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Design Considerations in the Development of a Modern Cavitation Tunnel

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Abstract

The specification and overall design of the new Australian Maritime College Cavitation Tunnel is presented. This facility has been funded under the Australian Government Major National Research Facilities Program as part of the Australian Maritime Hydrodynamics Research Centre (AMHRC). The AMHRC is a joint venture between the Australian Maritime College, the Defence Science and Technology Organisation and the University of Tasmania. The facility has been developed for naval hydrodynamics research with particular emphasis on the modelling of cavitating and turbulent flow physics. Development of circuit architecture and components are discussed in detail as well as ancillary systems. The facility's specific capabilities include the ability to strictly control circuit water gas content (both dissolved and free), continuous high-volume injection and separation of incondensable gases, control of the boundary layer on one wall of the test section, and low background noise and vibration levels.

Introduction

The Australian Maritime College (AMC) has operated a conventional medium-sized (0.6 m square cross-section test section) cavitation tunnel since 1998 [4]. The tunnel has mostly been used for basic and applied research in the development of naval and high speed craft, but also for general fluid mechanics investigations. Typical applications include studies of flow about surface and underwater vehicles and their propulsion and control equipment. Investigations may involve the study of cavitation and other two-phase flows, steady and unsteady flows, turbulence, hydro-acoustics and hydro-elasticity. The facility provides a useful balance between physical scale and economy of operation, and is satisfactory for most basic and applied investigations. Since the development of the present facility, demand for naval hydrodynamic research has increased both within Australia and overseas. This demand relates to research and design studies for in-country developed naval and high speed craft or foreign design evaluation and international collaboration with interested parties.

During the initial operation of the current facility research capabilities were limited by equipment availability. These problems have since been overcome with the development or purchase of a range of instrumentation. Limitations now relate to the conventional nature of the tunnel circuit and ancillaries in terms of flow quality, background noise level, control of dissolved and free gas content and the ability to precisely model wake fields. The range and sophistication of modern diagnostic equipment and increasing research demand largely dictate the requirements for modern experimental capabilities. Modern laser instrumentation and high speed digital photography permit ever increasing detail in experimental investigation of cavitating/turbulent flow physics and greater ability to validate and develop Computational Fluid Dynamics (CFD) techniques. Rigorous modelling of basic cavitation and turbulence physics requires the ability to model body wake fields with correct velocity and turbulence distributions, strict control of the dissolved gas content and nuclei spectra for extended test periods, and the continuous injection and removal of nuclei and high volumes of incondensable gas.

In 2001 funding was secured for the development of a new tunnel under the Australian Government's Major National Research Facilities program. The facility is currently under construction and is due to be commissioned in late 2007. It forms part of the Australian Maritime Hydrodynamics Research Centre (AMHRC) - a partnership for research collaboration between the AMC, the Maritime Platforms Division of the Australian Defence Science and Technology Organisation and the University of Tasmania. The existing AMC tunnel was decommissioned in early 2007 with the test section, main pump and major instrumentation being retained for the new facility.

Cavitation research has had a rich history in development of experimental facilities, most recently with the development of the world's three largest cavitation tunnel facilities: the French Grand Tunnel Hydrodynamique (GTH) [11], the US Large Cavitation Channel (LCC) and German Hydrodynamics and Cavitation Tunnel (HYKAT) [15, 16]. The development of these facilities provides considerable guidance in the special treatment given to flow quality, background noise levels and, perhaps most importantly, the control of dissolved and free gas content. Design studies and tunnel development relating to the above facilities and others have been reported in detail by several workers [e.g. 10, 8, 15, 16]. The literature also contains abundant publications on the importance of the dissolved and free gas content in modelling of cavitation phenomena [e.g. 12, 5, 9]. Of particular significance are the limitations involving the complex, often transient, nature of interactions between a cavitating model and the tunnel circuit itself in controlling the nuclei concentration deemed responsible for the variation of results between different facilities [12, 13]. For the control of dissolved and free gas content, similar systems and circuit architecture to the French GTH were adopted. These include a fast degasser using micro-bubble injection and nuclei injectors upstream of the test section. Continuous removal of injected gas and nuclei is achieved via sequential coalescence/gravity separation and dissolution using a large volume downstream tank and resorber. Experience with the current facility has shown the frequent need in basic and applied studies for the control of at least one test section boundary layer; it was therefore decided that a system for active control of the ceiling boundary layer should also be implemented. Measures taken for noise reduction in all the above-mentioned facilities involving hydraulic design, design of flow conditioning/control devices, and ancillary equipment isolation have also been incorporated in the new facility. This paper presents an overview of the facility design process, together with the tunnel architecture, capabilities and instrumentation. A more detailed description of circuit components and their design are given in [2].

Tunnel specification

The principal capabilities sought in the development of the new facility are as follows:

- high uniformity, low turbulence test section flow
- fine control of test section velocity and pressure
- low test section cavitation number
- independent control of free and dissolved gas content
- continuous injection and separation of high volumes of incondensable gases
- boundary layer control on one wall of the test section
- low background noise and vibration levels

The implementation of these design aims will be now be discussed.

From the outset in deciding the specification of the new cavitation tunnel there were no plans to increase the test section size, maximum flow rate or static pressure. It was therefore decided that the test section and main pump from the previous facility be reused. This also permitted the retention of a range of instrumentation specifically developed to suit the present test section geometry and its maximum operating velocity/pressure. The basic test section specifications remain as for the previous facility: dimensions of 0.6m x 0.6m cross-section by 2.6m long, velocity range of 2 to 12m/s, and centreline pressure range of 0.4 to 400 kPa absolute. Experience with the previous tunnel provided knowledge of test section flow qualities that could be enhanced through improved technology and design at moderate expense, as well as those that required greater expense.

