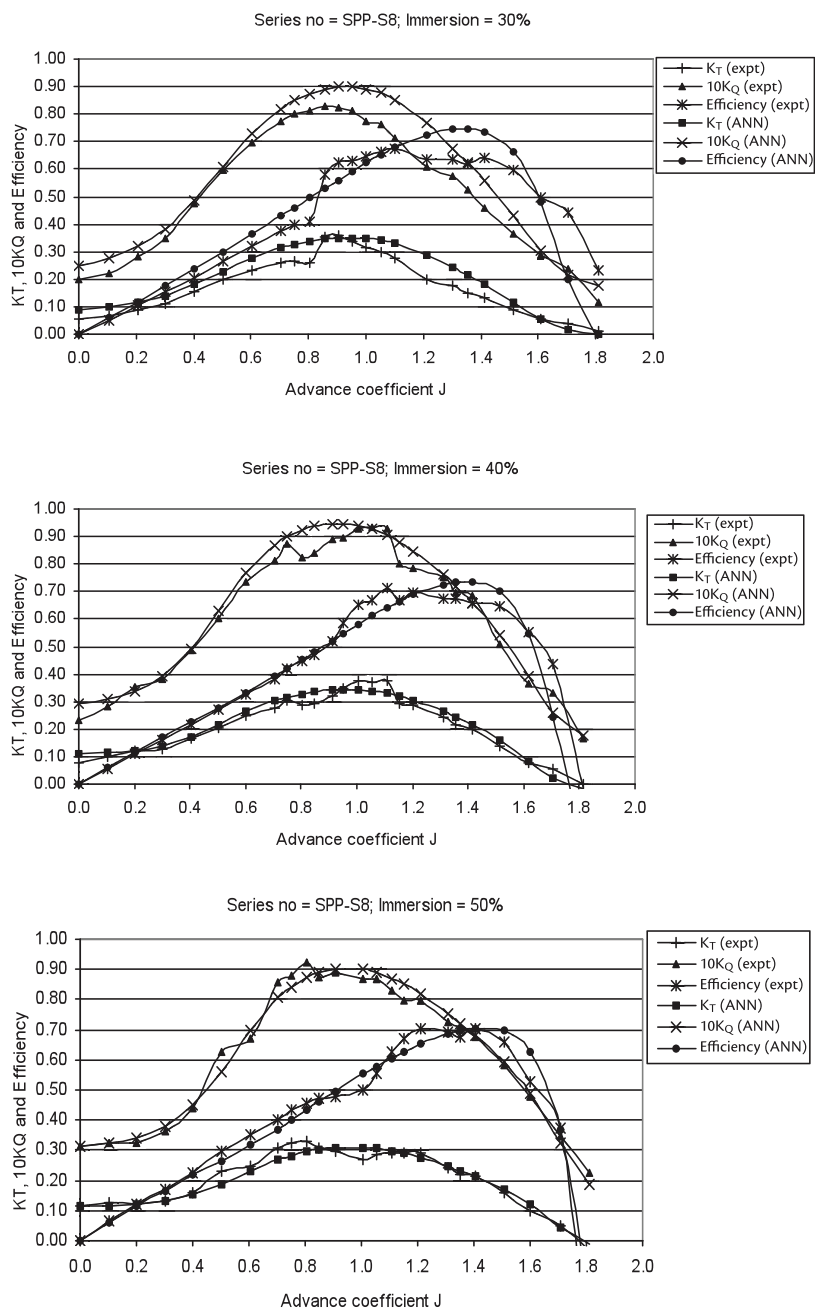


FIGURE 22. Open water characteristics of SPP-S8 for varying immersions

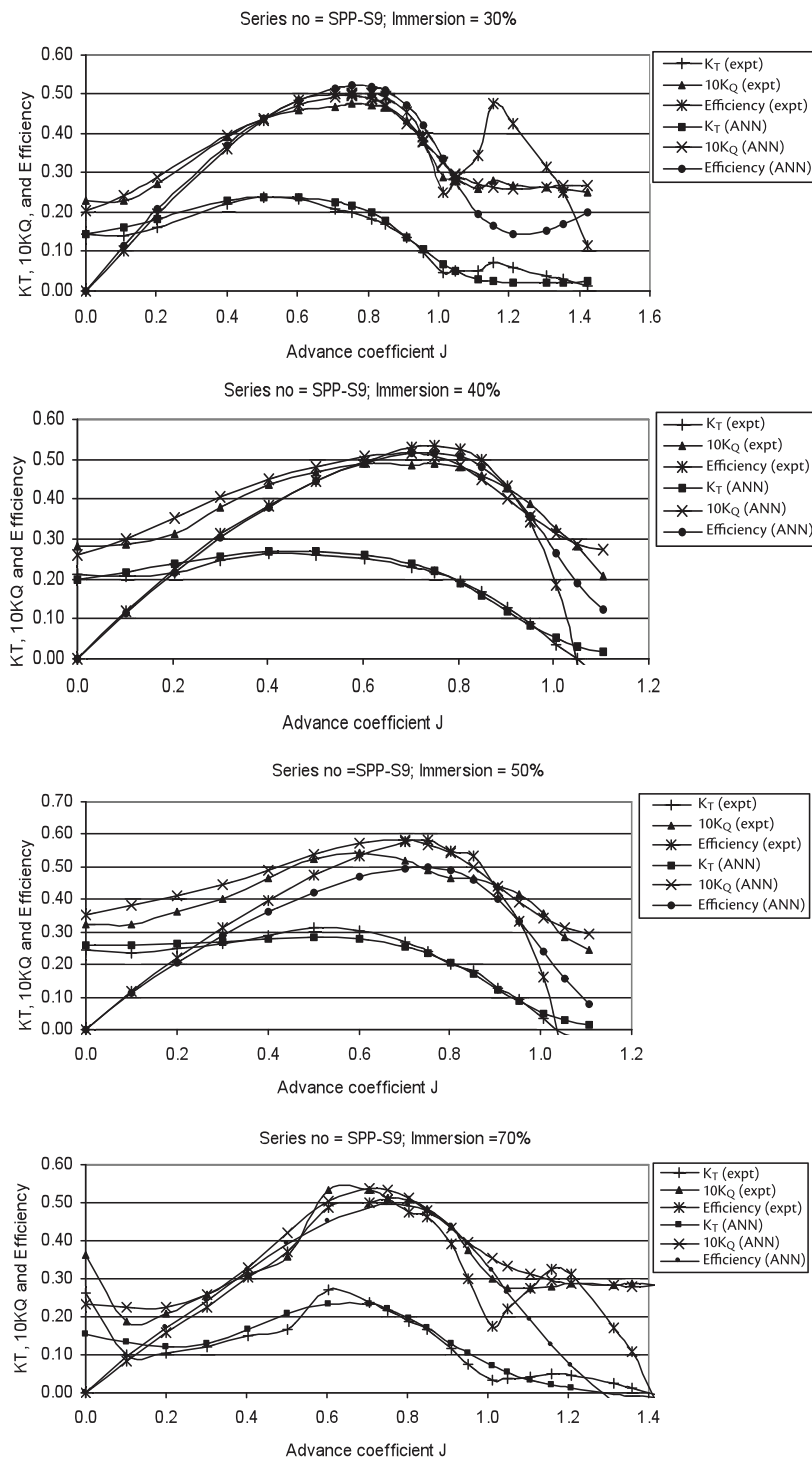


