International Symposium on Outfall Systems, 2016
Organized by:
IAHR-IWA Joint Committee on Marine Outfall Systems
May 10th-13th, 2016, Ottawa, Canada

Duckbill Nozzle Knowledge Base for Inland and Marine Outfall Diffuser Designers and Modelers

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ABSTRACT

Duckbill check valve nozzles (DBNs) are utilized extensively in the design of inland and marine multiport outfall diffusers for both industrial and municipal discharges. When duckbill valves were initially utilized on outfall diffusers circa 1980, the sole intended purpose was to prevent the intrusion of sediment and salt water into the outfall pipe. With continuous hydraulic testing, modeling and research and development, other significant practical, physical, and hydraulic benefits of DBNs, such as enhanced initial dilution, improved salt water purging, and uniform flow distribution among ports have been discovered and presented in Lee (1997), Duer (2000), and Duer (2002).

Presented herein are physical and hydraulic characteristics of DBNs that may not be well known to outfall designers and modelers currently and therefore will improve their design and analysis efforts. A detailed discussion on the construction and fabrication of DBNs is presented to illustrate the large number of hydraulic variations achievable per nominal size. Guidance on sizing and mixing zone modeling of DBNs is provided. Specification criteria and guidance are presented that can be used by outfall designers to evaluate DBN manufacturers as there is currently no international standard governing the design and construction of DBNs.

Keywords: Duckbill Nozzle, Variable Orifice, Jet Velocity, Backflow, Outfall, Diffuser, Dilution

1 PHYSICAL CHARACTERISTICS OF ELASTOMERIC DUCKBILL NOZZLES

1.1 *History and Evolution of Duckbill Valves*

The first duckbill valves (DBV) were manufactured in the late 1970's in relatively small sizes, under 250mm, were typically used for inline pumped applications, and were manufactured with unique "bill" geometries (with triple and quadruple "lobes" or "bills"). Hydraulic and backpressure testing was limited and the valves were prone to leakage due to them being structurally unstable. It was not until a 1983 United States EPA-funded project entitled "Development and Evaluation of a Rubber 'Duck Bill' Tide Gate" (Freeman et al., 1990) that extensive research and development, testing, and evaluation was conducted for over three years on a 1350mm (54") duckbill valve having the conventional geometry as shown in Figure 1. The valve was installed on a combined sewer overflow (CSO) and it was compared to the performance of a conventional hinged flap gate valve. The monitoring showed the duckbill did not require maintenance as there were no mechanical parts, had a low cracking pressure and ability to discharge large flow rates, improved performance in preventing backflow, and much greater performance in being able to "self-clean" and purge entrapped debris. These physical and hydraulic characteristics were especially advantageous to single-point and multiport outfall diffusers given the effluent can contain large solids and they are very susceptible to saline and sediment intrusion. That EPA research spurred continuous R&D and testing and duckbill valves are now commercially available in sizes 12mm – 3,000 mm (0.5" – 120") of varying geometries, physical construction, and mounting styles.

1.2 *Operating Principle*

Figure 1 shows the geometry and operating principle of a conventional elastomeric duckbill valve. The valve transitions from a cylindrical shape (the cuff), thru a transitional flaring section (the saddle), to a planar bill or "duckbill". The cuff portion slides onto a pipe and gets clamped, or it can be flanged. The valve operates solely on differential pressure.

