

# The Specialist Committee on Validation of Waterjet Test Procedures

## Final Report and Recommendations to the 23rd ITTC

### 1. GENERAL

#### 1.1. Membership and Meetings

The 22nd ITTC appointed the Specialist Committee on Validation of Waterjet Test Procedures with the following membership:

- Prof. dr. Tom van Terwisga (The Netherlands), Chairman; MARIN
- Mr. John George Hoyt III (USA), Vice Chairman; Naval Surface Warfare Center, Carderock Division (NSWCCD)
- Dr. Mehrdad Zangeneh (United Kingdom), Secretary; University College London
- Dr. Gun-Il Choi (South Korea); Hyundai Maritime Research Institute
- Dr. Niclas Oloffson (Sweden); Rolls-Royce AB - Kamewa Hydrodynamic Research Centre (part of term)
- Dr. Daniele Ranocchia (Italy); INSEAN
- Dr. Dmitry Sadovnikov (Russia); Krylov Research Institute

At the first meeting of the Committee, mr. John Hoyt was elected Vice Chairman and dr. Mehrdad Zangeneh was elected Secretary of the Committee. Responsibilities for the coordination of the various standardization tests were delegated as follows:

- Self Propulsion Tests - dr. Daniele Ranocchia
- Pump and Waterjet System Tests - dr. Gun-Il Choi

On August 31 2000, mr. Nicolas Olofsson (Rolls Royce) indicated that he wished to resign from the committee because of a change of affiliation. Mr. Reima Aartojärvi was appointed as the new Committee Member by the Executive Committee in March 2001.

Mr. Alan Becnel (USA – Band, Lavis and Associates) attended the meetings as an observer, in which he made a vital contribution to coordinate the ITTC work with related work in the GCRMTC project.

Four meetings were held as follows:

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|----------------|--|
| Jan. 24-25 '00 | University of New Orleans (USA) in conjunction with a GCRMTC project meeting |
| Oct. 16-17 '00 | INSEAN (Rome, Italy)   |
| July 23-24 '01 | UCL (London, UK)   |
| Jan. 21-22 '02 | MARIN (Wageningen, The Netherlands)  |

#### 1.2. Introduction

The objective of the Specialist Committee on Validation of Waterjet Test Procedures is to provide proven procedures for the determination of the powering characteristics of waterjet propelled vessels. The objective includes an uncertainty study for the prediction of the main powering characteristics such as power-speed and impeller rotation rate-speed relation.

To meet this objective, a series of standardization tests will be conducted by several ITTC members. The procedure for these tests and the requested results will be prescribed in global terms, leaving sufficient freedom for the individual institutes to use their own preferred methods. This variation in execution of the tests will allow for an assessment of bias errors, needed for the overall uncertainty analysis. It is furthermore expected that this set-up of the test series will lead to an optimal balance in simplicity of the experimental procedure and acceptable uncertainty.

The above series of tests were recommended by the 22nd ITTC “Specialist Committee on Waterjets” and accepted by the Conference. The 23rd ITTC “Specialist Committee on the Validation of Waterjet Test Procedures” was tasked to carry out the corresponding work.

Validation of the Waterjet Test Procedures has become possible by teaming up with a three year project, sponsored by the United States Office of Naval Research (ONR). This project is administrated by the Gulf Coast Region Maritime Technology Center (GCRMTC), situated at the University of New Orleans. The GCRMTC Project provides two hull models with representative stock jets and intakes, as well as one scaled waterjet model. The GCRMTC Project will in the following be referred to as “Gulf Coast Project”.

Due to the fact that the ship models and stock jets were only ready for shipment after March 1, 2002, the most important part of the Committee’s work is yet to be done. This work consists of data collection, analysis, procedure recommendation and a concise uncertainty analysis.

As pointed out in the Report of the 22nd Specialist Committee on Waterjets, the standardization tests consist of three types of tests:

- Self propulsion tests with a model of a high speed displacement monohull, driven by two waterjets

- Waterjet System tests with the aim to determine the system characteristics in terms of flow rate, head and torque, and in terms of thrust and required power.
- Pump tests with the aim to determine the hydraulic characteristics of the pump without the flow distortion caused by the intake and hull boundary layer.

An extensive description of each of the three tests is given in Hoyt et al. (1999).

Apart from the three types of standardization tests, an important emphasis is put on the role of CFD in understanding details of the flow phenomena. A good knowledge of velocity and pressure distributions is necessary to support the underlying assumptions. The importance of CFD will be explained in more detail in section 4 on the outstanding issues.

As pointed out by the 22nd ITTC Committee on Waterjets, the scope of the current standardization effort is limited to the determination of the powering characteristics of the waterjet driven vessel, including determination of the characteristics of its components. The effect of cavitation on the powering characteristics and possible erosion effects is deliberately left out of the scope, as this was regarded to disclose a whole new problem area. It is assumed in the work of our committee that the possible cavitation that may occur in the pump or in the intake during operation of the vessel, does not affect the powering characteristics. This seems to be a realistic assumption for most vessels in operation, but should nevertheless be checked with the jet manufacturer for each individual application.

Another issue in the definition of the scope of the Committee’s work is the introduction of a number of propulsor concepts that could be situated in between the open shaft propeller and the ‘conventional’ waterjet. One can think in this respect of other so called ‘hull integrated propulsors’, completely or partly surrounded by the hull, and of the so called ventilated waterjet. The current Specialist Committee has, in consultation with the

Propulsion Committee, limited itself to non ventilated hull integrated propulsors, of which the conventional waterjet is the most important example.

The first part of this report deals with technical issues related to the mission of this Committee. Section 2 gives a review of relevant literature, published during the last three years. Section 3 provides a market review and as such provides the relevance of this work from a market point of view. Section 4 finally presents a detailed description of the problems as they have evolved during the meetings of the Committee.

The second part of the report deals with administrative issues regarding the standardization project. Section 5 starts with a summary of the rationale behind the standardization tests and the progress made thus far in initiating them. Much of the work of the committee was dedicated to the definition of the results that are requested from the participants. The results of this can be found on the Committee's Web site, as explained in Section 5.2. The time schedule for the experimental work is presented in Section 5.4. The status of the associated Gulf Coast project is presented in Section 6. This section also presents a description of the models made available to the ITTC community. Finally, conclusions and recommendations to the Conference are listed in Section 7.

## 2. LITERATURE UPDATE

The review of published literature will be divided into main sections relating to intake design and analysis, pump design and analysis, hull/waterjet interactions, off-design predictions and finally ventilated waterjets.

### 2.1. Intake Design and Analysis

Brandner and Walker (2001) present the capabilities of the Tom Fink cavitation tunnel at the Australian Maritime College. This tun-

nel is equipped with a special return circuit where the waterjet discharge flow is returned to the tunnel flow at a remote position. An example is given of an intake analysis experiment. Attention is given to a correct modeling of the velocity and the turbulence distribution of the boundary layer ingested by the intake. For a typical 100 m vessel operating at 40 kts, the ingested boundary layer has a thickness in the order of magnitude of the inlet duct diameter. This means in practice that significant turbulence stimulation has to be applied along the wall of the cavitation tunnel. The authors conclude that the most successful boundary layer stimulation consisted of a fence with contiguous triangular elements of base 20 mm and height 10 mm. "The drag of the triangular "teeth" introduces the momentum deficit needed to thicken the boundary layer and the flow around the teeth introduces streamwise vortices of a scale comparable to the tooth width. The vortices are very effective in promoting transverse mixing and rapidly distributing the momentum deficit over the boundary layer height."

Verbeek and Bulten (2001) discuss the interpretation of the results from an experimental intake analysis on a water tunnel. They conclude from a CFD analysis that the effect of the tunnel walls on the pressure distribution and consequently on cavitation extent and inception cannot be neglected. They also conclude that their CFD calculations correlate well with the experimental results when the proper boundary conditions are applied. This evaluation is carried out in the IVR range of 0.53 to 0.93. In case a prediction of the cavitation extent is desired, suitable two phase CFD tools are not yet available and resort has to be taken to experimental work.

Hu and Zangeneh (1999), present the result of a RANS computation of the intake duct of a waterjet. They investigate the effect of the impeller shaft, shaft rotation, Reynold's number and boat trim on the exit flow field from the duct. They found that the presence of the shaft has an important effect on the flow field in the duct and should not be neglected in any

CFD computations of the intake duct. Furthermore, they found that the shaft rotation has a significant effect on the duct flow at relatively low Reynold's numbers. In addition they used their results to predict the shape of the intake capture area at different IVRs. They found the capture area to be almost elliptical in shape.

Similarly, Seil (2001) presents results of a RANS study on the effect of a shaft, shaft rotation and Reynolds number on the flow in a waterjet intake. The results were validated with experimental data, obtained from a waterjet mounted on the cavitation tunnel of the Rolls Royce Hydrodynamic Research Center. Seil concludes that the computed data are in good qualitative and quantitative agreement with the experimental data for the velocity distribution at the duct exit. It is noted that the uncertainty for off design conditions increases due to the difficulty in handling flow separation by the code. This is attributed to the applied turbulence model.

Many symbols are used in the literature to designate the intake working point, and all these definitions come down to some sort of intake velocity ratio. It is suggested to standardize the nomenclature here and only use the originally ITTC proposed symbol IVR or, when the reciprocal value is used, indicate this in the symbol as  $IVR_R$ . A further refinement in the definition is to indicate the station where the mean intake velocity ratio is taken. By default, this position is taken in the throat of the intake.

## 2.2. Pump Design and Analysis

Only few papers about waterjet pump design and analysis have been published. In the last three years however, a number of valuable contributions has been made. Allison et al. (1998) have re-viewed the waterjet pump design methods which includes application of lifting surface theory to the pump design. Taylor and Kerwin (1998) introduced a procedure of coupled lifting-surface and RANS for wa-

terjet pump design. Taylor and Kimball (1999) performed an experimental validation of this design method. Detailed experimental and computational analysis work is presented by Taylor and Kimball (1999) and Kimball et al. (2001) on the losses occurring in a waterjet pump. For their computational analysis, the authors use a coupled lifting surface/RANS technique. In an iterative way, the flow field through the impeller/stator is calculated with a RANS solver, incorporating force fields that are predicted from the lifting surface code. The pro-grams use each others output as improved input for the next iteration, until satisfactory convergence is reached.

A first comparison of results from this computational method with experimental data showed that the overall results in terms of head and torque were reasonable (1% and 3% deviations respectively) (Taylor and Kimball, 1999), although deviations in outlet swirl profile were found. A further experimental analysis in Kimball et al. (2001) revealed that significant deviations in rotor and stator losses were present in the tip region of the blade. It was furthermore found that these losses appeared to be very sensitive to tip gap. Adaptation of the empirical drag coefficients used in the lifting surface analysis to the experimentally derived values, greatly improved the flow profiles through the blade row, but appeared to be insufficient modification to improve the torque prediction. It is suggested that further corrections on blade loading distribution will be necessary.