FIGURE 23. Open water characteristics of SPP-S9 for varying immersions

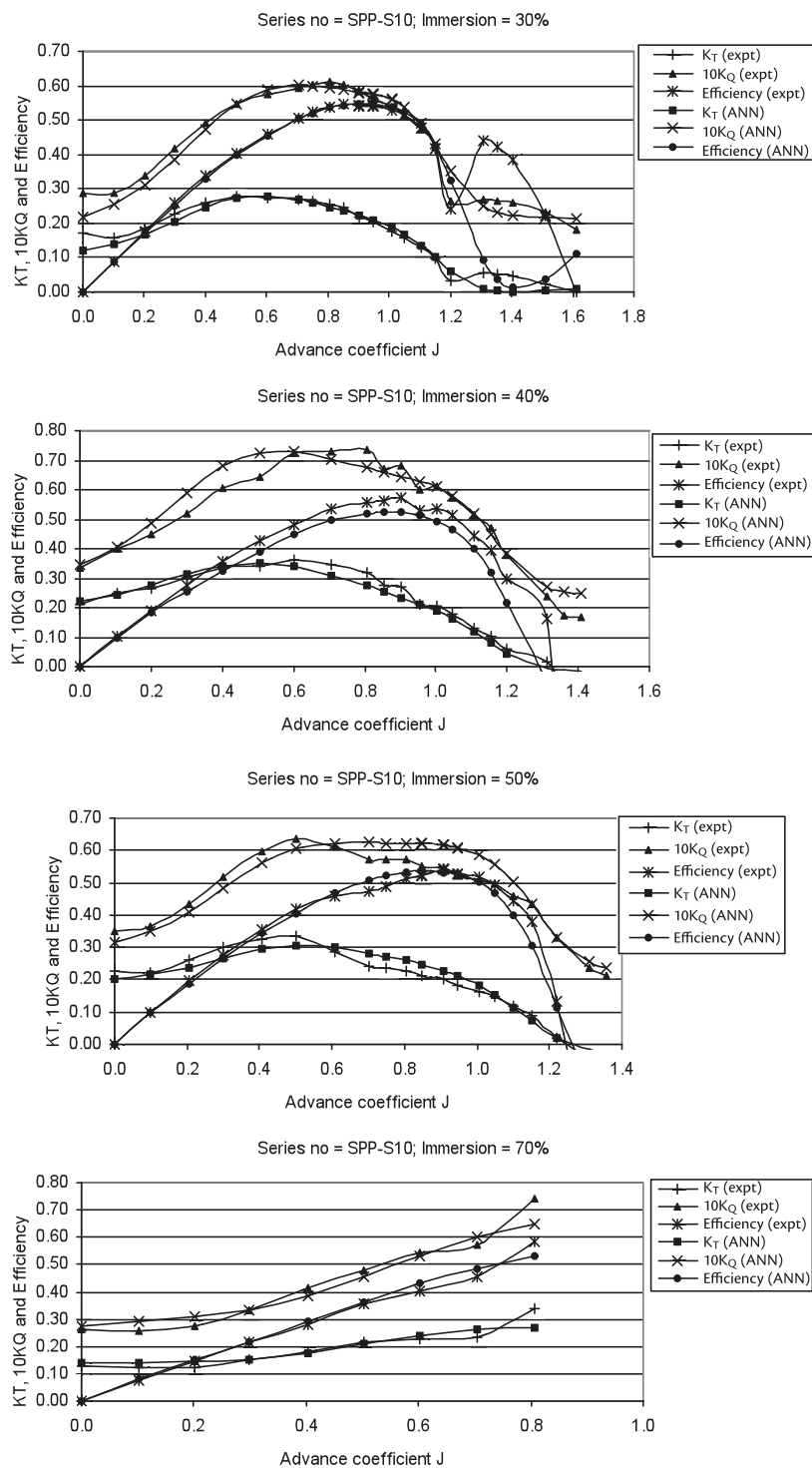


FIGURE 24. Open water characteristics of SPP-S10 for varying immersions.