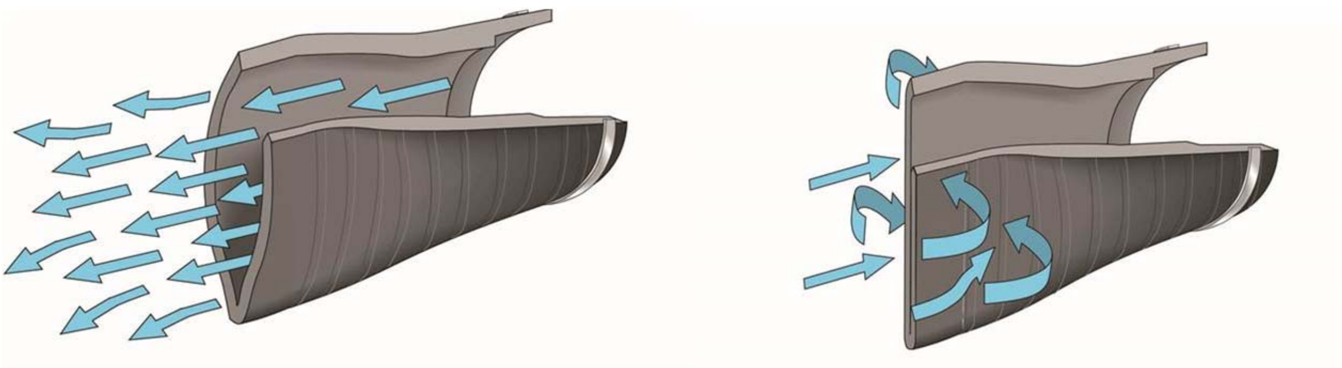

Figure 1 - Duckbill valve and duckbill nozzle operating principle

Positive/forward differential pressure results in a progressive linear increase in flow with linear increase in head, and zero or negative/reverse differential pressure closes and seals the valve preventing backflow. The valve has no mechanical parts, such as pins and hinges, so periodic maintenance is not required making it well suited for outfalls that are typically difficult to access and inspect. It is application-specific but the typical life for DBVs that are properly sized and designed is over 25 years.

1.3 *Duckbill valve (DBV) and Duckbill nozzle (DBN)*

The difference between a duckbill valve (DBV) and duckbill nozzle (DBN) is a DBV is installed on a single outfall pipe and is designed to withstand the maximum backpressure and generate the lowest possible headloss. Typical applications for DBVs are storm water and CSO outfalls where a minimum initial dilution does not need to be achieved within a specified mixing zone. Therefore, the other hydraulic characteristics of the DBV do not need to be modeled nor optimized. DBNs have the same operating principle as DBVs (Figure 1) but the geometry and relative stiffness are tightly controlled to produce precise hydraulic characteristics of effective diameter, open area, jet velocity, and headloss throughout the range of flows in order to achieve the required initial dilution. Rarely are the geometry and stiffness of DBN designed for an outfall diffuser application the same geometry and stiffness as a DBV for the same size and backpressure condition.

1.4 *Geometry and Relative Stiffness*

As a result of the relatively simple appearance of the DBN from the exterior, a common misconception in the industry is that all duckbill nozzles of the same nominal size have the same hydraulic characteristics and the long term ability to repeatedly operate as designed over many years of service. Indiscriminate use of DBVs have caused operational issues with outfalls having significantly reduced hydraulic capacity due to higher headloss than expected, by orders of magnitude not percent, or reduced initial dilution due to lower than predicted jet velocity. And there are outfalls that have experienced significant sediment intrusion in the header pipe due to the duckbill nozzles inability to close and seal over years of operational service.

There are four primary factors that influence the hydraulics and life of duckbill nozzles: 1) the geometry from the cuff thru the bill, 2) the relative stiffness produced by the composite laminate structure of various natural and synthetic rubber and fabric materials thru the wall thickness, 3) the strategic reinforcement or relief of specific areas thru the rubber matrix, and 4) the curing and vulcanization procedures and processes.

Figure 2 shows some of the geometry and relative stiffness combinations possible with duckbill nozzles. The DBNs in the photos are all nominal 100mm. The geometry varies from the bill not flaring at all to the bill flaring out to several times the nominal diameter. There are, in theory, an unlimited number of geometry and stiffness variations but there are typically 50 per nominal size with the extremes having a headloss difference of a factor over 50. Each one of the variations will have its own hydraulic characteristic and backpressure rating. Experienced DBN manufacturers can custom design and fabricate DBNs to achieve established target headloss or jet velocity criteria.

Figure 2 – Some of the geometry (left) and relative stiffness (right) variations of duckbill nozzles

Figure 3 is a cross section thru the wall thickness of one of the fifty available DBN’s showing the degrees of freedom with materials used in fabrication. There are several variables that yield the dedicated composite structure with its own unique hydraulic characteristic which are: 1) the various hyperelastic natural and synthetic elastomers used and their unique physical properties (durometer, elongation, resilience, compression set, etc.), 2) the various types of orthotropic fabric reinforcement and their physical properties, 3) the order in which the natural and/or synthetic materials are placed thru the wall thickness, and 4) the strategic reinforcement or relief of specific areas thru the lateral and longitudinal cross section of the nozzle.