Allison et al. (2001) describe the pump design procedure as developed for the Gulf Coast project. A first characterization of the waterjet pump can be obtained from a parametric prediction pro-gram, with which both the design condition and off design conditions are analyzed. This parametric analysis provides the starting parameters for the detailed pump design. The waterjet pump design is initiated using the "streamline curvature method". This method is used to determine the hub and shroud surfaces as well as the radial and chord-wise blade-row loading distri-

butions. The subsequent design of the impeller and stator is done with the “mean streamline design method”.

Hu and Zangeneh (2001) present the results of a series of RANS calculations on an impeller with two stator rows (one ahead and one aft of the impeller), including a converging nozzle. The authors conclude that grid insensitivity is essentially reached for some 70000 cells for a single channel. The effect of modeling the whole impeller versus the modeling of a single blade to blade channel is also studied. It is concluded from this study that the flow near the leading edge is the same for both models, but that deviations occur near the trailing edge. The cause for this discrepancy is mentioned to be caused by the periodic condition used in the single blade-to-blade model, which requires further studies. A clear distinction between calculated torque for the case with a uniform inflow as compared to the case with a non-uniform representative inflow could not be discerned.

Finally, Hu and Zangeneh calculate the velocity distribution in the discharged jet flow and compare the actual momentum velocity with the average velocity. If the momentum coefficient  $c_m$  is defined as:

$$c_m = \frac{M_6 A_6}{\rho Q_j^2} \quad (1)$$

a momentum coefficient  $c_m=1.004$  is found. This indicates that an error of 0.4 % in the jet momentum is made if the average volumetric velocity is taken instead of the momentum velocity.

Huntsman and Hothersall (2001) present a re-view of the design methodology used at Hamilton Jet. The authors show the use of three theories with increasing degree of sophistication. The first tool used in the design is based on a combined use of a streamline curvature throughflow calculations together with a 2D inviscid panel method. This quasi-3D approach has been used in the past for the design of turbomachinery blades. The main

shortcoming of this approach is its inability to cope with highly loaded blades especially in the region around the leading and trailing edges. The authors also discuss the development of a 3D RANS code for the analysis of flow through the pump impeller.

In addition to papers published on waterjet pumps, a number of publications on industrial pump design has been reported which are of direct relevance to the design of waterjet pumps. An important development in this area is the application of the 3D inverse design method of Zangeneh (1991) to pump impeller and diffuser design. This method designs the blade shape subject to a specified distribution of blade loading and blade thickness. It has been applied to design of pump impellers and diffusers leading to important design breakthroughs such as suppression of secondary flows in impellers (see Zangeneh et al., 1998 and 1999) and corner separation in vaned diffusers (Goto and Zangeneh, 1998). In addition, the method has been applied to the design of pump stages with improved suction performance (Ashihara and Goto, 1999 and 2000). This method has also been applied to the design of very compact pump stages, see Goto and Ashihara (1999). This is an area of particular importance to large water-jet design since a compact pump stage will not only free up considerable space towards the stern but it will also minimize the weight of water within the waterjet. The application of this method to the design of marine ducted propulsors is reported by Yiu and Zangeneh (1998).

### 2.3. Waterjet-Hull Interaction

An important objective in the Gulf Coast project is to develop tools and knowledge on waterjet-hull interaction. The issues addressed in Allison et al. (2001) are the effect of the ingested boundary layer on the jet performance, and vice versa, the effect the active jet has on the boundary layer development. To get an appreciation of the mutual jet-hull interference, detailed RANS calculations on the

hull and inlet were conducted with the UNCLE code (Taylor and Whitfield, 1991).

Allison et al. (2001) also focus on the interaction between discharged jet and hull. They focus on the effect the discharged jet has on jet induced lift on the hull. To get an indication of its effect, they model the unmixed jet to behave as an equivalent lifting flap, with an equivalent flap width equal to the jet width. The resulting lift prediction is to be incorporated in the force and moment equilibrium of the vessel to find the associated thrust required.

The issue of the effect of the boundary layer on waterjet thrust and separation in the intake is addressed by Bulten (1999). He concludes that a thicker boundary layer reduces the risk for flow separation. He explains this from the smaller decelerating pressure gradient in the intake for the thicker boundary layer. Separation in the intake example presented, seems to become noticeable in the pressure distribution at the intake roof below IVR values of approximately 0.65. Bulten also states that separation of the intake flow cannot be calculated properly by current CFD codes.

A literature review on the full scale boundary layer velocity prediction is included in Section 4.4.

## 2.4. Off Design Studies

The growth in Waterjet Power absorption levels has raised questions again on the unsteady behaviour of forces, stresses and thermodynamics of the prime mover. Practical experience is abundant with the smaller jets in lighter craft. However, it appears that little quantitative and complete data sets on these smaller units have been published. Two serious research efforts have been published in the term of the present committee.

Aartojärvi and Häger (2001) present measurements of a waterjet model mounted on the free surface cavitation tunnel. A newly developed test set-up is described in detail,

with a special focus on the equipment used for measuring transient loads on the pump unit. All relevant transient loads on different waterjet components were measured: impeller, stator and the steering and reversing unit. The authors show that the effect of IVR on the recovery phase after a full emergence of the intake is significant, whereas the effect of the pump cavitation number only has a minor effect. Examples of other quantities such as strains and pressure pulses were also shown. The character of these signals in time is similar to that of the torque signal. However, the level of fluctuations differs significantly for different quantities and geometric positions.

Tronstad et al. (2001) present results from measurement campaigns supplemented with time domain engine simulations, on three high speed vessels propelled by waterjets. Two of these vessels were diesel engine driven, one of them gas turbine driven. One of the vessels was a monohull, the two others were catamarans. Measurements were made of the pressure fluctuations in the intake, on the impeller torque and bending moments and on impeller shaft speed. The engines were monitored through exhaust temperatures and fuel flow. Furthermore, the movements in the diesel engine foundation were measured. Measurements were taken during calm weather conditions, heavy seas, during manoeuvring and during waterjet aeration. It was concluded that "rough sea operation doesn't seem to induce greater loads to the shafting system or the engines than operation in calm sea", based on shaft torque vibrations and engine exhaust temperature fluctuations. Only aeration of the waterjet introduces a momentary heavy load shed. "The shaft torque vibrations that are also generated are of moderate magnitudes only. Typically in the range of 15-30% of the nominal torque." Heavy cavitation on the impeller occurs however during acceleration where significant torsional vibrations are introduced, with amplitudes in the range of 50-60% of the nominal torque.

## 2.5. Ventilated Waterjets

The Ventilated Waterjet, a novel type of waterjet, has first been described in the open literature by Mavludov et al. (1998). This type of waterjet has been first proposed in Russia by researchers of KSRI, and several ships with this propulsor are now operating in Russia. A recent paper by Sadovnikov and Mavludov (2001) describes the state-of-the-art in VWJ, showing various aspects of their design and model tests.

At high ship speeds, the propulsor is usually located very close to the water surface thus increasing the risk of air ingestion into the propulsor. This phenomenon occurs in particular in the intake of conventional waterjets. On the other hand, deeper positioned propulsors (e.g. propellers) result in a significant appendage drag. Surface-piercing propellers (SPPs) are intended for operation very close to the water-air interface and are designed to operate at this interface. However, the authors conclude that SPPs have drawbacks such as a large propeller diameter, transverse shaft forces and impact loads on the blades upon entering the water.

Sadovnikov and Mavludov (2001) describe two typical configurations of VWJ and its principles. In general, the VWJ consists of a water intake and an impeller with wedge-shaped blade sections, situated close to the nozzle discharge. Upstream of the impeller, the shaft is stiffened by a bracket. Unlike an SPP, the ventilated waterjet impeller is fully submerged into the flow so that it utilizes the complete impeller disk area. The VWJ is positioned at the transom stern in such a way that at the design speed the jet is either in whole or in part discharged into the air. This position ensures that the blades get ventilated from behind. The air cavities tend to break the flow behind the propulsor into several screw-shaped jets.

Efficiencies of the VWJ are reported of nearly 0.70 (Sadovnikov and Mavludov, 2001; McMahan et al., 2000). The VWJ is

furthermore claimed to feature low noise and steady operation near the water surface even in heavy seas when the intake is ventilated. The absence of cavitation on the impeller prevents a number of cavitation problems typical for high speed propulsors. Furthermore, the VWJ is claimed to offer a low weight and cost unit at relatively small size.

Outside Russia, the VWJ has been studied by McMahan et al. (2000), who report on tests of ventilated impellers in a uniform flow in a cavitation tunnel. Their results confirm the propulsive performance of the VWJ. McMahan et al. (2000) report furthermore on an attempt to calculate the air cavity parameters, using software originally intended for cavitating propellers.

An alternative VWJ, designated Hydro Air Drive, is described by Woodyard (2000). Perhaps the main difference with the earlier VWJ descriptions is a movable flap in the intake which intends to control impeller submersion.

## 3. MARKET REVIEW

A brief review of market developments is given here, as an investment of the ITTC community in knowledge and experimental and computational procedures cannot be regarded separately from the market perspective. A lower power limit of 3.5 MW is arbitrarily chosen for the review, as model testing or extensive computations are likely to be conducted only for the bigger jet units where the financial risks are higher.

Waterjets are generally accepted as an efficient propulsor at the higher speeds, offering low noise and vibration levels. Waterjets are usually applied for speeds in excess of 30-35 kts. A speed range where propellers suffer from significant cavitation with a corresponding risk of vibrations and cavitation erosion.

Waterjet propulsion is used in high speed ferries, military and paramilitary craft, and

workboats. The biggest ships using waterjet propulsion to date are passenger ferries for speeds of 30 kts or higher. Typically these ferries are lightweight IMO HSC-Code compliant monohulls and catamarans, featuring service speeds of 35 to 40 kts. The biggest waterjet that is currently in operation, is a 25 MW unit, built in the 140 m monohull ferry *Cor-saire 14000*. This unit features an intake diameter of 2 m at an impeller diameter of approximately 2.7 m.

A recent type of high speed ferry is the so called "SOLAS compliant ferry". This ferry distinguishes itself from the lighter HSC Code ferry in that it has a substantially higher ro-ro freight capacity. Furthermore, they have a provision of passenger sleeping cabins, making them suitable for longer ferry journeys of say six hours or more. It appears that these bigger Solas ferries have an upper speed limit slightly above 30 kts. These larger ferries are fitted with propeller propulsion, either on open shafts or on pods. A possible rise of the service speed of these vessels is governed by the introduction of new technology that allows for a profitable operation (Wilson, 2001b). This type of ship is obviously suited for propulsion by either propellers or by waterjets. Currently, propellers seem to be the preferred choice.