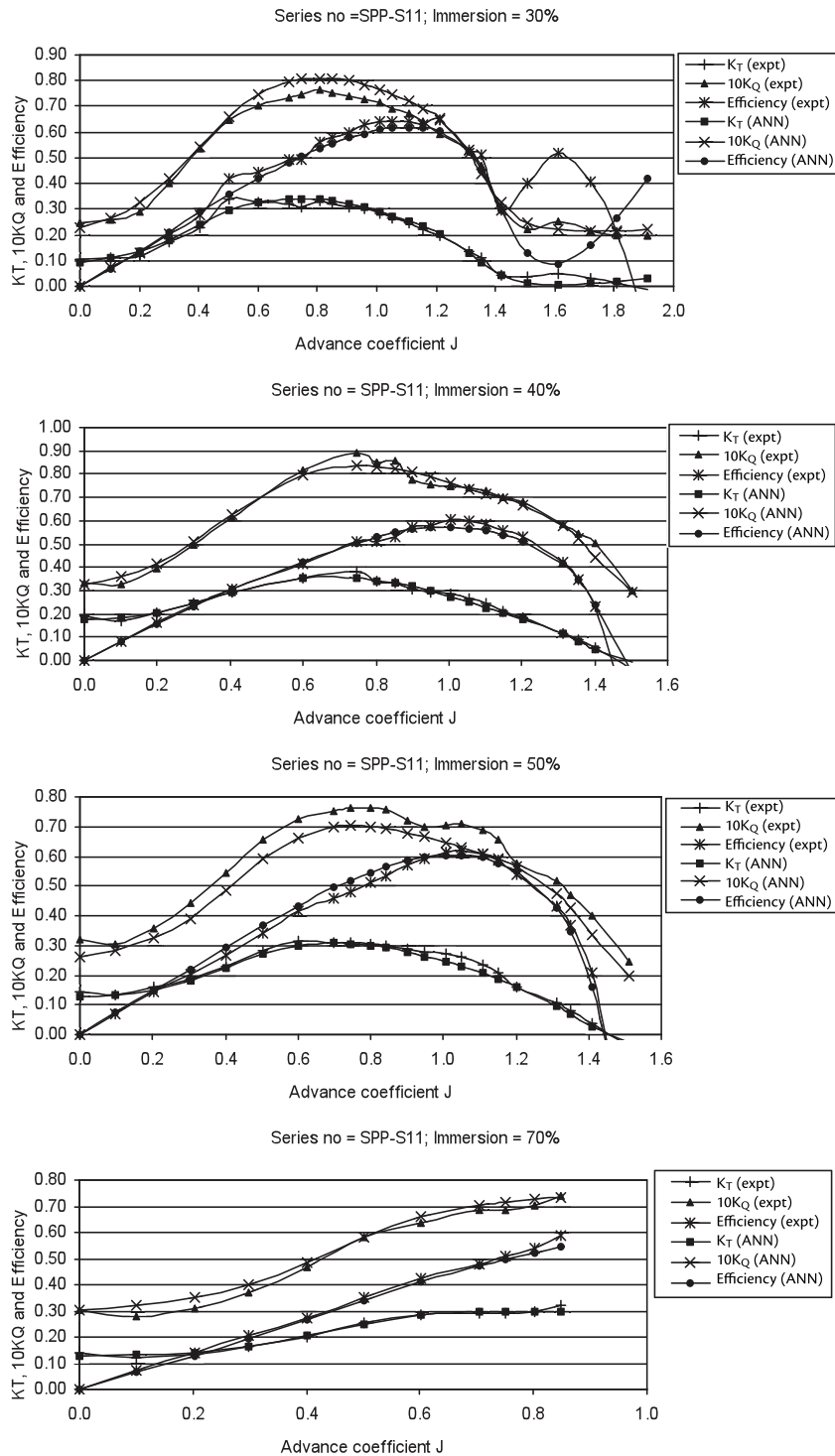


FIGURE 25. Open water characteristics of SPP-S11 for varying immersions

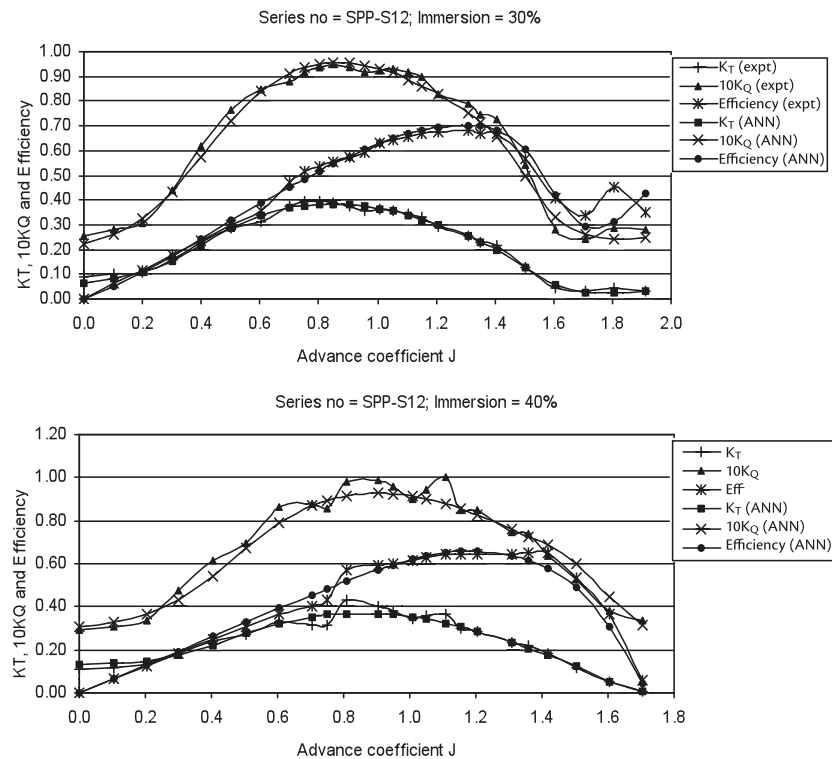


FIGURE 26. Open water characteristics of SPP-S12 for varying immersions.

Artificial Neural Networks In Fitting Experimental Data

Artificial neural networks (ANN) (Haykins, 1999) are computer models of processes and mechanisms that are similar to biological nerve systems. These networks are parallel computational models comprised of densely adaptive units and have become popular among researchers of linear and non-linear systems. Such networks are being gainfully used for faster computation of non-linear systems. A very important feature of these networks is their adaptive nature, where “learning by example” replaces “programming” in solving problems. This feature makes such computational models very effective where a sufficiently large sample of data is readily available. In addition to their utility in solving complex nonlinear problems, neural networks are attractive because of their high execution speed and their relatively modest computer hardware requirements. These features make the use of tools based on artificial neural networks very attractive for modelling problems related to propeller design. In the present work, data generated from the model experiments have been used to “train” the ANN to determine the

characteristics of a propeller with the same geometrical features (e.g., type of blade section and expanded outline) as the model propeller series tested, but any combination of pitch ratio, blade area ratio and immersion ratio within the limits of these variables in the series.

In the back propagation neural network that has been used here, each *node* (or processing element) resembles the connected neurons in biological systems. A processing element accepts one or more signals, which may be produced by other processing elements or applied externally (e.g., provided by a process sensor). The various signals are individually amplified, or *weighted*, and then summed together within the processing element. The resulting sum is applied to a specific *transfer function*, and the function value becomes the output of the processing element. The transfer function used in the back propagation network is known as the *sigmoid function*:

$$f(s) = \frac{1}{1 + e^{-s}} \quad (6)$$

where s is the sum of the node inputs. Clearly the node output will be confined to the range $0 \leq f(s) \leq 1$.

The network starts calculating its output values by passing the weighted inputs to the nodes in the first layer. The resulting node outputs of that layer are passed on, through a new set of weights, to the second layer, and so on until the nodes of the output layer compute the final outputs.

Before practical application, the network has to be trained to perform the mapping of the input parameters (i.e., BAR , P/D , h/D , and J) to the output parameters K_T and K_Q . This is done by repeatedly applying the training data as its inputs, calculating the corresponding outputs by the network, comparing them to the desired outputs, and altering the internal parameters of the network for the next iteration. The training starts by assigning small random values to all the weights. The first set of input values are presented to the network, which then calculates the output values. Because the initial weights are random, the calculated values will generally vary from the desired output values. Therefore, the differences between the desired and calculated outputs have to be considered in order to improve network values, tuning each weight through back propagation. The weights preceding each output node are updated according to Eq. (7):

$$w_{ij}(t+1) = w_{ij}(t) + \mu x_i(d - a) \quad (7)$$

where w_{ij} represents the weight connecting the i^{th} neuron of the input vector and the j^{th} neuron of the output vector and μ represents the learning rate. The variable x_i represents the i^{th} component of the input vector. The variable d represents the

desired output of the neuron and the variable a represents the actual output of the neuron.