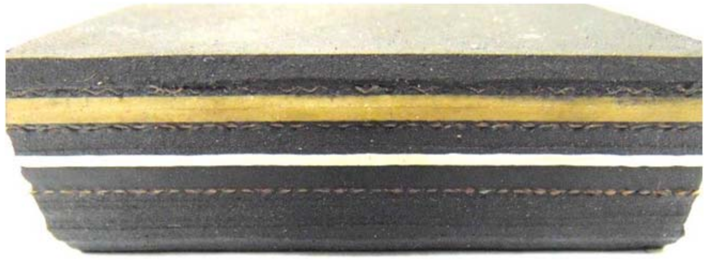

Figure 3 - Cross-section thru wall thickness of a duckbill nozzle

Conventional-geometry DBNs were commonly used until the early 2000's. The height of the bill is 40-60% larger in dimension than the nominal pipe diameter depending on manufacturer. The leftmost DBN shown in Figure 2 is a newer development in DBN technology, circa 2000. It is a "Wide Bill" DBN that required the design of unique fabrication equipment as the equipment and methods used to fabricate conventional DBNs could not be used to fabricate the Wide-Bill DBNs. Wide Bill DBNs open up to and beyond the nominal pipe diameter at peak flow which is discussed in Section 2.

1.4.1 *Strategic Reinforcement*

It is a misconception that duckbill nozzles are molded from one rubber compound, with no fabric reinforcement, and with a consistent wall thickness throughout. Or if it is realized they are hand-fabricated of a laminated composite construction, that it is one consistent wall thickness comprised of uniform circumferential wraps. However, DBNs experience large stress, strain, and deflection variations throughout the cross section during flowing and reverse differential (backpressure) conditions. There are areas of the DBN that require extra reinforcement in order to structurally support it, similar to reinforcing "doubler" plates or "repads" in steel weldments, and other areas that cannot be heavily reinforced as it will negatively affect the hydraulics and the ability of the nozzle to open and close over a long-term operation. What presents a significant challenge is the stress, strain and deflection characteristics vary greatly depending on flow rate and on whether the DBN is submerged or discharging to atmosphere. Atmospheric discharges are challenging as the DBN not only has to withstand the weight of the nozzle but also of the water in it which can be many times greater. Similarly, applications where the DBN can be submerged, but with atmospheric upstream pressure, have unique considerations given introduction of positive buoyancy effects. Finite Element Analysis (FEA) is an invaluable tool to analyze the deflection and stress/strain characteristics given the wide range of operating conditions and the analyses are used to properly design and reinforce the DBNs.

1.4.2 *Vulcanization Process*

Given the variations in physical dimensions per nominal size, DBNs are typically not shrouded in a mold and vulcanized like vehicle tires. DBNs are fabricated with the use of a metal mandrel in which the individual layers of rubber and fabric are placed until the raw rubber matrix is complete. Custom tools, chemicals, adhesives, and release agents are used throughout the building process to ensure the layers are chemically bonded to form a unibody construction after vulcanization. For vulcanization, the entire assembly of raw materials is wrapped in a synthetic material that shrinks and provides compression at the higher pressure and temperature in the autoclave to ensure all layers are chemically bonded. Custom curing plates are also mechanically fastened to the mandrel and DBN that ensures the entire surface area is under compression in order to be fully vulcanized. This process needs to be tightly controlled because if the tension in the compression wrap material or compression in the curing plates is not to specification, the DBN stiffness and hydraulics can vary considerably, even between identically-constructed DBNs.

1.5 *Backpressure Rating*

For a given size of duckbill nozzle, the type, amount, layering, and reinforcement of materials, as discussed in 1.3, yield a duckbill nozzle with a specific backpressure rating. When a DBN experiences backpressure, reverse differential pressure, the saddle progressively deflects inward as the backpressure increases. This is normal and there are no deleterious effects. However, there is a specific backpressure at which the DBN will invert, or turn inside out, and it is no longer effective at preventing backflow. It is difficult, but sometimes possible, to "re-invert" the DBN to its normal position by increasing the flow rate. But, if the backpressure rating is once again exceeded, the DBN will invert. It is critical that any duckbill manufacturer perform extensive backpressure testing to establish backpressure ratings with an appropriate safety factor.