The test section velocity uniformity of the previous facility was within ± 1% of mean for the operating Reynolds number range. This facility incorporated a pipe penetrating the upstream bend for insertion of an upstream propeller dynamometer that was never used but unfortunately affected test section flow uniformity. The lack of a settling chamber between the upstream bend and the honeycomb was another possible source of test section flow non-uniformity. The upstream bend turning vane design was also relatively crude. On this basis it was felt that considerable improvements could be made with improved upstream bend design and provision of a settling chamber (also required for accommodation of nuclei injectors and turbulence reduction). Improvements made to lower limb and upstream vertical limb flows (required for optimising bubble dissolution) should also contribute to improved test section flow uniformity.

As a result of these improvements and cavitation requirements no change was made to the contraction ratio of 7.11 used in the previous facility. The contraction profile was however entirely redesigned using both CFD and ¼ scale model wind tunnel testing. As a result of these investigations improvements in the minimum operable cavitation number were achieved. For asymmetric contractions with a flat top, as used on many modern cavitation tunnels, cavitation inception may occur on the test section ceiling or contraction exit floor. Whichever of these occurs depends on a critical Froude number (based on test section velocity and height) dependent on the contraction exit minimum pressure coefficient. The minimum operable test section centreline cavitation number corresponds to the critical Froude number. By reducing the magnitude of the minimum pressure coefficient the critical Froude number is increased and the minimum cavitation number reduced. This critical Froude number was increased from 2.9 for the previous contraction to 3.8 for the new design with corresponding reduction in the minimum cavitation number from 0.12 to 0.07, respectively. Above the critical Froude number cavitation inception occurs on the floor of the contraction exit. The minimum cavitation number at maximum Froude number of 4.9 was improved from 0.2 for the previous contraction to 0.1 for the new design.

The test section turbulence intensity for the previous facility was measured at about 0.6%, and it was felt that only small improvements could be made for manageable expense. The honeycomb sizing of 6.35mm hex cell, as used for the previous tunnel, was therefore retained. Minor improvements are expected with additional duct lengths added either side of the contraction for incorporation of degassing and boundary layer manipulation hardware.

Speed and pressure control for the previous tunnel were limited by various factors including precision of controlling digital electronics, drive train mechanical design, and control valve sophistication. These factors have been given detailed consideration in control system design for the new facility. For the previous tunnel velocity control precision was about 0.05% of maximum speed. Replacement of the main pump motor and variable speed drive is expected to improve this to 0.01% of maximum speed. Further improvements are also expected from improved drive train design including the addition of a flywheel and double compliant couplings between the gearbox and external main pump bearing. Considerable improvements have been made in the sophistication of the pressure control system, including separate valve systems for coarse ranging and fine control and control software programmed for changing system characteristics. Due to different circuit architecture and requirements, the gas volume in the ceiling of the downstream tank required for pressure control and gas removal is 10 times greater than that of the surge tank in the previous tunnel. From these changes and enhancements, it is estimated that improvements for pressure control should approximate those for velocity. The combined effects of better pressure and velocity control should also improve the regulation of cavitation number which, involves the ratio of static and dynamic pressures.

Cavitation phenomena are fundamentally dependent on the gas content present in all liquid volumes, either dissolved or free as bubbles. The practical importance of dissolved gas content has been considered from virtually the beginning of the development of large scale experimental facilities. Maintaining constant cavitation number, a necessary but insufficient parameter for cavitation testing, requires reduction of static pressure when the velocity at model scale is reduced. As a consequence, cavitation tunnels have traditionally been developed with some facility for degassing of tunnel water to avoid the release of large quantities of gas. Beyond the obvious practical importance of avoiding populations of large bubbles, the gas content may be important in modelling cavitation physics and is critical in the management of nuclei populations within the tunnel circuit. Traditional means of degassing have ranged from simple systems, such as tunnel low speed operation with the upper limb only partially filled under vacuum, to dedicated ancillary systems using sprays and vacuum vessels. Both methods are slow requiring up to 12 hours for degassing down to 20% of saturation at atmospheric pressure

To enable strict control of nuclei content and removal of all free gas requires large circuit volumes making the traditional means of degassing impractical: for the same size test section the circuit volume for the new AMC facility is 365 m^3 whereas that for the previous was 75 m^3. In the development of the GTH with 3600 m^3 circuit volume, a system enabling rapid degassing of large volumes by using micro-bubble injection was devised [11, 12]. Time consuming degassing procedures used with the previous AMC facility significantly hindered productivity, and a rapid degassing capability was considered essential for the new facility. Fortunately, the ancillary requirements for implementation of a rapid degassing system also encompass those for nuclei injection. The new tunnel specification calls for degassing of the tunnel volume to 20% of saturation at atmospheric pressure within 2 hours. A detailed description of the function and incorporation of the rapid degassing system is given below.

Nuclei populations of minute bubbles are present in all practical liquid volumes with typical of sizes of 1 to 100 μm and concentrations of 0.001 to 1 cm^{-3}. These nuclei control both the inception and dynamic character of cavitation. Liquid volumes with low nuclei concentration or small nuclei diameter may sustain significant negative pressures (or tension) below vapour pressure before cavitation or phase change occurs. The combined effects of internal gas pressure and surface tension are such that a critical pressure exists where (depending on gas content and diameter) the nuclei equilibrium becomes unstable and leads to rapid growth. The complexity of these phenomena makes the control of the nuclei population essential in basic modelling of cavitation physics. Scaling of both the nuclei concentration and nuclei size spectra are required for modelling of some cavitation phenomena. The so-called λ^3 law applies in these circumstances, whereby the nuclei concentration should scale with the cube of the length scale. As an example testing of a model at 1:20 scale model to simulate a natural nuclei concentration of 1 dm^{-3} would require model nuclei concentrations of 8 cm^{-3}. From these and other considerations required for general modelling, the nuclei injection system was designed to produce concentrations of 0.1 to 10 cm^{-3}. The upper value is approximately that needed to produce saturation beyond which no additional influence occurs. The system was designed to produce nuclei sizes in the range 10 to 100 μm depending on the system configuration. The nuclei injectors were located so as to minimise residence time between production and their convection to the test section, and to avoid passage of nuclei through the honeycomb. The time for gaseous diffusion and the possibilities for nuclei coalescence are thereby minimised. The nuclei injection system and injector arrangement are discussed in further detail below.