Military applications of bigger waterjet driven vessels were recently introduced with the exploitation of an 81 m Wavepiercing Catamaran by the Royal Australian Navy in the UN peace keeping mission in East Timor. Moreover, the US army and the US Marine Corps are currently experimenting with these type of craft as an alternative for aircraft transportation. Another example of military interest in waterjet propulsion is the development of fully submerged waterjets as prime propulsors for future naval destroyers (Scherer et al., 2001). The waterjet installed as a booster for the upper speed range, also seems to offer perspectives for military purposes. This is illustrated by the MEKO200 class corvettes, currently being built for the South African Navy. It is expected that the

military market offers a good potential for increased use of waterjet propulsion.

Although several studies on high speed cargo vessels have been done, up till now little of these projects have taken off. Perhaps the most renowned fast freight carrier project is the "Fastship" Project, in which a 265 m Container vessel is developed, able to carry 1432 TEU at a service speed of 38 kts over the North Atlantic. To this end, five waterjets capable of absorbing 50 MW per unit are envisaged. This waterjet development currently spans the top in power absorption.

As for the current market for the bigger jet units, the following remarks are taken over from Wilson (2001a): "Without question, the fast ferry market has been suffering from a shortage of orders. Several builders have laid off workers, and others have put them on yard maintenance duties. .... In terms of number of vessels being ordered, the signs are encouraging. Sources indicate that the level of new-building enquiries has increased significantly in recent months, and concrete evidence is offered by the fact that some yards have been taking new orders for vessels of varying sizes".

#### **4. OUTSTANDING ISSUES IN WATERJET POWERING PREDICTIONS**

##### **4.1. Introduction**

"How to measure the thrust and power from a waterjet" has been the central question of several ITTC waterjet related committees. The 21st ITTC Specialist Committee on Waterjets recommended that experience with the experimental momentum flux method be collected and evaluated, where direct thrust measurements were mentioned as an alternative that needed further evaluation. The 22nd ITTC Specialist Committee on Waterjets recommended that experience with powering predictions through model tests be collected

through the organisation of a world-wide standardization test in conjunction with the Gulf Coast project. As in the mean time, there are little or no institutions willing to perform a direct thrust measurement, the Committee has focussed its efforts on the momentum flux method. This section provides a detailed definition of problems that exist in the “momentum flux method”.

The most outstanding issues are related to the determination of the flow rate and the momentum and energy fluxes. The following problems will be addressed here:

- relation between waterjet thrust and bare hull resistance
- measurement of flow rate
- determination of ingested momentum and energy flux
- determination of discharged momentum and energy flux
- determination of tow force
- waterjet modeling

#### 4.2. Relation between Waterjet Thrust and Bare Hull Resistance

In the design process of a ship, a suitable propulsor for the hull needs to be selected. This process involves matching of the demand by the hull and the capacity of the jet. The most suitable parameter to be matched is the thrust required by the hull (derived from the resistance) and the thrust from the jet. This is the prime argument why the definition of thrust from a waterjet and its determination is an issue.

The 21st ITTC Specialist Committee on Waterjets has not addressed explicitly the relation between the change in momentum flux  $\Delta M$  and the bare hull resistance, where  $\Delta M$  is defined as:

$$\Delta M = M_7 - M_1 \quad (2)$$

Here the subscripts 7 and 1 refer to the vena contracta in the jet, in or behind the nozzle discharge, and station 1 is situated slightly

upstream of the intake ramp tangency point. A net thrust could be derived applying the momentum conservation law, that should balance the effective resistance of the hull under self propelled conditions.

This was elaborated by Van Terwisga (1996a) who found that a difference between  $\Delta M$  and net thrust may especially occur around ship speeds where the transom is not fully cleared. For higher speeds, the difference between change in momentum flux  $\Delta M$  and net waterjet thrust is practically zero. For the higher speeds, the difference between  $\Delta M$  and bare hull resistance is therefore a good measure for the resistance increment of the hull due to the waterjet induced flow. This could be expressed in a thrust deduction fraction  $t$ , analogous to what is used in propeller terminology:

$$\Delta M(1-t) = R_{BH} \quad (3)$$

Collecting thrust deduction data will assist the designer in matching the waterjet performance with the required hull performance. For cleared transom flows, these thrust deductions are especially depending on the type of hull used.

#### 4.3. Measurement of Flow Rate

A recent paper by Scherer et al. (2001) highlights many of the difficulties in performing the Momentum Flux Experiment. As implied by Scherer et al. (2001), shown by Van Terwisga (1996a) and discussed by the 22nd ITTC Waterjet Committee (Hoyt et al., 1999), the determination of mass flow is one of the most critical components of this method.

If the mass flow is estimated through the use of a velocity survey, then estimation of power is dependent upon velocity cubed and thrust by the square of velocity.

The importance of a reliable and accurate flow rate measurement can be understood when one considers the definitions of energy and momentum flow rate.

The momentum flux vector in  $i$  direction is defined by:

$$\bar{M}_i = \iint_A \rho u_i (u_k n_k) dA \quad (4)$$

The energy flux scalar through a surface  $A$  is defined as:

$$E = \iint_A \rho \left( \frac{1}{2} u^2 - g_j x_j \right) u_i n_i dA \quad (5)$$

Estimates for the local velocities are usually obtained from the measured flow rate  $Q$ :

$$\bar{u}_i = \frac{Q}{A \bar{n}_i} \quad (6)$$

It should be noted here that the definitions of momentum and energy flux introduced here differ from the ones introduced by the 21st ITTC Waterjet Committee and currently used in the ITTC Quality Manual. In the former definition, pressure terms were included in the definition of momentum and energy flux, which is not consistent with the generally accepted definitions.

The 21st ITTC Waterjet Committee (Kruppa et al., 1996) indicated that a 3-4% error in the estimation of predicted power could result due to a 1% error in flow rate. Van Terwisga (1996b) shows in an uncertainty analysis of propulsion tests that the error in power that is made by a flow rate error, increases with decreasing JVR.

There are several methods for flow rate measurement available to the experimenter. In case a surrogate pump is used during the tests, a conventional flow meter can often be used. If a scaled model of the waterjet system is used with the purpose to directly use the power/rpm relation from the model pump, then a non-evasive method of determining flow rate is desired to mitigate impacting scale effects on the pump performance.

Some of the more commonly used flow rate measurements techniques are discussed here:

Calibration of Pressure Drop in a Converging Nozzle. If a converging nozzle is present in model waterjet system, then the pressure drop measured between two static taps located longitudinally in the nozzle at Stations 5 and 6 can be calibrated to the flow rate. This is typically done in either a calibration stand or, as some do, during a bollard experiment. Either an independent flow meter or a catch can have been used for this calibration. This is a non-evasive method.

Installation of a Conventional Flow Meter in the Waterjet Internal Flow Path. This is more common when a surrogate pump is used. If the plumbing of the surrogate pump can be remote, then the location of a venturi, orifice plate, turbine type, or other flow meter can be used. Typically scale model waterjets do not allow the space claim for a flowmeter let alone the proper settling length required prior to the entrance of the meter.

Measurement and Integration of the Velocity Profile within the Waterjet System. A Pitot-Static Rake or LDV can be used within the circular portion of the internal ducting. Scherer et al. (2001) indicate that the change in static pressure is small at the capture area and vena contracta. If this is also true within the duct at the survey plane, then a total head or Kiel probe can be used as well. The advantage of the internal survey is the clear definition of the outer boundary of the stream tube. This method is more readily used with a surrogate pump where shaft and ducting are typically not co-linear.

Measurement and Integration of the Velocity Profile of the Jet. As with the internal measurement, a Pitot-Static probe or LDV can be used within the stream for a submerged jet, usually at the vena contracta. If the jet is above water, the use of the LDV is not possible and a Pitot-Static probe is required. Scherer et al. (2001) found in their experiment that the change in static pressure was small at the vena contracta in their experiment allowing the use of a total head or Kiel probe.

There is still a concern with determining the exact boundaries of the jet stream at the vena contracta. The entrained water it carries with it affects the submerged jet. The above water jet may tend to break down at the circumference producing spray and making the use of a pressure type velocity probe difficult if not impossible. One solution often used is to measure the velocity profile at the nozzle exit plane. At this location the stream velocity is defined, although the static pressure outside the jet is not ambient. Here again, Scherer et al. (2001) suggest a way in which the measurement of the velocity near the nozzle exit can be improved.

Measurement and Integration of the Velocity Profile of the Jet Using Wedge or Prism Head Probes. It should be pointed out that although the process of determining the flow rate within the jet stream is akin to determining the momentum and energy flux, the measurement of the axial component is all that is required for the determination of both flow rate and axial momentum flux. However, the tangential and radial components of the flow are required to accurately determine the energy flux.

A Pitot-Static probe does average over a small incident angle, but small enough to permit the estimation of the axial flow. The use of a Kiel probe provides a larger cone angle required for the determination of the energy flux. The Kiel probe may adversely effect the determination of both the flow rate and momentum flux by including the off axial components if there is a large swirl in the jet stream. If the change in static pressure is small through the jet stream, then a 3 axis LDV survey would produce the data required to separate the axial and off axis velocity components as shown by Scherer et al. (2001). If the static pressure change is found to be large then either a static pressure survey, or a 5-hole probe can be used.

A potentially easier method may be to use a wedge or prism head type velocity probe. If these probes are used for radial surveys, the

axial and tangential velocity components as well as the local static pressure can be measured. By rotating the probe within the flow both the incident angle and resultant velocity can be measured. One draw back however, is that the radial component will not be measured.

The most simple approach to determine an estimated value of the average jet velocity is based upon the flow rate and nozzle area. This might be used if the flow rate was measured by some means other than a jet velocity survey. A disadvantage in doing this is that the off axis components are assumed to be zero and will not be correctly accounted for in the estimation of the energy flux.

Use of a Reference Velocity or Total Pressure. Another suggestion by Scherer et al. (2001) is the use of a measured “reference” velocity. A detailed velocity profile using LDV at several shaft speeds can be used for the interpolation of the results off speed. This concept is propagated to the estimation of both energy and momentum flux in the paper, however the estimation of flow rate using this method is:

$$Q_7 = \int_{A_7} u_{x7} \cdot dA_7 = \overline{V_7} \cdot \int_{A_7} \left( \frac{u_x}{V} \right)_7 \cdot dA_7 \quad (7)$$

A Pitot -Static or Kiel probe can be used to measure a reference velocity or total pressure in the jet stream or even remotely in the waterjet duct. Since this measurement is only a reference value which was used to normalize the measured velocity of interest, both the flow rate, momentum and energy flux can be estimated provided the proper database is used.

Interpolation of a Waterjet Performance Map. The performance map for the model waterjet system can be predicted numerically and verified through a combination of water tunnel and towing basin experiments. By mapping shaft speed, shaft torque, thrust, headrise across the pump, flow rate or any other desired parameter unmeasured values can be estimated by interpolation using any combination of the mapped parameters.