The weights of the neural network are recalculated during the back propagation as outlined above. Then, the network repeats the calculation of output values based on the same input data but with the new weights, and compares them to the desired output values—readjusting the network parameters through yet another back propagation phase. This cycle is repeated until the calculated outputs converge sufficiently close to the desired outputs, or an iteration limit is reached. Once the neural network has been tuned to the first set of input/output data, additional data sets can be used for further training in the same manner. To ensure concurrent network adaptation to all sets of data, the entire training process may be repeated until all data transformations are adequately modelled by the network. This requires, of course, that all the data sets are from the same process, and therefore that the underlying input/output transformation is consistent.

This *training mode* is a precondition for actually applying the neural network in the *application mode*. In the application mode, entirely new input data are presented to the network, which in turn predicts new outputs based on the transfer characteristics learned during the training. If these new data have been obtained from the same local region of operation in the process as the training phase, data from the input/output relations should be calculated by the same underlying process and the neural network should perform adequately. Figure 27 shows the flow diagram of a

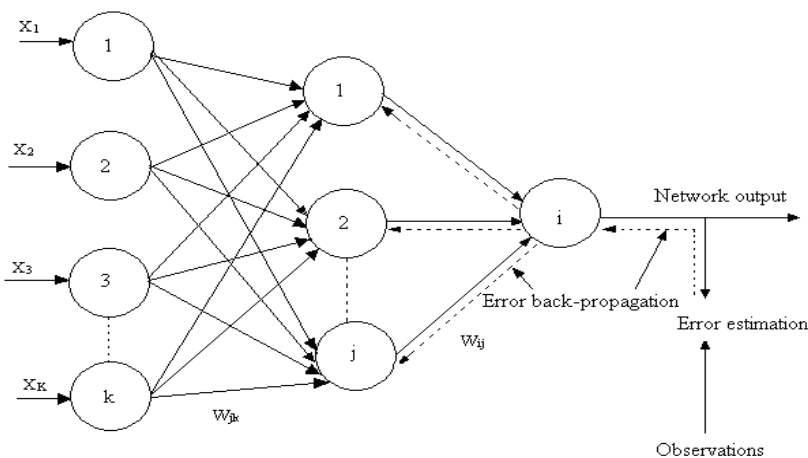


FIGURE 27. Topology of a back propagation algorithm.

back propagation neural network and the topology of a back propagation algorithm.

An ANN program was written and the network was trained using experimental data. The trained ANN program was then used to predict the values of the propeller series. The training process depends on the number of iterations. The software was written to calculate the mean-square-error of each iteration. Therefore, one may assume the training to be successful if the mean-square-error can be minimized. Figure 28 shows the mean-square-error as a function of the number of iterations.

This ANN program has been used to predict the K_T and K_Q values as functions of J and the efficiency has been calculated from the predicted values as:

$$\eta_o = \frac{K_T \cdot J}{K_Q \cdot 2\pi} \quad (8)$$

Figures 15 through 26 show a comparison between the experimentally-obtained data and the predicted values, the experimental values having the label (expt) and the predicted values having the label (ANN).

The following is a summary of observations from the figures:

- The experimental K_T and K_Q values show a large number of oscillations. The values predicted by the ANN program generally have smaller oscillations.
- The critical advance coefficient cannot be identified in most of the experiments.

However, in some cases J_{cr} is well marked and the transition range can be clearly identified.

- In a few cases, particularly with the small blade area ratio propellers, the critical J seems to be very high, varying between 1.0 and 1.8 with very low K_T and K_Q values, and large fluctuations across the transition zone. This raises a doubt whether this is the critical or there is some other phenomenon involved.
- In a few cases, the ANN program predicts slightly higher or lower K_T and K_Q values over the entire range of J .
- In most cases, although the ANN predictions of K_T and K_Q have much smaller oscillations with variation of J than the experimental data, the predictions match the experimental data very well.

Design of Surface Piercing Propeller Using Series Data

Using the data of propeller characteristics from the ANN program, it is possible to get the optimum efficiency values for each propeller and each immersion ratio. Figures 29 and 30 give the values of optimum efficiency η_o and $10K_Q/J^3$ respectively as functions of J for all the propellers at different immersion ratios. These diagrams can be utilized to design a propeller for the required conditions. Values for 70% immersion are not given in Figures 29 and 30 since a surface piercing propeller is not normally designed for this immersion.