1.6 *Mounting Configurations*

Duckbill Nozzles can be fastened to riser pipes by slip-on and clamped or flanged methods. For slip-on applications, the DBN is manufactured to be a press-fit onto the pipe outside diameter. Clamps of stainless steel or higher grade alloys are supplied to provide compression from the DBN to the pipe and the friction fit provides the seal and restrains it. Given the difficulty of access and severe operating conditions common to multiport diffusers, slip-on and clamped DBNs should be pinned to the pipe with non-corrosive fasteners, especially when the pipe material is smooth such as PVC, MDPE, HDPE and GRP. Worm-drive hose clamps/clips are standard for many manufacturers for sizes under 300mm but these should never be used for outfall diffusers. Fabricated clamps with pre-drilled holes in the band are suggested as they are robust and can be used for pinning. Duckbill Nozzle manufacturers can be consulted for pinning options based on DBN size, style, and riser pipe material.

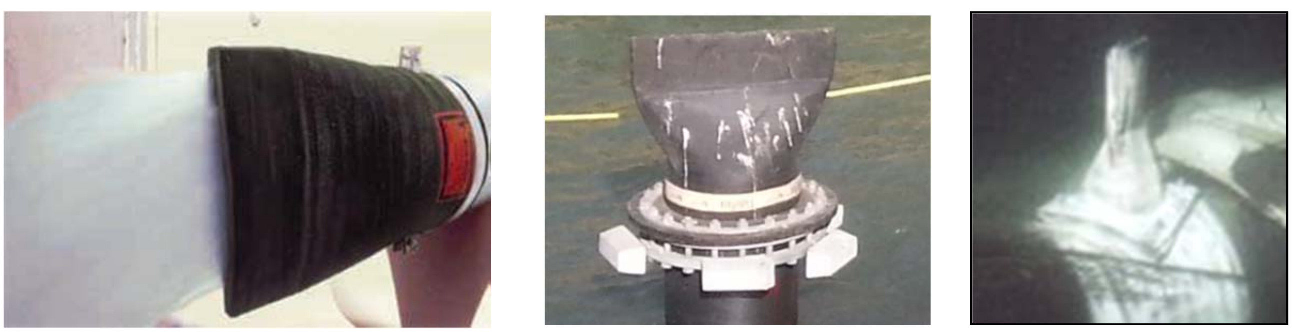

Figure 4 – Slip-on, circular flanged, and square flanged (courtesy Ivo Van Bastelaere, P.Eng) duckbill nozzles

Flanged connection methods are numerous including circular with any standard flange drilling (ANSI, DIN, etc.), square flanged, and custom flange geometry. DBNs are supplied with plastic, stainless, or higher grade alloy retaining rings that compress the rubber flange to the mating flange to restrain and form a seal. Flanged connections are more secure and recommended over slip-on DBNs for outfall diffusers. For diffuser header pipes with wall ports cast or drilled into the sidewall, 4-hole square-flanged DBNs and the retaining rings can be manufactured with the radius of the pipe O.D. so they can be anchored directly to the outside of the pipe. DBN manufacturers can be consulted for alternative fastening methods. Caution if anchoring to the O.D. of a pipe using stud-type anchors, they should not be pre-installed in all four holes as the square-flanged DBN will not be able to be placed over the end of the studs due the varying radial chord length.

1.7 *Wire-Reinforced Rubber Risers and Elbows*

Many multiport diffuser header pipes are buried in the seabed or riverbed with flow discharging thru riser pipes that protrude above the bottom. These riser pipes are prone to shearing from impact loads from dragging anchors or fishing equipment (Grace 1997). Inland outfalls in rivers and streams also get exposed to submerged debris, such as tree branches, moving with the current. If a riser pipe shears below the sediment layer, significant intrusion occurs that can drastically reduce the hydraulic capacity of the outfall and compromise the initial dilution. Restoration costs can be high especially if the sediments become toxic as they may need treatment before disposal (Grace 1997).