A common practice is to measure shaft speed and headrise across the pump, which are two relatively easy parameters to obtain reliably. These two measurements are then used to interpolate flow rate from a surface map as shown in Figure 4.1.

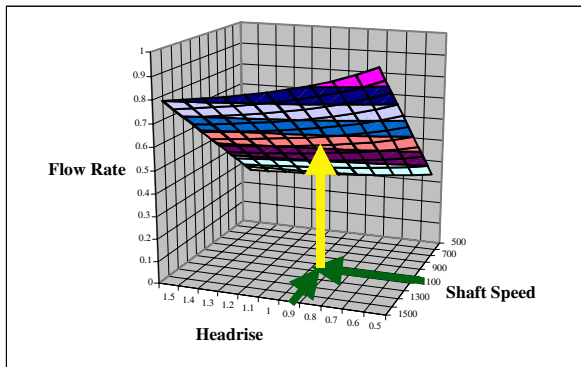


Figure 4.1 Interpolation Scheme using Waterjet Performance Map.

A draw back is that often the calibration in a pump loop or water tunnel does not simultaneously correspond to the conditions measured in the self-propulsion model. Therefore, either a preferred measurement (i.e. nozzle pressure drop, headrise, shaft speed, etc.) or an averaging scheme must then be used.

Interaction Nozzle-Stern Flow and Consequences for Flowrate Measurement. For a stern mounted nozzle, discharging the jet at or above the still waterline, the nozzle is mostly submerged during low speed operation. This speed dependent nozzle immersion causes a speed dependent pressure gradient in the nozzle. Whenever differential pressure transducers are used for the flow rate measurement, care should be taken that this pressure gradient does not affect the measurement. An important condition resulting from this constraint is that the distance over which the pressure difference is measured be small.

#### 4.4. Determination of Ingested Momentum and Energy Flux

The determination of momentum and energy flux is mostly done from an integration over a properly defined capture area with a

measured or calculated velocity profile. When the velocity profile and the flow rate is known, the only missing parameter is the geometry of the capture area.

Capture Area. The determination of the inlet capture area is another potential source of error when performing the momentum flux method. This concern is usually twofold. There is concern with the location of the inlet survey plane, referred to as Station 1 and shown in Figure 4.2, and the effect on the velocity measurements made there due to the proximity of the inlet. Another concern is with the determination of the shape and size of the capture area.

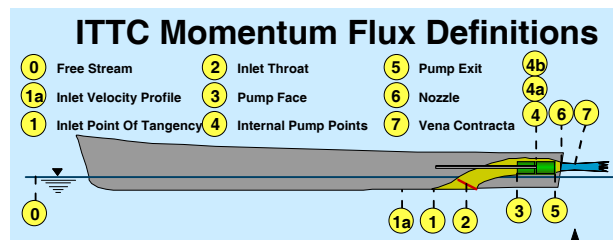


Figure 4.2 Definition of the Momentum Flux Method Reference Stations.

Location of Station 1. As pointed out in the 21st ITTC Waterjet Committee Report (Kruppa et al., 1996), the location of Station 1 is somewhat arbitrary. The recommendation was to place this measurement Station forward of the point of tangency shown in Figure 4.2 as Station 1. In an attempt to standardize testing practices in order to reduce potential bias errors, the current Committee recommends placing the measurement Station, referred to as Station 1a, one inlet width forward of Station 1. Originally the use of the waterjet diameter was suggested as a “rule of thumb” measure for the placement of the measurement plane. However there is much variation in the definition for waterjet diameter and the use of inlet width has a more direct physical connection. The width of the inlet is defined as the maximum width between the port and starboard transverse points of tangency as shown in Figure 4.3.

**Shape of Capture Area.** The recommendation of the 21st ITTC Waterjet Committee (Kruppa et al., 1996) was to use a rectangular capture area with a width  $b_1$ , which is to be 30% wider than the inlet width. Inlet height would then be obtained by computing the height required to obtain the proper flow rate given the velocity profile there. They felt that both power and thrust estimates were insensitive to capture area shape. Previous experiments had shown that a 20% variation in capture area width produced only a 1% change in estimated power. Similar conclusions were reached by Van Terwisga (1996a) and Scherer et al. (2001). Van Terwisga concluded that the effect on power between a rectangular capture area ( $1.3 \times$  intake width) and an elliptical capture area ( $1.5 \times$  width) would remain within 0.5% for a representative JVR value of 1.7. This value slightly increases for lower JVR values. Scherer et al. (2001) used a trapezoidal shape guided by Computational Fluid Dynamics (CFD) results and stated, “We note that it is not necessary to have the capture area determined with high accuracy”.

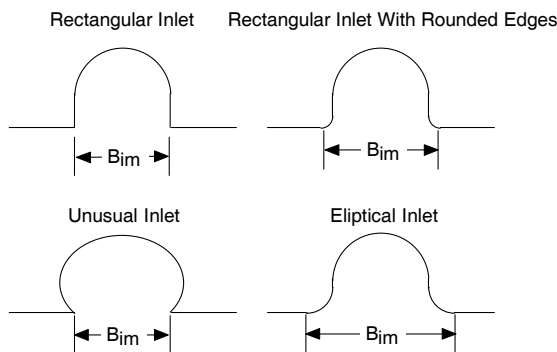


Figure 4.3 Definition of Inlet Width.

Of course this may be dependent upon the flow relative to the inlet. In the case of planing craft, the primary examples used by the 23rd ITTC Waterjet Committee, the boundary layers are both relatively thin and the flow 2-dimensional. In the case of the hull evaluated by Scherer et al. (2001) the waterjets were contained in dropped nacelles giving the inlets considerable drop below the hull, or as described by the author as “semi-flush”. The ex-

periments by McMahon et al. (1999) on a flush elliptical inlet on a more conventional displacement hull showed considerable non-uniformity in the flow at Station 1.

It is recommended that a sensitivity study be done into the effect of various intake shapes and the selection of the most suitable capture area.

**Determination of Capture Area using CFD.** Based on the above literature, it is anticipated at this point that the derived momentum and energy fluxes in the region of Station 1 are insensitive to minor variation in area shape. This greatly simplifies the data reduction procedure used in conjunction with experiments, as well as adds to the confidence of the momentum flux method. It is noted at this point however that there is at least one reference (Roberts and Walker, 1998) claiming that the choice of a rectangular capture area may lead to an under-prediction of gross thrust by some 10% for a typical high speed ferry.

Given the growing use of CFD, estimation of the capture area using CFD tools is becoming more feasible and could be advantageous, if found to provide reliable results. The capture area can be estimated by CFD, by tracing back the streamlines ingested into the inlet as shown in Figure 4.4 for the “Athena” design.

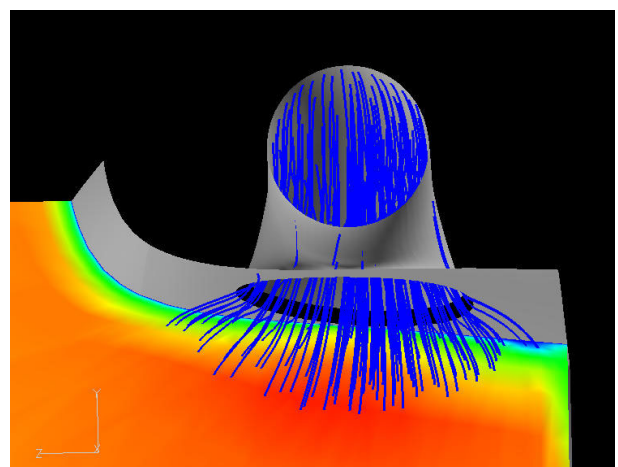


Figure 4.4 Use of CFD to determine Capture Area.

The recommendations made by Alexander et al. (1993) that an elliptical shape of the capture area is a more correct representation than a rectangular one is confirmed in Figure 4. The results shown also compare well to the experimental data presented by Roberts et al. (1997) and Roberts et al. (1998) where elliptical shapes were observed with widths 50 to 100% wider than the inlet.

Velocity Profile. Another feature shown in Figure 4.4 is the dip found in the transverse velocity profile even one inlet diameter forward of the point of tangency. This characteristic raises the question whether a velocity survey should be made with closed intake (nominal wakefield) or with open intake and active waterjet (total wakefield).

Ideally, one would like to measure the effective wake ingested by the intake. That is the flow field including the suction effects on the flow about the hull, without any effect of the intake flow itself. This so called “effective wake” is however difficult to measure (intake flow is always present) and depends on the working point of the intake (in terms of IVR). For that reason, it is suggested to measure the boundary layer velocity profile with closed intake openings, unless there are forcing reasons to measure the effective wake. This proposal contradicts the current tentative procedure described in the ITTC Quality Manual (4.9-03-03-05.2).

As with the determination of the energy and momentum flux in the jet stream, the measurement of the axial component is all that is required for the determination of the momentum flux. However, the tangential and radial components of the flow are required to accurately determine the energy flux, although the off axis components are expected to be smaller. Their effect becomes even smaller due to the fact that the velocity vector needs to be squared or cubed for the determination of momentum and energy fluxes respectively.

In the absence of a 3 dimensional survey by LDV or a 5 hole probe, a comparison of

the measured results using a Pitot static probe can be compared to that obtained using a total head or Kiel probe to check for the presence of off axis components.

Looking at Figure 4.4 it appears that the capture area at this location is 60% wider than the inlet width. It also appears that the ingested flow is not symmetrical about the intake stream tube centreplane with the influence of the skeg clearly visible. At a minimum it appears that 5 transverse cuts may be required to adequately define the flow in this example. Care will also be necessary to avoid the skeg wake by performing the inboard survey too close to the skeg.

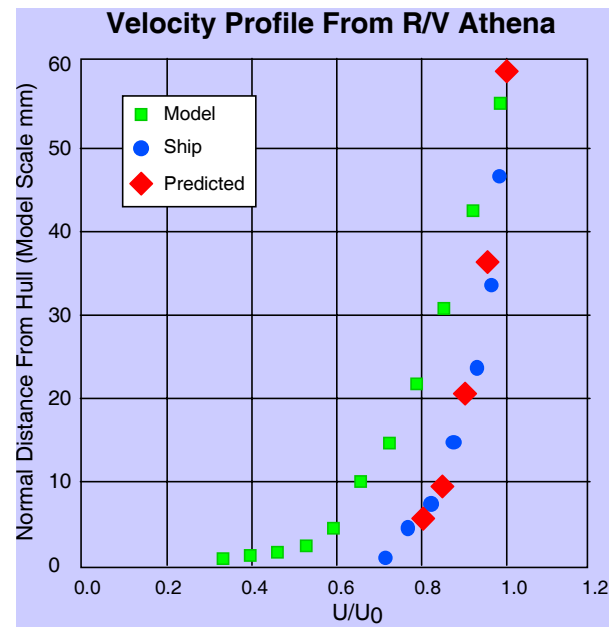


Figure 4.5 Velocity profile.