To investigate cavitation and bubbly flows for extended periods requires the ability to maintain a set gas content and to continuously inject and remove nuclei and large volumes of incondensable gas. Separation requirements are therefore based on the expected injected nuclei, bubbles produced from model cavitation, and expected volumes of injected incondensable gas. Cavitation occurring on a model in the test section is a source of nuclei and bubbles due to diffusion of dissolved gas into the cavity, which is then left as small bubbles in the wake after vapour condensation. The required maximum flow rate of injected incondensable gases was based on various requirements associated with the investigation of bubbly wakes, ventilated super-cavitating hydrofoils, and propulsion devices. These considerations indicated that a maximum flow of 200 ℓ/s (atmospheric conditions) would be required. The basic requirements of bubble separation and dissolution dictate that the tunnel circuit must contain sections of low velocity with conditions suitable for bubble coalescence and gravity separation, as well as an extended residence time for dissolution of small bubbles. Hence two relatively large volumes are needed of about 100 to 150 m^3 to totally eliminate free gas within one complete circuit of the tunnel. These volumes were implemented with a downstream tank of volume 135 m^3, in which bubbles nominally greater than 100 μm are separated, and a so-called resorber of 120 m^3 in which bubbles below 100 μm are dissolved. The features largely determined the overall circuit architecture discussed in detail below along with the functional design of each section. The final design has a total circuit volume of 365 m^3, giving a bubble residence time of about 85 s at the maximum flow rate of 4.32 m^3s^{-1}.

Experience in operation of the previous AMC tunnel showed that the test section boundary layer thickness was often a limiting factor; for example, in testing of underwater vehicle control surfaces or marine water-jet propulsors. Instances where the boundary layer was too thin could be overcome by thickening [3, 4], although the use of drag producing or mixing devices were ultimately limited by cavitation occurrence or vibration. To avoid the use of solid devices and to enable boundary layer thinning a system for manipulation of the test section ceiling boundary layer using injection or suction was incorporated. The use of such methods for boundary layer thickening is reported in [14]. This device consists of a full-width plenum and perforated plate located at the end of the contraction. The specification for the boundary layer control system was determined from momentum considerations based on thickening of the ceiling natural boundary layer, about 12 mm thick, to 100 mm thick. From this analysis a maximum injection rate of 50 ℓ/s was chosen; this capacity allows the boundary layer to be almost totally ingested at maximum tunnel flow.

A formal specification for noise and vibration levels was not decided upon, but an overall strategy or design philosophy was adopted for their minimisation. The siting of the tunnel on the AMC campus was not considered to be vulnerable to external noise sources such loud machinery and therefore no special measures were taken to insulate the external building walls. However the tunnel was designed as completely free standing with no connections to the enclosing building, including semi-compliant isolation between tunnel foundations and building concrete slabs and foundations. All ancillary machinery and pipework are isolated by rubber connections. Additionally all continuously operating machinery such as air compressors, vacuum pumps and the main pump drive are located in an acoustic enclosure rated at 70 dB attenuation. Should this prove inadequate, additional isolation can be easily provided. The main pump drive train employs double compliant couplings between the gearbox and external main pump bearing for both improved drive dynamics and noise and vibration isolation.

The structural design included global static and dynamic finite element modelling of the tunnel shell to investigate vibration modes and the response to internal forced excitation and external earthquake loading. The excitation spectra used for the analysis were determined from natural vibration measurements and impact tests made on the previous tunnel. Minimisation of flow noise has been addressed through careful design of bends and diffusers and by the need for a large tunnel volume reducing circuit velocities. The flow conditioning devices throughout the circuit for bubble separation and promotion of dissolution also provide damping of noise transmission. The main pump is potentially one of the greatest sources of noise, and the new tunnel structure has been designed to facilitate its replacement with a larger diameter machine. Additional power capacity for this purpose has been provided.

Experience with the previous tunnel showed that electrical earthing and isolation needed detailed consideration. The new tunnel has separate electrical power supplies for the water drives and instrumentation, along with an earth net to minimise grounding problems for instrumentation and control equipment.

Sufficient external water storage is provided to accommodate the upper limb volume. The transfer pump capacity allows filling or emptying of the test section in 10 minutes.

Circuit architecture and capability realisation

The requirement for continuous injection and removal of nuclei and high volumes of incondensable gases determined the need for two large volumes for bubble coalescence and gravity separation and for bubble dissolution. The incorporation of these volumes in the circuit is the major factor determining the tunnel architecture. Several smaller facilities have incorporated such volumes as distinct sections connected by relatively small duct, work such as designs reported by [1, 6]. In the design of the GTH, a large tunnel developed with similar capabilities to the new medium sized AMC tunnel, these volumes were incorporated as part of a relatively conventional circuit architecture [11]. For the new AMC tunnel, although only medium sized, it was decided that a similar architecture was suitable and would be compatible with minimising circuit cost and main pump power requirements. A general arrangement of the new tunnel circuit is shown in Figure 1.