DBNs can be manufactured integrally with wire-reinforced rubber fittings, usually elbows and risers or a combination thereof. The wire-reinforced rubber fittings are able to deflect and return when exposed to impact loads thereby preserving the structural and operational integrity of the outfall. Figure 5 shows several custom fabricated DBNs with integral rubber fittings. The entire header pipe and risers are buried up to and including the DBN mating flange. The only material protruding above the riverbed is flexible wire-reinforced rubber.

Figure 5 – Duckbill nozzles with integral wire-reinforced rubber elbows, risers, and 4-port rosette

1.8 *Shallow Receiving Waters*

Many inland diffusers are installed in shallow streams and rivers, some even becoming dry at certain times of the year. For those applications with limited water depth, DBNs with the bill oriented horizontally (left image in Figure 5) allow the discharge to be located as close to the riverbed as possible without concern for backflow. The horizontal elliptically-shaped jet also has dilution advantageous by delaying the jet interaction with the surface and riverbed. The DBNs need to be specially reinforced in order for the bill to be oriented horizontally. Field observations have shown that DBNs have exhibited the ability to scour sediment maintaining their ability to discharge should the sediment layer overtop the DBNs.

1.9 *Marine Fouling*

The relatively soft material and continual flexing of the DBNs makes them less susceptible to severe barnacle and zebra mussel fouling. They can become partially or completely covered in marine growth but it tends to be soft. In 2002, DBNs were removed from an outfall in Australia and hydraulic tests were conducted on two identical 100mm DBNs, one covered in marine growth and one with the marine growth removed. The testing confirmed three was no difference in hydraulics between the two.

2 HYDRAULIC CHARACTERISTICS

2.1 *Variable Orifice*

Figure 6 illustrates the hydraulic characteristics of just one size, geometry, and relative stiffness of variable orifice DBN and is compared to a fixed diameter port. A DBN's headloss is a linear function of flow, and the jet velocity and effective open area are non-linear.