#### Prediction of Full Scale Boundary Layer.

The effect of boundary layer ingestion on thrust is one of the most dominant jet-hull interaction factors and has been addressed by many others, e.g. Kruppa et al. (1968), Etter et al. (1980), Van Terwisga (1995) and Hoyt et al. (1999). Bulten (1999) addresses the method for the prediction of the full scale boundary layer velocity profile and thickness. He emphasizes that the power law velocity distribution should be used within its limitations and proposes to derive the Reynolds effect in the boundary layer displacement thick-

ness from the relation between the flat plate friction coefficient and Reynolds number. He refers here to the ITTC'57 plate friction line. There is a good argument to use the relation between displacement thickness and flat plate friction line to arrive at a realistic value of the full scale boundary layer and velocity profile. It is however questionable whether the ITTC'57 friction line, with all its acknowledged correlation factors is the most appropriate choice. The theory based Schoenherr line could principally be a better choice.

The issue of the full scale boundary layer thickness and velocity profile has also been addressed by Svensson et al. (1998). These authors also provide full scale measurements of the boundary layer velocity profile.

#### 4.5. Determination of Discharged Momentum and Energy Flux

The discharged momentum and energy fluxes from the nozzle play an important part in the determination of thrust and power. In the determination of these fluxes, it is generally assumed that the deviations from a uniform velocity and pressure distribution are sufficiently small to neglect them. This assumption gives the advantage that no detailed measurements need to be conducted on the discharged flow. This assumption and its consequences on the uncertainty need however further consideration.

#### 4.6. Determination of Tow Force

This section deals with the issue as to whether thrust identity or flow rate identity should be applied to the model.

For propeller driven ships, the tow force is adjusted (or corrected) in such a way that the propeller loading is free of scale effects. This procedure aims at a correct modeling of propeller hull interaction effects by correctly modeling the suction force of the propeller.

In the case of waterjets however, the major part of the ingested flow is obtained from boundary layer flow, necessitating a reconsideration of the experimental technique. If the conventional thrust identity would be used to unload the model propulsor, relatively too little flow rate would be ingested because of the thicker boundary layer on model scale.

As the self propulsion test yields especially information about the interaction phenomena, which are expected to be controlled by flow rate, one could however argue that flow rate identity would be the better choice. This procedure has been worked out in the Gulf Coast Project. The resulting capture areas are plotted in Figure 4.6 and the resulting propulsion data in Table 4.1.

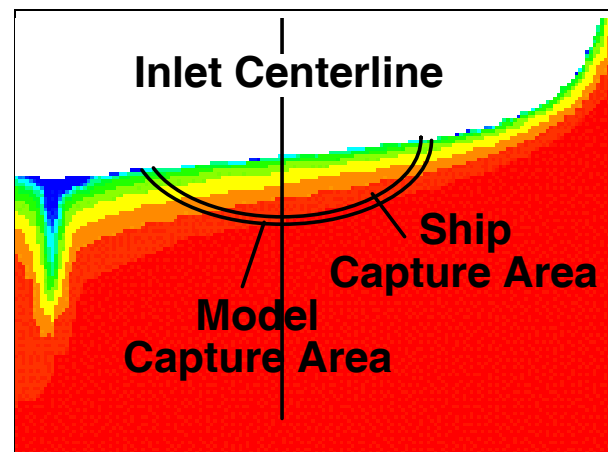


Figure 4.6 Difference in capture area for conventional tow force calculation.

Table 4.1 Comparison of propulsion data for flow rate identity.

	Model	Ship
Advance Speed	4.398 m/s	25 kts
Flow Rate	0.0394 m <sup>3</sup> /s	0.0394 m <sup>3</sup> /s
Avg Jet Velocity	7.032 m/s	7.032 m/s
Capture Height	6.43 cm	6.10 cm
Capture Width	19.41 cm	19.13 cm
Capture Area	0.0124 sqm	0.0106 sqm
Avg Inlet Velocity	3.203 m/s	3.740 m/s
IVR At Sta. 1	0.73	0.85
Est Thrust Per Jet	150.83 N	129.76 N
Friction Coef.	2.644E-03	1.688E-03
Conventional Tow Force	40.61 N	
Thrust Differential, 2 Jets	42.15 N	
Reccomended Tow Force	-1.54 N	

#### 4.7. Waterjet Modeling

It is generally accepted that waterjet self propulsion tests be conducted with a pump of convenience (also referred to as “surrogate” or “dummy” pump).

There is however less agreement as to what extent the waterjet intake should be modeled. This is sometimes an issue when a compact waterjet has to be modeled and the geometrically scaled intake is to be matched with the surrogate pump. It is hoped that CFD will provide some guidance in this issue.

### 5. STATUS OF STANDARDISATION TESTS

#### 5.1. Selection of Standardization Tests

For the determination of the overall powering characteristics, the working point of the waterjet should be determined. To learn this point of the waterjet, the demand by the hull should be quantified.

The demand of the hull is usually quantified by a thrust-speed relation. This relation needs to be converted to a relation between pump required power, pump rpm and ship speed. Most often, this conversion is made on the basis of a flow rate  $Q$  through the waterjet system.

The relation between flow rate  $Q$ , thrust and hydraulic power ( $QH$ ) is affected by the non-uniformity of the velocity distribution in the streamtube that models the jet. This is caused by the relation between flow rate, momentum flux and energy flux. Corrections on the momentum and energy flux, when obtained from an average volumetric flow velocity may be as high as some 10% for the momentum flux and some 25% for the energy flux due to the non-uniformity of the velocity distribution (see Scherer et al., 2001).

These corrections apply at the interface of the system considered with its environment.

Relations between the powering characteristics of the distinct elements and the jet system are schematized in Figure 5.1 below.

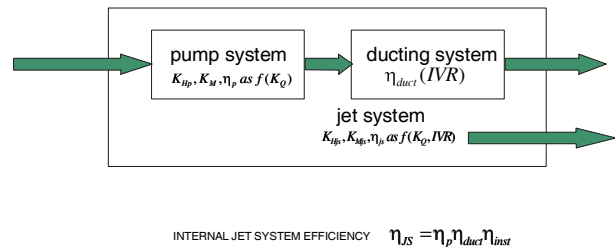


Figure 5.1 Scheme of waterjet system elements and their characteristics.

This implies that momentum and energy flux corrections (for constant flow rate) may be required for the pump system when its environment is changed from a pump loop setup to a pump mounted in a waterjet system. That is that the corresponding quantities (torque and head respectively) will be affected by the non-uniformity of the inflow. Furthermore, additional differences in viscous and rotational losses may be induced by the impeller and stator blades.

An estimate of the magnitude of these effects on e.g. efficiency is given by Kruppa (1993).

He presents in a written contribution to a workshop on waterjets (20th ITTC), results that were obtained with a mixed flow pump that was tested in several distorted inflow conditions. The difference in pump performance between performance in a pump loop and that in distorted conditions can be summarized by an installation efficiency. This installation efficiency is reported to be approximately 0.96 for a mixed flow pump, originally designed as a waterjet pump, working behind a 90 deg elbow in a pump loop. The effects on head coefficient and torque coefficient may however be greater (some 6.5% reduction in head coefficient at the maximum efficiency operating point). It is furthermore noted by Kruppa that “there is a general tendency for high specific speed devices, such as axial flow pumps, to react more sensitive to inflow disturbances than medium or low specific speed runners”.

Taken the above considerations into account, there is no ground to neglect installation effects beforehand. Furthermore, there is insufficient public knowledge to sufficiently accurately estimate the installation effects for representative mixed flow and axial flow pumps behind a representative intake. Even less knowledge is available for more exotic designs (see e.g. Scherer et al., 2001). These two facts lead to the conclusion that there is a need for a waterjet system test procedure with corresponding uncertainty estimate, even if the characteristics of the pump and the intake are known from measurements on the isolated elements.

This policy does however not suggest that at particular institutes or companies, there would not be sufficient proprietary knowledge on installation effects to skip a waterjet system test and compose the jet system characteristics from the characteristics obtained from the pump and the intake.

It seems that a separate intake test provides valuable information to the designer for the intake and the pump. The waterjet system tests however also give information on the product of  $\eta_{inst}\eta_{duct}$ . Important differences with intake tests are that no flow field is measured at the pump inlet, and that installation effects and intake efficiency are not separated.

## 5.2. Web Site

In order to exploit to the ITTC community the work and the results of the Committee, a web site has been developed and published. Its URL is <http://www.ittc-wjc.insean.it/> and is hosted by INSEAN. The site is structured in three parts: a public one, a member's area, and a restricted area.

The visitors can access the public area without any limitation. In this area, the work of the Committee is reported in detail. Special emphasis is put on the four programmes going on, i.e., self-propulsion tests, waterjet system

test, pump test, and numerical investigations. All the participating institutions are reported in a specific page as well as the time schedule of each programme. For each programme the "Task Specification List" is also reported. Important milestones are also indicated, when necessary.

An important part of the site is dedicated to recent information related to waterjets. Most recent and relevant papers are listed in the references. When available, some of them can be downloaded as pdf files. Other resources available on the web are highlighted and the relative links reported. Links to waterjet manufacturers and industries involved in some way to waterjet propulsion are also indicated.

ITTC official documents, like Symbols and Terminology List, can also be downloaded in the public area.

The Committee aims at a site which becomes a landmark for everybody interested in waterjet propulsion.

The member's area is reserved to the Committee's members and contains restricted and unfinished information.

The restricted area can be accessed by the responsible of each participating institution to the Committee's programmes. In this area, confidential documents like drawings, information related to the tests, status of the programmes and so on are reported. Because each responsible can reach each other, the exchange of information, knowledge and experience, is expected to further contribute to the benefit of participation to this program.

Both areas, members and restricted, can be accessed by a username and password assigned to the authorised people by the webmaster.

### 5.3. Proposed Data Formats

The Committee has taken care that the information from the standardization tests is collected in a complete and systematic way, ready for evaluation. The data formats for the three different types of standardization tests, including explanations, are available through the aforementioned web site of the Waterjet Committee.

### 5.4. Time Schedule

As for the hardware required for the standardization tests, the Gulf Coast project has provided two hull models with representative stock jets and intakes, as well as one larger scale waterjet model. Of the two ship models, the first one will tour Europe, the other one will tour Asia and the USA. Testing of the ship models is scheduled to start in May 2002.

Table 5.1 Tentative time schedule for the Self Propulsion Tests.