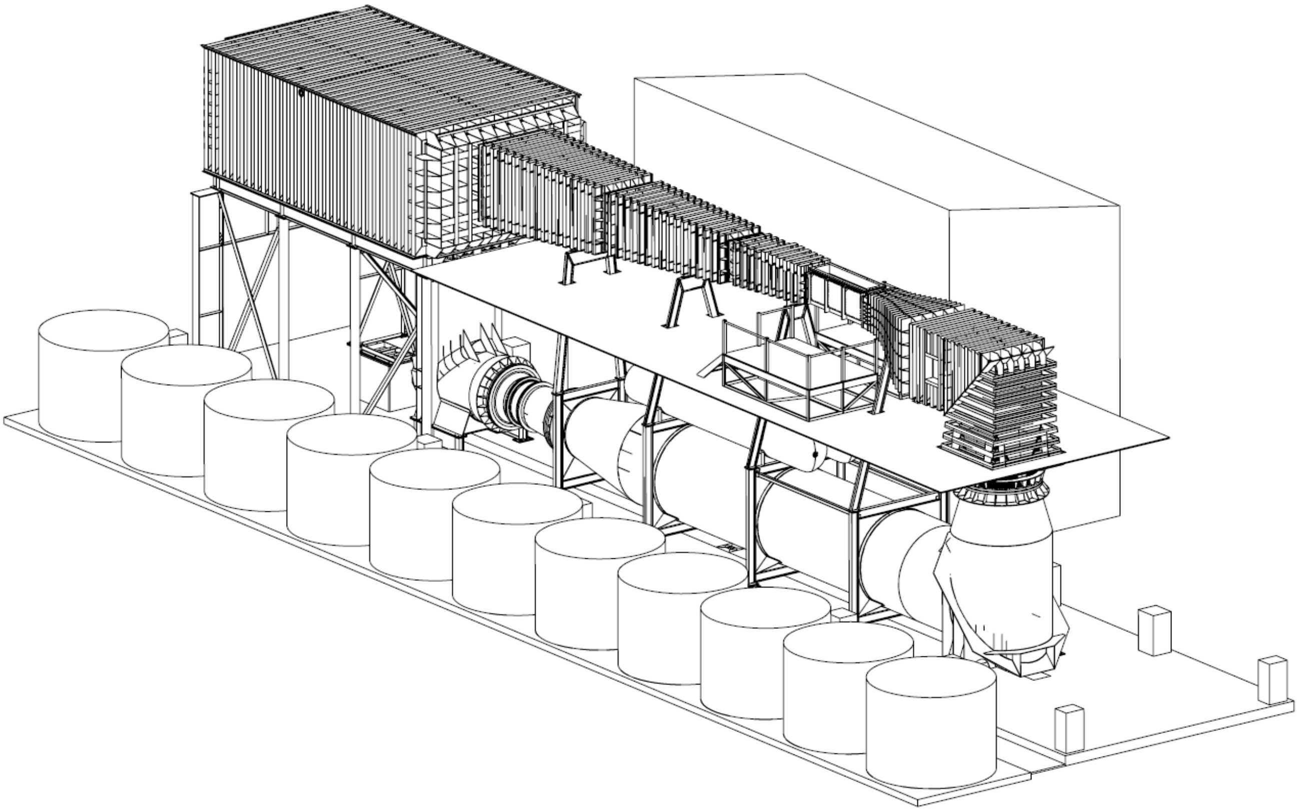

Figure 1. Cavitation tunnel general arrangement – 3 dimensional view

The tunnel circuit has a large area ratio diffuser downstream of the test section to slow the flow sufficiently before entering the downstream tank where separation of larger bubbles and nuclei occurs. Bubbles/nuclei nominally greater than 100 μm in diameter are removed through a series of honeycombs via a coalescence/gravity separation process. The downstream tank contains 135 m^3 of water, is prismatic in shape, and contains two banks of bubble separators arranged either side of the vertical centreline. Figure 2 shows horizontal and vertical cross sections of the downstream tank. Within the tank the velocity is slowed to 0.1 m/s at maximum flow rate, and then passed through a slatted wall/perforated plate conditioner to achieve flow uniformity before entering the bubble separators. The separators each consist of three stages of honeycombs, the first of which is a large-cell inclined honeycomb to gravity separate large bubbles via reverse flow. The second is a small-cell horizontal honeycomb to promote nuclei coalescence before passing a final stage similar to the first.

The downstream tank contains an internal ceiling spanning the entire area of the tank profiled to match the top of the separators. The cavity within the ceiling space is divided by a series of weirs corresponding to each separator stage, each partially filled with water at differing levels corresponding to the head loss through each stage. The air space above the water within the ceiling cavity is used for pressure control of the tunnel. Water and separated gases are exchanged through the internal ceiling at each stage via upright and inverted chimneys. As the chimney areas represent only a small proportion of the total tank horizontal cross-section, dissolved gas exchange between the water volumes above and below the ceiling is negligible. After the separators the flow reverses through an internal passage in the tank floor and exits via a conditioner into the vertical limb. The conditioner contains a honeycomb to promote parallel and uniform flow before entering the pump bend and pump.

The pump is located in the lower limb to maximise available NPSH. Downstream of the pump is a 20º split conical diffuser combined with a Zanker conditioner to achieve uniform flow of low turbulence intensity for promotion of dissolution in the lower limb. Bubbles/nuclei less than 100 μm in diameter are predominately dissolved in the lower limb (resorber). The 120 m^3 resorber volume promotes dissolution via a combination of low uniform velocity, low turbulence, extended residence time and low dissolved gas content. Whilst bubble dissolution is optimised in the resorber due to extended residence it also occurs throughout the remainder of the circuit. In the preliminary design of the tunnel, a mathematical model of bubble dissolution applied to the circuit between the downstream tank and the test section was developed. The model was used to investigate levels of degassing and residence times required for dissolution of 100 μm diameter bubbles leaving the downstream tank. The results of this analysis showed that bubbles of at least 100 μm diameter could be dissolved for both moderate and low levels of degassed tunnel water at the maximum flow rate. The resorber outlet bend is implemented with a 90° mitre bend in a honeycomb. This, combined with area-ratio contraction in the vertical limb, is used to further promote flow uniformity and low turbulence intensity before the upstream bend, settling chamber and contraction. Figure 3 shows a schematic of the bubble removal process.