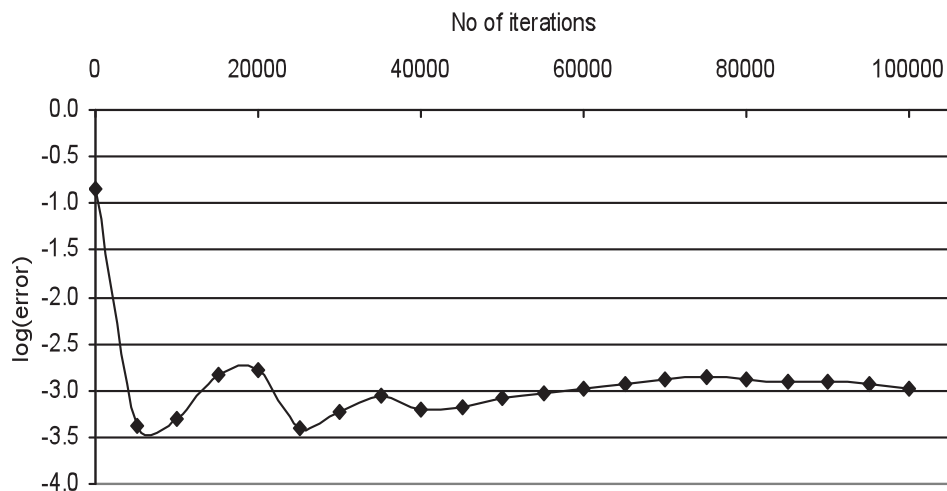


FIGURE 28. Mean-square-error as a function of the number of iterations.

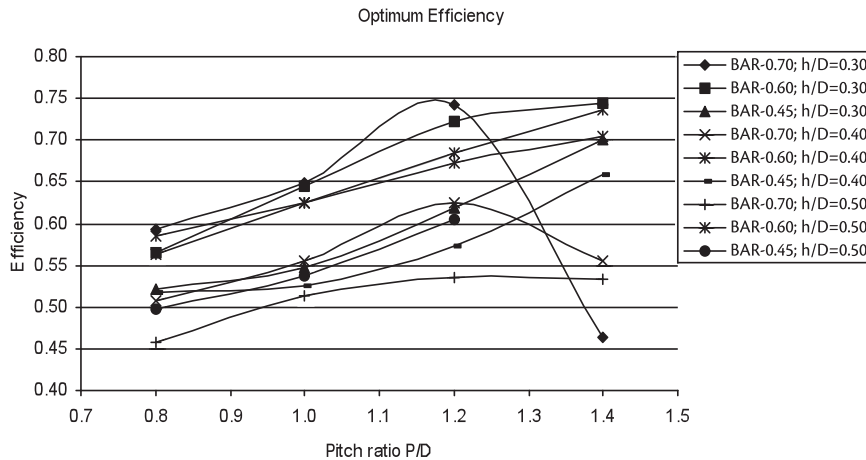


FIGURE 29. Optimum efficiency η_o as a function of pitch ratio P/D .

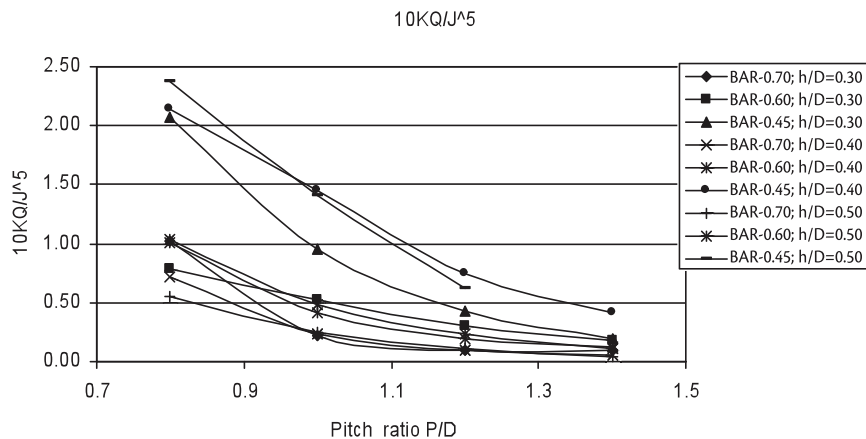


FIGURE 30. $10KQ/J^5$ as a function of pitch ratio P/D .

For a given delivered power P_D and revolutions n of the propeller, the quantity K_Q/J^5 (which is independent of the diameter D) can be calculated as:

$$\frac{K_Q}{J^5} = \frac{n^2 P_D}{2\pi \rho c V_A^3} \quad (9)$$

Here, $c=A'_o/A_o$ is a function of h/D , $A_o=\pi D^2/4$ being the total disc area and A'_o the immersed propeller disc area. V_A can be taken as a value near the expected operating speed of advance. Entering the optimum efficiency diagram for a given h/D ratio and a given blade area ratio, one can obtain the values of P/D , J , and η_o for the calculated K_Q/J^5 . From these values, the propeller diameter D and the corresponding thrust T can be calculated. This can be repeated for various blade area ratios, and

the optimum blade area ratio can be chosen for the highest efficiency. Repeating this calculation for a number of speeds, and equating the thrust developed with the thrust required, one can obtain the optimum diameter and the pitch ratio for the required delivered power and revolutions. Then, one can enter the trained ANN program to obtain the open water performance characteristics of the propeller.