No.	Institute	Start	End
<b>EUROPE</b>			
1	<b>MARIN</b> – Maritime Research Institute – NL	02.04.22	02.09.27
2	<b>INSEAN</b> – Istituto Nazionale per Studi ed Esperienze di Architettura Navale – IT	02.09.09	03.01.31
3	<b>CEHIPAR</b> – Canal de Experiencias Hidrodinámicas de El Pardo – ES	03.01.13	03.06.06
4	<b>SVA</b> – Schiffbau – Versuchsanstalt Potsdam GmbH – DE	03.05.19	03.10.10
5	<b>SSPA</b> – SE	03.09.22	04.02.13
6	<b>KRILOV</b> – Shipbuilding Research Institute – RU	04.01.26	04.06.18
7	<b>NTUA</b> – National Technical University of Athens – GR	04.05.31	04.10.22
<b>ASIA &amp; USA</b>			
8	<b>KRISO</b> – Korea Research Institute of Ships and Ocean Engineering – KR	02.04.22	02.09.27
9	<b>SSMB</b> – Samsung Heavy Industries Co., Ltd. – Ship Model Basin – KR	02.09.09	03.01.31
10	<b>HMRI</b> – Hyundai Maritime Research Institute – KR	03.01.13	03.06.06
11	<b>NET</b> – Nagasaki Experimental Tank – Mitsubishi Heavy Industries Ltd. – JP	03.05.19	03.10.10
12	<b>DTMB</b> – Naval Surface Warfare Center – David Taylor Model Basin – USA	03.09.22	04.02.13

The time schedule for the Self Propulsion Tests (SPT) was prepared from the starting point that each participating institution would need a useful period of three months. Assuming two weeks for shipment from one institute to the next, the first month should be reserved to the fitting out of the model, test set-up, and calibration. The period reserved for the testing

amounts to approximately forty-five days. This is expected to be sufficient to accommodate the ITTC required tests, which can be finalized within a few days. At the end of tests, the institute ought to deliver the model to the successive institute. There are thirty days for reporting and delivery of results.

Table 5.1 reports all the SPT participating institutions and the period of their involvement, considering that the models were available for shipment on April 1st, 2002.

The same criteria were adopted in defining the time schedule of the Waterjet System

Tests (WST) and the Pump Tests (PT). As in Table 5.1, Table 5.2 reports the participating institutions and the scheduled period of their involvement.

Table 5.2 Tentative time schedule for the Waterjet System and Pump Tests.

No.	Institute	Start	End
1	<b>DTMB</b> – Naval Surface Warfare Center – David Taylor Model Basin – USA	02.04.22	02.09.27
2	<b>Rolls-Royce</b> – Hydrodynamic Research Center - SE	02.09.09	03.01.31
3	<b>KRISO</b> – Korea Research Institute of Ships and Ocean Engineering – KR	03.01.13	03.06.06
4	<b>HMRI</b> – Hyundai Maritime Research Institute - KR	03.05.19	03.10.10
5	<b>SSMB</b> – Samsung Heavy Industries Co., Ltd. – Ship Model Basin – KR	03.09.22	04.02.13
6	<b>ARL</b> – Applied Research Laboratory – Pennsylvania University – USA – Only PT	04.01.26	04.06.18

## 6. REVIEW OF GULF COAST PROJECT

### 6.1. Objectives

The overall objectives of the Gulf Coast Region Maritime Technology Center's (GCRMTC) project entitled: "Development of Design Technology for Integrated Waterjet Inlets, Nozzles, and Hullforms" are as follows:

- Develop predictive methods and database sufficient to allow accurate force, moment, and powering predictions for integrated waterjet installations in monohull, multihull and surface effect ship (SES) designs.
- Analyze inlet/hull interactions in detail and define potential improvements in performance that may be gained by interactively designing hullforms and

inlets.

- Expand on the range of geometries in objective 1, above, by developing the capability of predicting the effects of jet interaction with near-hull flows.
- Develop an integrated waterjet system design that takes full advantage of the jet/free surface or near surface flow interaction phenomena. Correlate force and moment predictions with model test data obtained using a self-propelled towed scale model.

Approach. Performance prediction methods, as currently developed for waterjet systems, are very simple and cannot adequately account for interacting hull and propulsor flows. With the availability of advanced computational techniques, accurate means may be developed to predict both forces and powering characteristics of waterjet installations. To date, no consideration of jet/hull flow interaction phenomena has been needed because im-

pingement occurs far from the hull in most cases. Some recent experimental work has shown that jets impinging on free-surface or near-surface hull flows can favorably influence both lift and thrust forces. Means of understanding and modeling these effects are now available through the application of advanced CFD and panel code techniques.

A somewhat better understanding exists regarding inlet-hull interactions. Boundary layer ingestion is normally accounted for in the inlet design process. The effects of inlet flows on overall resistance, however, are not predictable except for configurations that have been the subject of model tests with full-scale trials correlations. It is likely that optimized geometries will feature hull afterbody lines that are quite different from the usual propeller-driven hullforms of today. Development of CFD-based models, capable of predicting forces and flows for integrated geometries, will bring about significant improvements in waterjet propulsive efficiencies, and may be expected to provide other benefits.

The technical approach for this three-year project is to develop a set of performance prediction models for an integrated waterjet system that takes into account the inlet-hull-jet interactions. This set of models will be validated for the inlet-hull interactions using model test data of the baseline hull, ATHENA, which is a former U.S. Navy PG 84 class ship displacing about 260 long tons. Model testing procedures for waterjet-propelled craft are being developed in cooperation with the ITTC. The jet-hull interactions are being studied at the conceptual level using North American Marine Jet's 25-foot test craft with modified hull lines in the afterbody region. The performance prediction model, baseline hull model test data and test boat results will feed a conceptual advanced design that takes advantage of the inlet-jet-hull interactions. This design will be based on the ATHENA hullform but with a modified afterbody. Validation of the advanced design will be studied in a follow-on program.

## 6.2. Organization

The joint project is led by Band, Lavis & Associates (BLA) with Marine Propulsors Company (MPC), Carderock Division Naval Surface Warfare Center (NSWCCD), and North American Marine Jet (NAMJ) as sub-contractors. Dr. William Vorus is the technical point of contact at the Gulf Coast Region Maritime Technology Center (GCRMTC). Ingalls Shipbuilding and Rolls-Royce Naval Marine are industry partners that have agreed to participate in technical review and meetings. A co-operative effort between the GCRMTC and the ITTC has been developed. A model of the baseline hullform as well as the waterjet and inlet design will be used by the ITTC for their "Standardization Test Program". The ITTC's role is to validate the self-propulsion, jet system, and pump experimental techniques so that the performance of the system can be evaluated and correlated to the numerical predictions.

Baseline Hull Design. The baseline hullform, which forms the nucleus of all integration studies, analyses, and model tests for this program, must be:

- a generic, widely adaptable type of hull shape with a wide transom stern;
- a form recognizable for possible use as a high speed cargo transport, high speed ferry, fast security ship, or possibly as a demi-hull in a multihull ship configuration;
- a ship hull which has a substantial data base of resistance, powering, and flow information to be used to aid the design and provide a benchmark for meaningful comparisons.

Out of a number of candidates, the hullform of the U.S. Navy's R/V ATHENA (originally the PGM 84 Asheville Class Patrol Gunboat) was chosen as the baseline hullform for this project (Day et al., 1980). The ATHENA is a transom stern, round bilge,

semi-planing, twin-screw ship that has proved a valuable asset in the U.S. Navy research and development community. It has a history of use for research in model-to-prototype scaling of propeller powering, wave making resistance, hull boundary layer, and propeller inflow wake studies (Hurwitz et al., 1980a; Day et al., 1980; Hurwitz et al., 1980b; Crook, 1981; Hurwitz et al., 1981). All information about this ship in its role as a research vessel is publicly releasable.



Figure 6.1 U.S. Navy's R/V ATHENA.

For this waterjet design integration study, the nominal design speed was chosen as 25-knots. At this speed, the ATHENA would serve as a Froude scaled model for the category of resistance-to-displacement characteristics of a 32-knot ship with a length of 76.8 m, or a 152.4 m long ship with a speed of 45-knots. Some fundamental data for ATHENA are:

Length: 50.29 m

Maximum beam: 6.68 m

Displacement: 260 long tons

Volume: 257.5 m<sup>3</sup>

$b/B$ : 0.828 (transom width ratio)

Figure 6.2 gives the profile lines and body plan for the ATHENA hull.

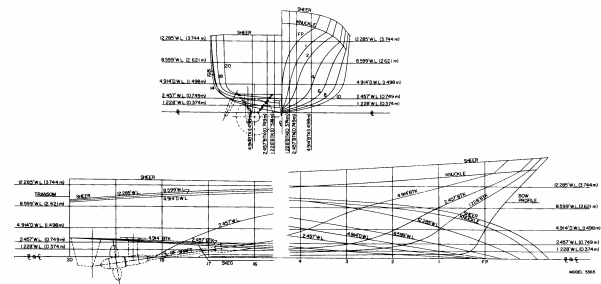


Figure 6.2 Profile Lines and Body Plan for the R/V ATHENA Represented by Model 5365.

**Baseline Pump Design.** The waterjet performance prediction starts with the required thrust and speed along with the wake fraction, calculated from the ingested hull boundary layer, and a cavitation margin as inputs into the computer program WJOPTBLA. For the baseline design, the design speed was chosen as 25-knots and the estimated required thrust from scaled model test data was 156 kN. Since the baseline hull is a twin waterjet installation, the required thrust per waterjet is 78 kN. The cavitation margin was set at 1.98, which is 1.98 times the net positive suction head (NPSH) at complete pump head breakdown. The wake fraction was calculated to be 0.1, based on full-scale measurements of the hull boundary on the ATHENA. The inlet total head, is calculated from an empirical relationship that is a function of inlet velocity ratio, IVR. WJOPTBLA requires two additional inputs that are parametrically varied to determine the design point. These are the pump flow coefficient and jet velocity ratio (JVR). The highest propulsive efficiency and therefore lowest SHP occurs at a JVR of 1.3. This results in a pump diameter of over 1.9 m, much too large to fit in the baseline hull. From investigating the baseline hull at a displacement of 260 LT, it was determined that the maximum pump diameter could be 1.07 m and still allow the system to be self-priming. The minimum JVR that meets this size requirement is 1.6. WJOFFBLA calculates the off-design performance of the waterjet system using a non-dimensional head-flow curve for the pump as a function of specific speed that

is matched to the system curve of the integrated waterjet to determine operating points.

The detailed design of the waterjet components begins with a streamline curvature analysis to determine the hub and shroud surfaces as well as the radial and chordwise blade-row loading distributions. The preliminary waterjet rotor and stator were designed using the ROTOR and STATOR programs, with initial choices of 7 rotor and 11 stator blades. ROTOR and STATOR are based on the mean-streamline design method (Allison et al., 1998). The parent airfoil profile is the NACA66 DTMB mod 1 with a rounded trailing edge. The blade numbers and chord lengths are determined iteratively by checking the resulting diffusion factor for each blade section that is output from ROTOR and STATOR. The maximum allowable diffusion factor is 0.4 and values higher than this can lead to blade designs that are prone to higher losses and possible flow separation. An alternate approach to the design of the waterjet rotor and stator was investigated using the Parametric Propulsor Design System (PPDS) under development at NSWCCD. The design produced by ROTOR and STATOR was compared to the output of PPDS and the resulting designs were found to be almost identical. In the second half of this project the waterjet pump design will be the subject of further analysis using the RANS code UNCLE to determine both design point and off-design performance.