Nuclei are introduced in the settling chamber upstream of the contraction (Figures 3 and 4) via an array of direct and dilute injectors penetrating the honeycomb. The nuclei injection system is designed to achieve test section nuclei concentrations of between 0.1 to 10/cm³ with a dominant size of O[100 μm] diameter via a system of direct internal injection or external one- or two-stage dilution followed by injection. The injector arrays are mounted on foils just upstream of the honeycomb, with tubes that extend to penetrate the honeycomb and inject nuclei immediately downstream. This arrangement minimises nuclei residence before reaching the test section, and eliminates problems of nuclei coalescence in passing through the honeycomb passages as occurs in previous facilities designed with nuclei seeding in the vertical limb. The injectors consist of an array of 100 direct injectors and 200 dilute injectors. The direct injectors are individually controlled from external manifolding such that any combination may be operated to achieve a particular pattern or target area in the test section. The dilute injectors produce such low nuclei concentrations that individual control is not generally necessary, although provision is also made for their individual control should it be required for specialised experiments. Figure 4 shows the general arrangement of the injector array support foils and the external manifolding and dilution systems.

The circuit shell is fabricated entirely from stainless steel with external mild steel structural stiffening. The complete tunnel structure is free-standing using structural supports integral to both the upper and lower limbs. The tunnel is founded on isolated pile caps and piles that extend to bedrock. The pump bend and downstream tank supports are rigidly connected to the foundations to providing anchoring for the whole structure. The remainder of supports bear on the foundations through Teflon plates to provide for thermal expansion and mechanical compliance and damping of vibration. All ancillary equipment that operates during testing is housed in the acoustic enclosure located below the downstream tank.

The degasser and boundary layer thickener have been integrated into the contraction, as shown in Figure 5. The implementation of the degasser is similar to that of the GTH [12] with the micro-bubble generator accommodated in a supplementary volume at the bottom of the contraction inlet, incorporating a lid that may be opened for degassing operation. This system uses the tunnel circuit itself as the degassing vessel with an immense surface area for diffusion created by injection of large numbers of millimetre sized bubbles. The bubbles, created by expansion of supersaturated water through a large number of orifices, are released into the tunnel at the bottom of the contraction entrance. The emulsion produced is of such a high void fraction that the flow appears like milk. The pressure reduction as bubbles rise during their transport to the test section promotes gaseous diffusion. This gaseous volume is then removed with vacuum in the downstream tank by the same mechanisms used for bubble separation, as described above.