For example, a propeller has been designed to absorb a delivered power of 4000kW at 600rpm to give a speed of 48 knots with the propeller operating at 30% immersion. The wake fraction and the thrust deduction fraction have been taken as zero. The thrust demanded by the vessel at 48 knots is 167kN. The designed propeller is of the present series with a diameter of 2.30m, a pitch

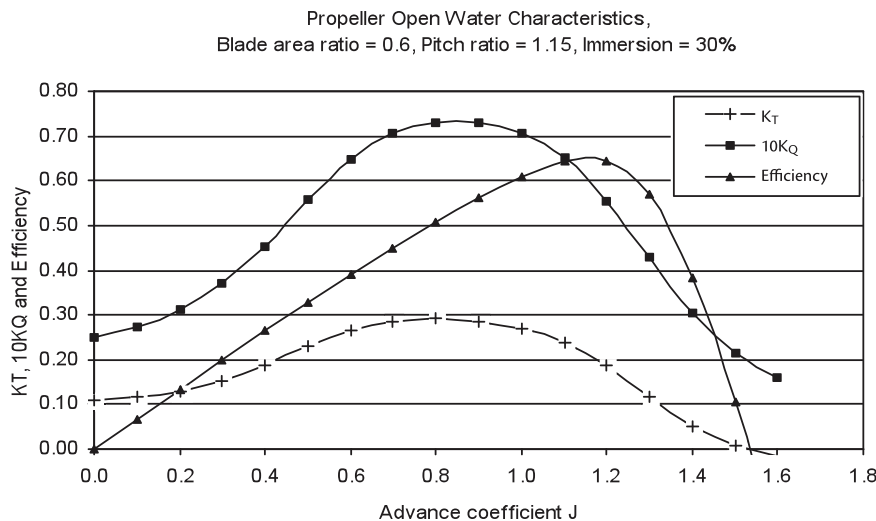


FIGURE 31. Open water characteristics of design example.

ratio of 1.15 and a blade area ratio of 0.60. Its open water characteristics calculated from the ANN program are shown in Figure 31.

Conclusion

The intent of this work was to develop a methodical series of four-bladed propellers of the surface piercing type so as to be able to design a surface piercing propeller for a given operating condition. A test rig, along with instrumentation, was developed at NSTL to determine the open water characteristics of surface piercing propellers experimentally. Initially, four model propellers were designed and manufactured with four different section shapes with the same pitch ratio and blade area ratio. The diameter of all the model propellers was fixed at 250mm. These propellers were of two basic section shapes: wedge and diamond back. To study the effect of trailing edge inclination (cup shape), three different wedge shapes were developed with the trailing edge making angles of 0° , 30° , and 60° to the horizontal, respectively. These four propellers were tested extensively in the High Speed Towing Tank of NSTL. Weber number effects were found to be small in the model tests that were carried out at 20rps for the 250mm diameter propellers. The best performance at all immersions was obtained from SPP-3, the propeller having wedge-shaped sections with the trailing edge inclined at 60° to the horizontal. The

astern performance of this propeller was found to be satisfactory from the limited number of tests that were conducted.

A series of twelve, four-bladed surface piercing propellers of 250mm diameter, having the same non-dimensional section geometry as propeller SPP-3 was developed and manufactured, with four pitch ratios and three blade area ratios. The twelve propellers were extensively tested at 30%, 40%, 50%, and 70% immersion, and the open water characteristics were determined and compiled. An Artificial Neural Network (ANN) was chosen to analyze the data by initially using the experimental data for learning, and then using this information to predict the open water characteristics of propellers of this series, as well as any other propeller with the same non-dimensional expanded blade section shapes and outlines. A comparison of the experimental and the predicted data was found to be satisfactory. A methodology was evolved for designing a surface piercing propeller given the engine power and propeller rpm, and the effective power or thrust characteristics of the vessel.

The experimental open water characteristics showed considerable oscillations in the values of K_T and K_Q as functions of J over the full range. It was not possible to develop a method for predicting the exact values of K_T and K_Q that include these oscillations. However, the prediction method based on an Artificial Neural Network was found to match the experimental data sufficiently well to design a surface piercing propeller

for given conditions, and predict its behavior within acceptable limits of accuracy.

To overcome some of the shortcomings of this work, an attempt should be made to develop equipment for the accurate measurement of vertical and side forces, and to make its use standard practice in surface piercing propeller testing. Perhaps it is also necessary to study the effect of Weber number with propellers with various numbers of blades to set experimental standards. Only a propeller series with four blades has been

developed in this work. It is necessary to extend this series to 3, 5, 6, and 7 blades. Surface piercing propellers with more than four blades are quite common in high-speed yachts.

This work was carried out under a project specially sanctioned by NSTL. The authors would like to express their gratitude to NSTL for extending all help in carrying out this project successfully.