**Baseline Inlet Design.** In order to avoid complex fairing geometries for the baseline waterjet design, the selected inlet features a flush-type lip geometry and S-shaped internal ducting. Design strategy was to utilize very simple methods for defining the baseline configuration, and then to bring together advanced computational tools for the analysis of the detailed flow velocities, local pressures, and performance predictions to refine the design.

For the inlet design, certain principal waterjet system parameters such as the pump rotor diameter and the required volume flow rate were derived from the detailed performance prediction program WJOPTBLA. Inputs to this program from the known ship characteristics included the choice of the ship design speed of 25-knots (Froude number 0.6), the model-measured scaled ship resistance versus speed curve, and the effective capture area wake factor  $(1-w) \cong 0.9$ , which was derived from the full scale measured boundary layer velocity profiles on the ATHENA hullform taken from Hurwitz and Jenkins (1980) and Day et al. (1980). Calculation of this wake factor was greatly simplified by the assumption of a trapezoidal shaped capture area which closely fitted the cross section shape of the ingested flush inlet stream tube measured experimentally by Roberts, et al. (1998). The results of that reference also showed that the width of the capture area of the ingested stream tube at the hull surface is about twice the inlet width for a range of inlet velocity ratios.

The footprint of the baseline inlet was chosen to be an ellipse that passes through the upstream tangency point of the inlet centerline roof curve. Circular cross section shapes were chosen for the inner duct portion of the inlet. The starting point for the specification of inlet geometry is the choice of the centerline roof shape as a fifth order polynomial. This function was chosen so that there would be no discontinuities in the second derivative (and hence the curvature) anywhere along the extent of the roof curve. Important inlet shaping parameters include the effective inlet ramp angle taken at the inflection point of the roof curve, the overall inlet length measured from the upstream tangency point to the pump inlet station, the height ratio of the jet exit centerline, the overall height ratio of the top of the duct at the pump inlet station, and the ratios of the horizontal distance and vertical height dimensions of the inflection point of the roof curve. Simple area rule relationships based on

constant volume flow rate were used to establish the dimensions of the duct cross-section areas. This approach was used to determine points on the lower boundary of the inlet duct that lie on the local normals of the roof curve downstream of the lip. A special Inlet Fairing Program developed for the Vertical Motor Propulsion project described by Dai, Peterson, and McMahon (1997) generated the detailed three-dimensional shape of the lip geometry. This mathematical fairing procedure employs Bezier curves for calculating the fillet-like surface that joins the inner duct shape with the outer boundary surface of the ship hull. The lip shape comes out as a natural part of this overall fairing computation.

To check for possible trouble spots with the proposed inlet design, first level analysis of the complete inlet flow regime was carried out using a three-dimensional potential flow surface panel computer code for the case of the elliptical footprint. Other footprint shapes were checked as well. The computed pressure distributions on the local outer hull boundary and the internal inlet surfaces showed very reasonable magnitudes and spatial variations, and gave preliminary confirmation that the elliptical footprint configuration would be satisfactory.

**RANS Computations.** To compute the viscous flow field, the incompressible Reynolds averaged Navier-Stokes equations are solved using UNCLE (Taylor et al., 1991; Taylor et al., 1995). Currently, the code is utilized by various groups including Navy laboratories, the university-affiliated laboratory at Pennsylvania State University, and shipyards, and has undergone extensive validation studies. The equations are solved using the pseudo-compressibility approach where an artificial time term is added to the continuity equation and all of the equations are marched in this artificial time till convergence. Only steady state computations are performed for this effort. More details of the solver can be found in the references provided.

The ATHENA hull, with no shafts or struts, is used for baseline bare hull calculations. The waterjet is then added, for a separate set of calculations, so that the differences in the flow field with and without the waterjet can be ascertained. The calculations are for a speed of 25-knots at full scale, giving a Reynolds number of 500 million based on waterline length. The RANS calculation provides pressure and velocity data at every grid point in the flow field. This can be investigated to obtain information on the hull surface as well as the entire flow field around the ship. This calculation provides the boundary layer on the hull as well as the interaction of the hull boundary layer with the skeg, which is included in the calculation. The waterjet inlet was designed using inviscid methods. For the RANS effort this inlet geometry has been combined with the bare hull geometry to provide a calculation of the hull and inlet combination. A view of the inlet from underneath and above the hull is shown in Figure 6.3 to demonstrate how the hull and inlet are faired together providing a smooth hullform. (Note: the transom has been removed from Figure 6.3 to better observe the inlets). The RANS calculation is performed for the entire inlet section shown as well as the entire hull as done previously for the bare hull calculation. Computations cover details of the flow around and inside the inlet, requiring a very detailed grid in this small region, as well as flow over the rest of the hull. A grid of over 6 million points for  $\frac{1}{2}$  the hull is used, with port/starboard symmetry assumed. The desired mass flow into the pump is specified as a boundary condition at the exit to the inlet for the RANS calculation.

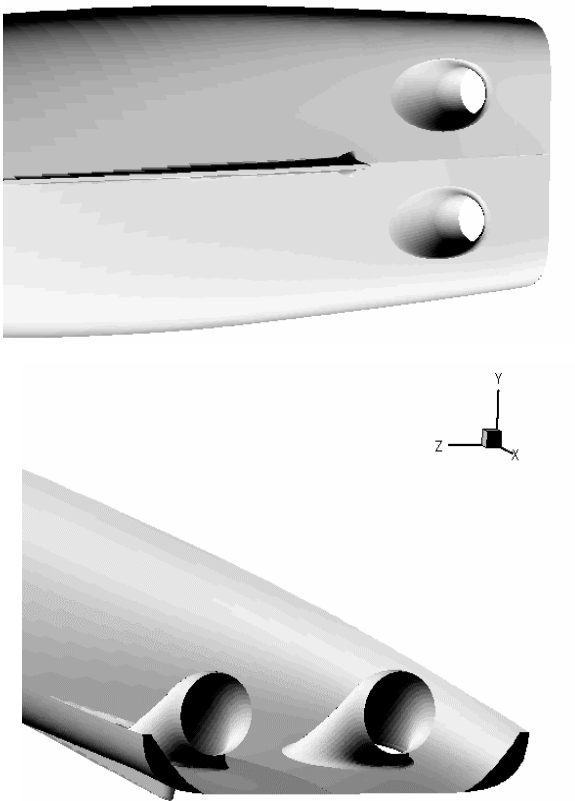


Figure 6.3 Three-dimensional views of the waterjet inlet.

Calculations are also being conducted on the model and full-scale pump for comparison and scaling with the pump test.

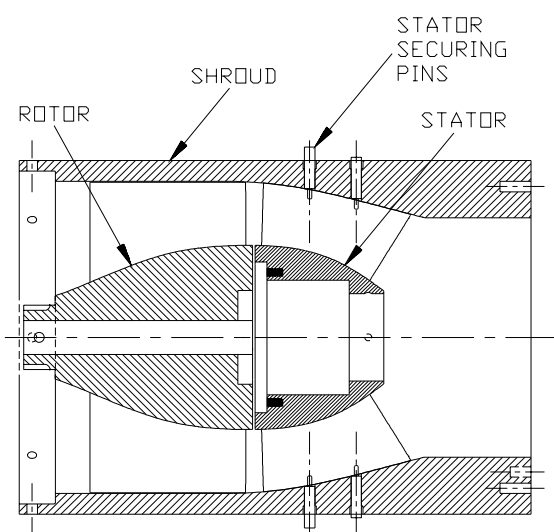


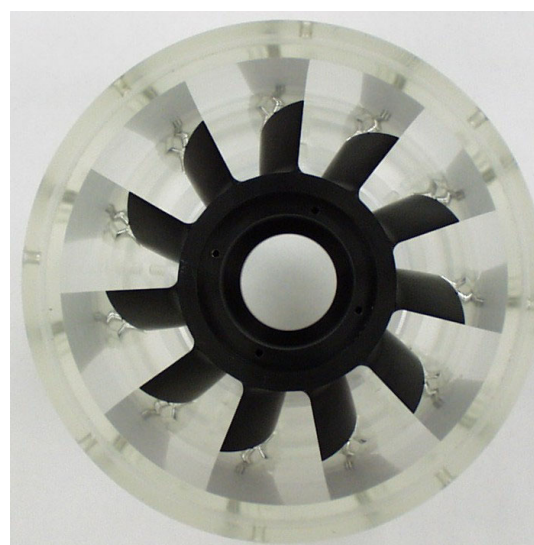
Figure 6.4 Assembly drawing of pump components.

Construction of Baseline Pump. One 19.05 cm diameter model baseline-design propulsion pump (impeller, stator, and housing) was built for testing in a pump loop circuit to validate the performance prediction model. A schematic of the assembly is shown in Figure 6.4.

The rotor and stator were manufactured from Aluminum 6061-T6 using a five axis CNC mill. After machining was completed each piece was anodized per MIL-A-8625, Type 3, Class 2 with a coating thickness of approximately 0.002 inches. Pictures of the machined rotor and stator can be seen in Figure 6.5.



a. Pump rotor



b. Pump stator installed in shroud

Figure 6.5 Model pump components.

The shroud was machined from acrylic tubing and polished to a smooth finish such that the finished product was optically clear. Finally, Nucon machined the stator securing pins from stainless steel and delivered the assembly with the stator secured inside of the shroud using the pins. Figure 6.6 shows a picture of the rotor and stator placed inside of the shroud with the stator securing pins in place.

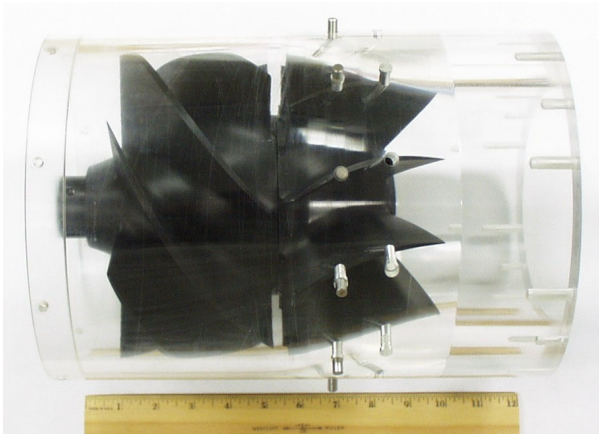


Figure 6.6 Pump Assembly.

Model Scale Self-Propulsion Test Waterjet. The model scale 12.34 cm diameter waterjet inlet and pump were constructed using stereolithography (STL). STL machining uses a computer controlled laser to cure a photo-sensitive resin, layer by layer, resulting in a finished 3D part. Figure 6.7 and Figure 6.8 show the STL models used to construct the model scale inlet and pump.