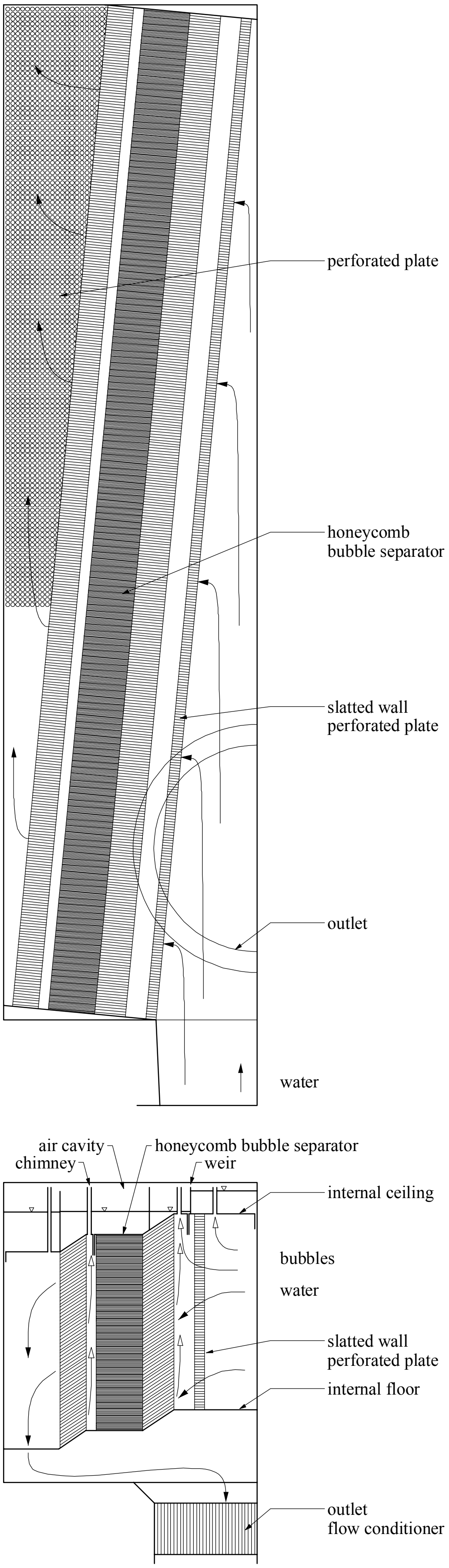

Figure 2 Horizontal and vertical half sections of the downstream tank

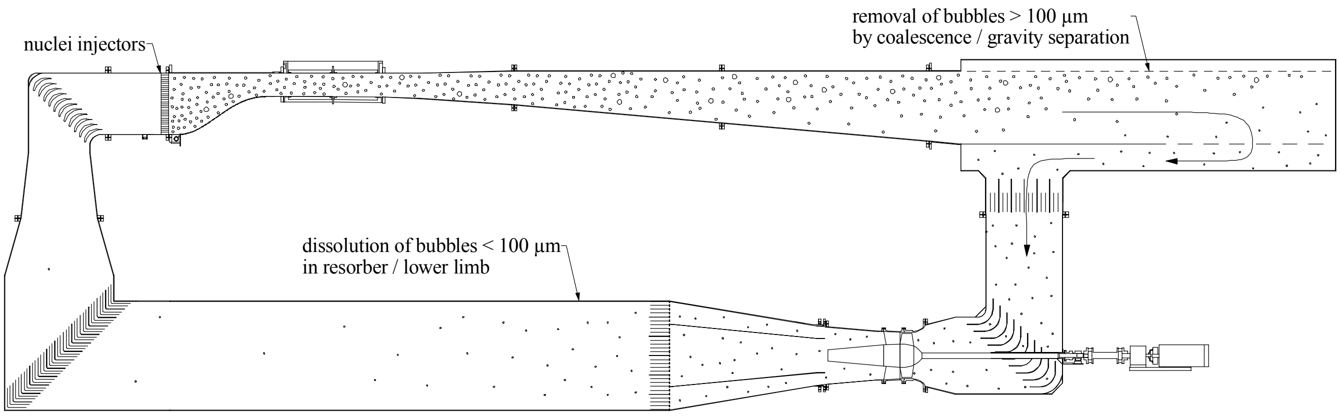

Figure 3 Schematic of nuclei/bubble injection and bubble removal process

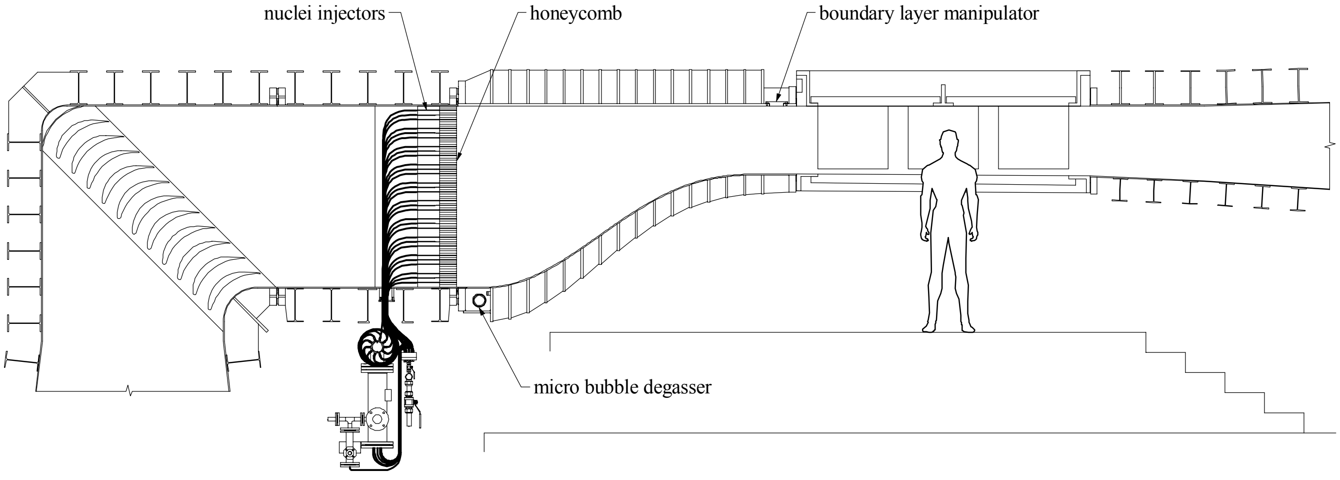

Figure 4 Vertical section of the contraction showing location of degasser and boundary layer manipulator

The test section ceiling boundary layer is the most convenient for boundary layer control, in terms of both test requirements and ease of implementation. Water may be either injected for thickening or removed for thinning through a full width interchangeable perforated plate via an external plenum. Water injected is pumped from the resorber; water removed by suction is re-injected as a wall jet above the internal floor of the downstream tank.

Control and circuit ancillaries

The control system makes extensive use of modern computer and electromechanical control, with automation of measurements implemented where possible. Figure 5 shows a schematic of tunnel ancillary systems and control equipment. The test section velocity and pressure may be controlled in a range of modes, including setting of the main pump rotational speed, dimensional velocity and pressure, and the test section cavitation number and Reynolds number. The tunnel pressure control may be operated with the vacuum and pressure systems online, or with two 8 m^3 pressure/vacuum accumulators used only for quiet modes where no compressors or vacuum pumps are in operation. The pressure control system was designed using a time-domain numerical simulation of all hardware and software to optimise control valve choices and feedback algorithms. Test section automatic pressure control, via downstream tank pressure, is achieved through the use of two control valves acting on a leakage air flow between the pressure and vacuum systems. The setting of one valve uses open loop control for coarse pressure ranging, while the second uses closed loop feedback for fine pressure control. As the air volume contained in the downstream tank is relatively large, bypass valving is used to achieve large pressure changes within an appropriate time.

The test section pressure is measured from wall tappings with high and low range absolute pressure transducers. Velocity is measured using the pressure differential across the contraction from wall tappings at the entrance and exit of the contraction, observed with high and low range differential pressure transducers. An alternative set of downstream tappings is provided for use when the boundary layer thickener is in operation. These tappings are located far enough upstream to be beyond the influence of the boundary layer thickener, regardless of its flow rate. The thickener flow rate is set using closed loop feedback control, with the desired boundary layer thickness being the control variable. The relationship between the boundary layer thickness and the flow rate will be determined from calibration using the test section dynamic pressure and the pressure differential across the thickener discharge nozzle as the reference variables.

Calibration of all pressure transducers may be carried out in-situ using a dead weight tester. Properties of the tunnel water measured directly include the temperature, dissolved oxygen content and electrical conductivity, from which other parameters of interest are derived using empirical numerical models.