NOMENCLATURE

A_E = Expanded blade area

$A_O = \frac{\pi D^2}{4}$ = Propeller disc area

A'_O = Immersed disc area of surface piercing propeller

$BAR = \frac{A_E}{A_O}$ = Blade area ratio

D = Propeller diameter

$F_n = \frac{nD}{\sqrt{gD}}$ = Froude number

g = Acceleration due to gravity

h = Maximum immersion of propeller blade tip

$J = \frac{V_A}{nD}$ = Advance coefficient

J_{cr} = Critical advance coefficient

$K_Q = \frac{Q}{\rho n^3 D^3 A'_O}$ = Torque coefficient

$K_T = \frac{T}{\rho n^3 D^3 A'_O}$ = Thrust coefficient

n = Propeller revolutions per unit time

P_D = Delivered power

$\frac{P}{D}$ = Pitch ratio

p = Pressure

p_v = Vapor pressure

Q = Propeller torque

$R_n = \frac{V_A D}{\nu}$ = Reynolds number

r = Radius of blade element

T = Propeller thrust

V_A = Speed of advance

$W_n = \frac{V^2 D}{\kappa}$ = Weber number $\left(V = \sqrt{V_A^2 + (\pi n D)^2} \right)$

$W'_n = \sqrt{\frac{n^2 D^3}{\kappa}}$ = Weber number as defined by Shiba (1953)

$W''_n = \sqrt{\frac{n^2 D^3 \left(\frac{h}{D} \right)}{\kappa}}$ = Weber number as defined by Ferrando et al (2001)

β = Angle between propeller axis and direction of advance

$\eta_o = \frac{T V_A}{2 \pi n Q} = \frac{K_T J}{K_Q 2 \pi}$ = Open water efficiency

κ = Kinematic capillarity

ν = Kinematic viscosity

ρ = Density

$\sigma = \frac{p - p_v}{\frac{1}{2} \rho V_A^2}$ = Cavitation number

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AUTHOR BIOGRAPHIES

DR S C MISRA obtained a degree in Naval Architecture in the early 1970s, after which he joined M/s Hindustan Shipyard as a design engineer. In pursuit of higher education, he went to the U.K. and obtained his Ph.D from Newcastle University. He then joined the Indian Institute of Technology, Kharagpur, and took up teaching. He has been a Professor and Head of the Department of Naval Architecture and Ocean Engineering since February 2009, whence he took over as Director of the National Ship Design and Research Centre, Visakhapatnam. Currently, he holds the post of Director of Indian Maritime University, Visakhapatnam Campus (formerly known as the national Ship Design and Research Center), under the Ministry of Shipping, Government of India. He teaches a wide variety of subjects at IIT Kharagpur, and his main areas of interest include ship design and production and experimental hydrodynamics. He is involved in a number of sponsored research and industrial consultancy projects. Since taking over as Director of Indian Maritime University, Visakhapatnam Campus, he started an undergraduate and postgraduate program in Naval Architecture and Ocean Engineering, and a post graduate program in dredging and harbor engineering. Under his leadership, IMU Visakhapatnam Campus is moving towards becoming a major centre for ship design and research.

R.P. GOKARN obtained a B.Tech (Hons) degree in Naval Architecture from the Indian Institute of Technology, Kharagpur, in 1962, a the Ph.D in 1971. He was appointed to the faculty of the Department of Naval Architecture and Marine Engineering at IIT Kharagpur in 1962, became a Professor in 1972, and retired in 2002. He was the Head of the Department of Naval Architecture, I.I.T. Kharagpur, Dean (Postgraduate Studies), and also a member of the Board of Governors of IIT Kharagpur during his tenure. Professor Gokarn taught a variety of subjects. In addition, he was in charge of the Ship Hydrodynamics Laboratory, which he modernized by setting up a towing carriage. He also designed and set up a large circulating water channel. He was also the Principal Investigator of several sponsored research and industrial consultancy projects. After his retirement from I.I.T. Kharagpur, Professor Gokarn has continued to be active in teaching and research. He is a consultant with the Ocean Education and Research Centre (OERC), Mumbai, through which he participated in the establishment of a degree program in Marine Engineering for the University of Mumbai. Along with Professor J.P. Ghose, his former colleague at I.I.T. Kharagpur, Professor Gokarn has written a book, *Basic Ship Propulsion*, published in 2004.

DR. O. P. SHA received his B.Tech. (Hons.) degree in Naval Architecture from the Indian Institute of Technology, Kharagpur in 1980; M.Sc. in Ship Production Technology from the University of Strathclyde, Scotland, U.K., in 1982; and Ph.D. in Engineering from the Indian Institute of Technology, Kharagpur in 1996. Presently, he is Professor and Head in the Department of Ocean Engineering and Naval Architecture at the Indian Institute of Technology, Kharagpur, India. He teaches a wide variety of subjects at the Institute and his main areas of interest include ship design and production, CAD/CAM, and high performance vehicles. He is involved in a number of sponsored research and industrial consultancy projects.
email: ops@naval.iitkgp.ernet.in