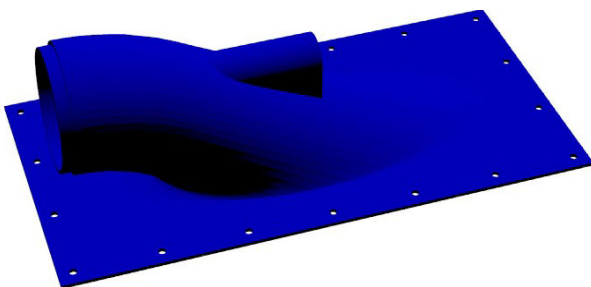


Figure 6.7 Model Scale Inlet for Waterjet Self-Propulsion Testing.

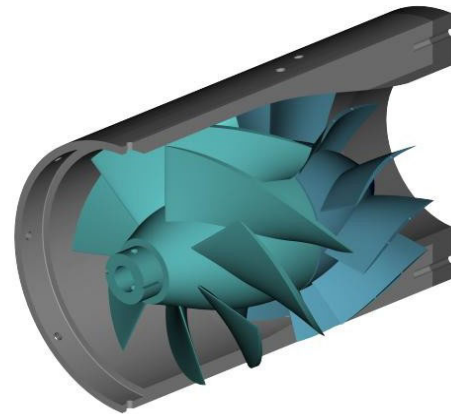


Figure 6.8 Model Scale Waterjet Pump for Self-Propulsion Testing.

Model Scale Hull Construction. Two 5.48 meter model hulls were built of the baseline ATHENA for use in the self-propulsion tests. The hulls were modified by CDNSWC to include two 12.34 cm waterjets. The waterjets contra-rotate with the tip rotating outwards. The two waterjets are setup for different types of measurements, with one setup for LDV measurements and the other setup for velocity probes and static pressure taps. Figure 6.9 shows the model ATHENA hull.



Figure 6.9 Model of the ATHENA Hull.

## 7. CONCLUSIONS AND RECOMMENDATIONS

### 7.1. Conclusions

Two types of conclusions are drawn. The first category refers to the administrative part of the standardization tests, the second to the technical problems that are addressed by these tests.

All ITTC members and a selected number of well-established waterjet manufacturers have received an invitation to participate in the standardization tests. These standardization tests are divided into self propulsion tests, pump tests and waterjet system tests. In addition to the tests, all addressees received an invitation to participate in a supporting CFD exercise. A review of letters of intent that were received back, stating the intention to participate and to assist in maintaining the time schedule, is given in Table 7.1. The positive reactions and the support from the ONR sponsored Gulf Coast Project have strengthened the belief of the committee that the ambitious objectives set forth by the 22nd Waterjet Committee can be met.

Table 7.1 Status of participation in standardization tests as per February 2002.

	LoI <sup>1</sup> received	LoI <sup>1</sup> to be expected	aspiration level
self propulsion tests	10	3	7
waterjet system tests	1	4	5
pump tests	2	2	5
CFD analysis	-	9	-

<sup>1</sup> LoI refers to Letter of Intent

The standardization tests have only started from April 2002, due to the fact that the Gulf Coast Project sponsored models could not be delivered earlier. This, together with the time required for preparations, is the main reason that the work of the 23rd ITTC Waterjets Committee is yet to be finished.

The issues that are to be addressed in the standardization tests have been defined in more detail by the current committee. The most important issues are discussed in Section 4 and are shortly summarized here:

- A number of methods to measure mass flow rate through a waterjet system is discussed.

- Difficulties in the determination of the ingested momentum and energy flux are due to uncertainty in the capture area geometry and in the 3D boundary layer velocity profile upstream of the intake.
- There is still uncertainty about the validity of the use of an average momentum and energy velocity from the nozzle, based on mass flow rate measurement and nozzle area.
- The issue of thrust identity versus flow rate identity during self propulsion tests is yet to be resolved.
- It is yet uncertain to what extent the waterjet needs to be modelled.
- The use of a surrogate pump is generally accepted, but the requirements for intake and nozzle modeling need to be specified further.

The results from the various methods that will be used and encouraged in the standardization methods are expected to play an essential role in providing guidance to the ITTC.

## 7.2. Recommendations to the Conference

Adopt ITTC Procedure 4.9-03-03-5.2 as an interim procedure for full scale power predictions.

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# The Specialist Committee on Validation of Waterjet Test Procedures

Committee Chair: Dr. Tomas J.C. van Terwisga (MARIN)

Session Chair: Dr. William B. Morgan (NSWC-CD)

## I. DISCUSSIONS

### I.1. Discussion on the Report of the 23rd ITTC Specialist Committee on Validation of Waterjet Test Procedures: Comparison between model tests and full scale trials

By: Pierre Perdon, Bassin d'Essais des Carènes, France

Is there any existing ship corresponding to the models that are to be tested?

If yes, does the Committee have any plans to make comparisons between model tests and full scale trials?

### I.2. Discussion on the Report of the 23rd ITTC Specialist Committee on Validation of Waterjet Test Procedures: The energy flow approach

By: Michael Schmiechen, Germany

Again I want to take the role of the *advocatus diaboli* and propose an alternative approach. While the Committee is completely relying on the momentum flow approach I want to mention that the energy flow approach, advocated by former Committees, has dramatic advantages. 'Of course' the two approaches have to complement each other adequately in any particular case.

The traditional, naive view of a thruster overcoming the resistance of the vehicle to be propelled may be quite adequate for conventional hull-propeller configurations. But in case of hull integrated propulsors the approach of pump designers is much more adequate, not only for the evaluation of the powering performance, but even for the design, as it has been shown in a project on ducted propellers carried out at VWS, the Berlin Model Basin, and discussed in a number of papers to be found on my website.

The starting point is the condition self-propulsion, of overall zero momentum flow, essentially the effective resistance, and the corresponding net power to be fed into the flow. As in pump design everything else is being dealt with in terms of energy flows and the thrust and all interactions are being treated implicitly observing the optimum condition from the beginning! As in pump design the thrust comes in only at the end, as a nasty by-product. All pumps develop thrust and need thrust bearings. Although pump designers do not want to produce thrust, they cannot avoid it and have to know it in order to design the bearing.

Even traditional open screw propellers may be looked at in the same way. Introducing the concept of equivalent propellers feeding the same net power into the same flow one obtains a relationship between the 'displacement' wake and thrust deduction fractions, implying that both 'together' are energetically neutral. Thus wake and thrust deduction as



such are not useful performance criteria as it has been pointed out on various occasions.

### **I.3. Discussion on the Report of the 23rd ITTC Specialist Committee on Validation of Waterjet Test Procedures: Wind tunnel tests of full scale waterjets**

By: Neil Bose, Memorial University of Newfoundland, Canada

Some of my students have tested full sized water-jet model in a wind tunnel.

Could the Committee comment on the use of wind tunnel testing for water-jets. Specifically could the Committee say whether the pump loop component of the proposed test schedule organised by the Committee could be done in a wind tunnel?

## **II. COMMITTEE REPLIES**

### **II.1. Reply of the 23rd ITTC Specialist Committee on Validation of Waterjet Test Procedures to Pierre Perdon**

The Committee values Dr. Perdon's question as a relevant question, as the value of a procedure depends on its suitability to predict the full scale case. And this suitability can only be fully ascertained when a number of cases is evaluated. We do however, not have the illusion that the committee will have the availability of a number of cases that can be used to correlate the full scale prediction with the full scale trials. This implies that the so called end to end approach for the uncertainty estimate is not useful.

Therefore, the committee seeks refuge into a validation on intermediate results, thereby assuming that the scaling procedure for the hull's resistance is equally valid for the pro-

PELLER driven hull as it is for the waterjet driven hull.

Yet, one would like to have at least one full scale dataset available, including intermediate results such as e.g. boundary layer data, to firm up on assumptions made during the process. To this end, the committee hopes that in due course, the U.S.N. R.V. Athena will be fitted with waterjets and that full scale data will be made available to ITTC for validation purposes. This hope was one of the driving factors to select this model for the standardization tests.

### **II.2. Reply of the 23rd ITTC Specialist Committee on Validation of Waterjet Test Procedures to M. Schmiechen**

Dr. Schmiechen's comment is welcomed by the committee as a philosophical contribution. However, the comments also breath an air of inadequacy of the committee's approach to the powering prediction issue of waterjet propelled vessels. An impression which is strongly rejected by the committee.

The essential criticism of Dr. Schmiechen focusses on the use of the conservation law of momentum to describe the waterjet hydrodynamics. Instead, he advocates the use of the energy conservation law, which, he mentions, is also successfully used in pump design.

The view of the committee on this comment is that the equations that are chosen for an overall powering analysis, depend on the problem at hand. There is of course a strong interdependency between the conservation laws of momentum and energy, as the latter relation is obtained from the first by taking the scalar product of the momentum equation with the velocity vector. This however also means that information is lost, as the vector equation is transformed into a scalar equation. The latter scalar equation is useful in analys-

ing the efficiency of the overall system and its components. It is however not useful when the demand of the ship, most often expressed in a resistance speed relation, is to be matched by the waterjet thrust. It is this balance of forces that generally leads to a speed prediction in early design stages.

The analogy with the pump design problem is not very suit here, as the main function of the pump is to provide head at a certain flow rate, closely related with energy (equivalent to the product of flow rate and head). The main function of the waterjet however is to produce thrust, which is more directly related with momentum.

It could well be that the preference for the use of either a momentum or an energy consideration is primarily driven by culture. But then, it is observed that almost every naval architect is acquainted with ways to produce a resistance speed curve of the hull in the early design stages of the ship where a waterjet needs to be selected. It seems therefore appropriate that one should be able to express the waterjet characteristics also in a thrust-speed relation that can be matched to overcome the hull's resistance after accounting for thrust deduction.

### **II.3. Reply of the 23rd ITTC Specialist Committee on Validation of Waterjet Test Procedures to Neil Bose**

Prof. Bose brings about an interesting technique to quantify the non-cavitating waterjet powering properties. However, a number of questions are raised.

An ever important issue is that of the viscous scale effects. To answer this question, it is important to know what Reynolds number can be achieved in the wind tunnel? It is of course important to keep the Reynolds number as high as possible in order to reduce the scale effects. For pump loop tests a Reynolds number (based on impeller diameter) exceeding  $1 \times 10^6$  is desirable.

A more serious issue may be the neglect of cavitation. What is the consequence of this neglect? Is the test objective limited to power prediction?

In most waterjet installations cavitation is present at normal operating conditions, although it would generally not have a significant effect on the performance at these conditions. Pump cavitation limits (thrust breakdown) however often determine the selection of the size of the waterjet unit in practice.

Furthermore, also inlet duct cavitation may restrict the operation of the waterjet.