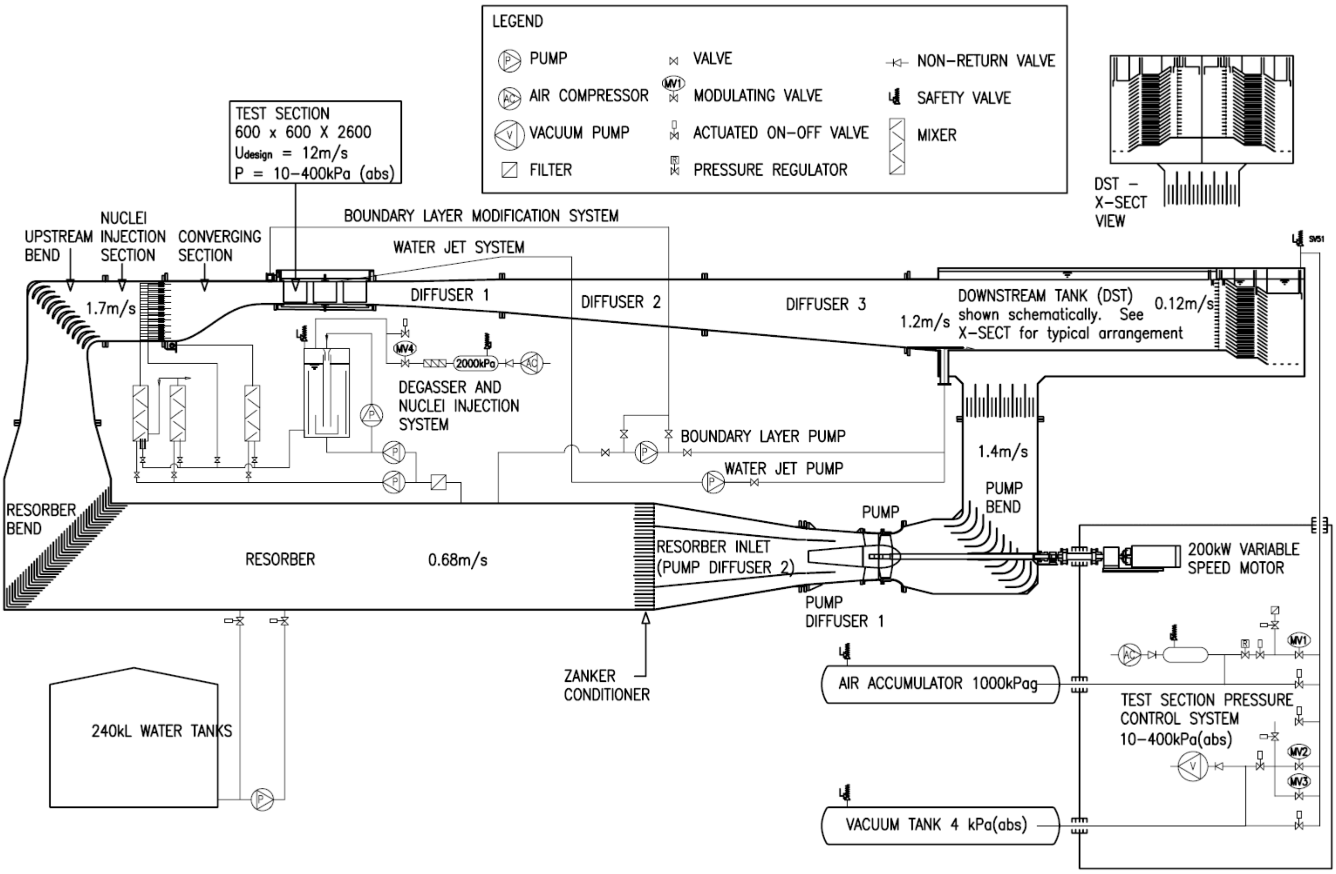

Figure 5 Schematic of cavitation tunnel ancillary systems and control equipment

The degassing and nucleation systems require supersaturated water for the production of both micro-bubbles and nuclei. The supersaturated water is produced in an 0.36 m^3 20 bar rated pressure vessel. The saturation vessel is supplied by a high pressure water pump and air compressor, and contains an internal recirculation and mixing system to accelerate the dissolution process. The operation of the saturation vessel is essentially fully automatic, with the control parameter being the saturation pressure. Depending upon on the required use, super-saturated water may be piped directly to the nuclei injectors or diluted for use in degassing. The degassing and nucleation system incorporates several specially developed non-cavitating mixers and valves that meet various design requirements of flow mixing and large head losses.

A secondary loop for the investigation of water-jet propulsors was developed as part of the previous facility and to date has been used for the investigation of water-jet inlet ducts [4]. The loop is to be reused for the new facility and is basically identical apart from changes made to the method of re-injection of ingested water. In the previous facility ingested water was re-injected in the vertical limb upstream of the pump. In the new facility the return circuit is shared with that for re-injection of ingested boundary layer fluid via the wall jet above the internal floor of the downstream tank, as shown in Figure 5.

Instrumentation

In addition to conventional tunnel instrumentation, a range of specialised equipment and instrumentation has already been developed or purchased as part of the existing tunnel, or is currently being developed as part of the new facility. This includes:

- High-speed camera, time-resolved particle imaging velocimetry (PIV) and shadowgraphy system
- Scanning laser vibrometer
- 3D automatic traverse and 1D/3D fast response pressure probes
- Waterjet test loop
- 2 propeller dynamometers
- 6 six-component force balances

The high-speed camera, time-resolved PIV and shadowgraphy system is intended for use in a range of basic investigations of single-phase flow and cavitation phenomena. These systems provide the opportunity for spatial and temporal resolution in flow field measurements, and greater ability to investigate flow field topology. The shadowgraphy part of the system is an integral part of the tunnel instrumentation as it will be used for measurement of test section nuclei spectra.

Greater scope for the investigation of hydro-elastic phenomena is possible with non-intrusive motion measurement, thus avoiding the need for excessive use of accelerometers in the test model design. For this purpose high-speed photography and laser vibrometry combined with synchronised flow field measurements provide the opportunity to gain greater insight into hydro-elastic behaviour.

In addition to the commercially available technology described above a range of custom-built instrumentation has been developed by AMC and its collaborators. Despite the possibilities of interference effects physical probes offer several advantages over non-intrusive measurements, including ease of use, observation of static pressure and relatively high precision. For this purpose 1D [3] and 3D fast response probes have been developed along with a 3D automatic traverse with operating range of 0.2 x 0.3 x 0.3m that provides sealing over the full working pressure range of the tunnel. These facilities have been used for investigation of wake fields and for mapping of boundary layer transition about underwater bodies [7].

The conventional 'torpedo'-type test-section-mounted propeller dynamometer previously developed for the existing tunnel will be complemented by a new significantly enhanced instrument currently under development. The first dynamometer may be operated with the propeller either upstream or downstream of the torpedo body, but with its axis fixed on that of the test section; it is capable of measuring static and dynamic propeller thrust and torque. The new dynamometer is of the same torpedo configuration but with direct electric drive of the propeller shaft rather than via gears as in the existing instrument. It will incorporate adjustments for both vertical position and angular orientation of the torpedo in the vertical centre-plane. The shaft-end-mounted transducer will be capable of measuring several force/moment components.

Several six-component force balances have been or are being developed for various specific experiments and model configurations. Three of these are conventional balances that are externally mounted in flooded volumes and consist of an array of parallel and orthogonal flexures that decouple the applied load in to measurable vector components. These are low frequency response devices (<100 Hz) that allow static or dynamic variation of model incidence. A fourth external balance currently under development is similar to the above-mentioned instruments, but with piezoelectric force transducers for high frequency or dynamic load measurement. The remaining two balances of conventional design can be fitted within models of underwater bodies using either side strut or sting mounting.

Conclusions

The development of a new medium sized cavitation tunnel for basic and applied research in naval hydrodynamics has been described. The design of the new facility builds on earlier significant work in the development of existing large tunnels (including the GTH, LCC and HYKAT) as well as modern developments in basic cavitation research. Design specifications include strict control of the circuit water gas content (both dissolved and free), continuous high-volume injection and separation of incondensable gases, control of the boundary layer on one wall of the test section, and low background noise and vibration levels. The capabilities of the tunnel have been developed for the rigorous modelling of cavitating/turbulent flow physics, and to fully utilise the capabilities of modern diagnostic instrumentation. A range of specialised instrumentation has been developed or purchased as part of the new tunnel development.

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References

[1] Avellan, F., Henry, P. and Rhyming, I., *A New high-speed Cavitation Tunnel for Cavitation Studies in Hydraulic Machinery*, International Symposium on Cavitation Research Facilities and Techniques, ASME FED-Vol. 54, pp 49-60, 1987.

[2] Brandner, P.A., Lecoffre, Y. and Walker, G.J., *Development of an Australian National Facility for Cavitation Research*, Sixth International Symposium on Cavitation – CAV2006, Wageningen, The Netherlands, September, 2006.

[3] Brandner, P.A., Clarke, D. B. and Walker G.J., *Development of a Fast Response Pressure Probe for Use in a Cavitation Tunnel*, Proceedings of the Fifteenth Australasian Fluid Mechanics Conference, Sydney, New South Wales, Dec, 2004, 4pp (on CD).

[4] Brandner, P.A. and Walker G.J., An Experimental Investigation into the Performance of a Flush Water-jet Inlet, *Journal of Ship Research*, SNAME, Vol 51, No. 1, March 2007, pp 1-.

[5] Brennan, C.E., *Cavitation and Bubble Dynamics*, Oxford University Press, 1995.

[6] Briancon-Marjollet, L. and Michel, J. M., The Hydrodynamic Tunnel of I.M.G: Former and Recent Equipments, ASME, *Journal of Fluids Engineering*, Vol. 112, 1990, pp 338-342.

[7] Clarke, D. B., Brandner, P.A., and Walker G.J., *Computational and Experimental Investigation of Flow Around a 3-1Prolate Spheroid* , Proceedings of the Sixteenth Australasian Fluid Mechanics Conference, Gold Coast, Queensland, Dec, 2007, 8pp (on CD).

[8] Farabee, T. M. and Arndt, R, E. A. (Ed.), Hydroacoustic Facilities, Instrumentation and Experimental Facilities, ASME, NCA-Vol 10, 1991.

[9] Franc J. P. & Michel, J. M., *Fundamentals of Cavitation*, Kluwer Academic Publishers, 2004.

[10] Holl J. W. and Billet, M. L. (Ed.), International Symposium on Cavitation Research Facilities and Techniques, ASME FED-Vol. 54, 1987.

[11] Lecoffre, Y., Chantrel, P. and Teiller, J., *Le Grand Tunnel Hydrodynamique (GTH): France's New Large Cavitation Tunnel for Hydrodynamics Research*, International Symposium on Cavitation Research Facilities and Techniques – 1987, ASME FED-Vol. 54, pp 1-10.

[12] Lecoffre, Y., *Procedures and Instrumentation for Monitoring Gas Content in Cavitation Test Loops*, International Symposium on Cavitation Research Facilities and Techniques – 1987, ASME FED-Vol. 54, pp 139-146.

[13] Liu, Z., Sato. K, and Brennen, C. E., *Cavitation Nuclei Population Dynamics in a Water Tunnel*, ASME Cavitation and Multiphase Flow Forum, 1993. FED-153. ASME, New York, pp. 119-124.

[14] Sargison, J.E., Walker, G.J., Bond, V., and Chevalier, G., *Experimental Review of Devices to Artificially Thicken Wind Tunnel Boundary Layers*, 15th AFMC, Sydney, Dec, 2004, 4pp (on CD).

[15] Wetzel J.M. and Arndt R.E.A., Hydrodynamic Design Considerations for Hydroacoustic Facilities: Part I – Flow Quality, ASME, *Journal of Fluids Engineering*, Vol. 116, 1994, pp 324-331.

[16] Wetzel J.M. and Arndt R.E.A., Hydrodynamic Design Considerations for Hydroacoustic Facilities: Part II – Pump Design Factors, ASME, *Journal of Fluids Engineering*, Vol. 116, 1994, pp 332-337