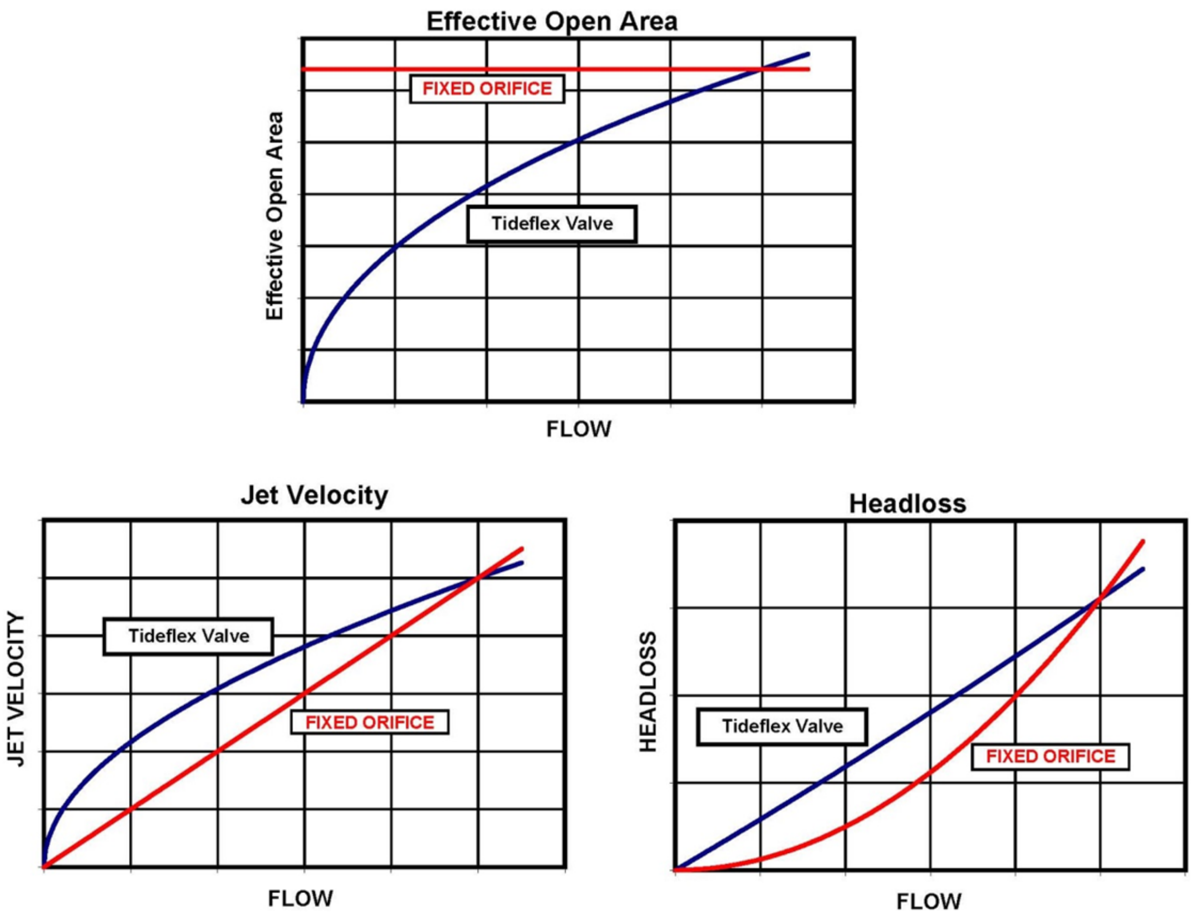

Figure 6 - Hydraulic comparison of one geometry/stiffness DBN to fixed diameter port

Fixed diameter ports have headloss that is a function of the square, doubling the flow results in quadrupling of the headloss, and a linear jet velocity profile. The primary advantages of the variable orifice DBN as it relates to multiport diffuser design are: 1) they maximize jet velocity at all flow rates which maximizes momentum flux and initial dilution and 2) they minimize headloss at peak flow when a minimum required jet velocity is required at low flow (such as when a regulatory agency requires a minimum jet velocity when discharging toxic substances), and 3) they are inherently "self-regulating" resulting in a more even flow distribution compared to fixed diameter ports.

As discussed in Section 1.4, there are over 50 possible hydraulic variations of DBNs available per nominal size. Each variation also has a definitive backpressure rating. The best practice is for the outfall designer to provide the flow range and target jet velocity or headloss criteria, then the DBN manufacturer provide detailed hydraulic analyses that specify the quantity, size, geometry, and relative stiffness of DBNs that achieve the hydraulic goals. Extensive independent hydraulic testing needs to be conducted by the DBN manufacturer on numerous sizes, geometries and relative stiffness DBNs, and comprehensive regression analysis is needed to accurately model and publish the hydraulic characteristics used in hydraulic design and dilution modeling of outfall diffusers.

2.2 *Wide-Bill DBN Hydraulics*

Conventional-geometry DBNs can only open between 50-85% of nominal pipe diameter at peak flow depending on the stiffness and backpressure rating. In the past, this required the DBNs to be oversized in order to have the same headloss as the fixed diameter port at peak flow to prevent the reduction in outfall flow capacity. For example, 200mm DBNs were utilized on 100mm ports in order to have a 100mm effective diameter at peak flow. This resulted in challenges in the physical design of the risers, the risers being prone to snag debris and boat anchors and nets, and was especially challenging when retrofitting existing outfalls. Wide-Bill DBN (WBDBN) open up to and beyond the nominal pipe diameter at peak flow so the same nominal size WBDBN can be fitted to the ports without a reduction in hydraulic capacity. In fact, at peak flow the net headloss of the port with the WBDBN fitted is actually less than the headloss of the fixed diameter port itself. The reason is the WBDBN effective diameter is greater than the port and the transition to the larger diameter thru the length of the WBDBN is gradual with negligible headloss. As a result, the WBDBN acts as a recovery cone for the velocity head and the resulting net headloss with the WBDBN installed is lower than without it installed.

2.3 *Dense Jets and Brine Discharges*

The jets from outfalls discharging wastewater with a density greater than the receiving water body, such as brine from desalination plants (Figure 7) and gypsum waste from fertilizer plants, are negatively

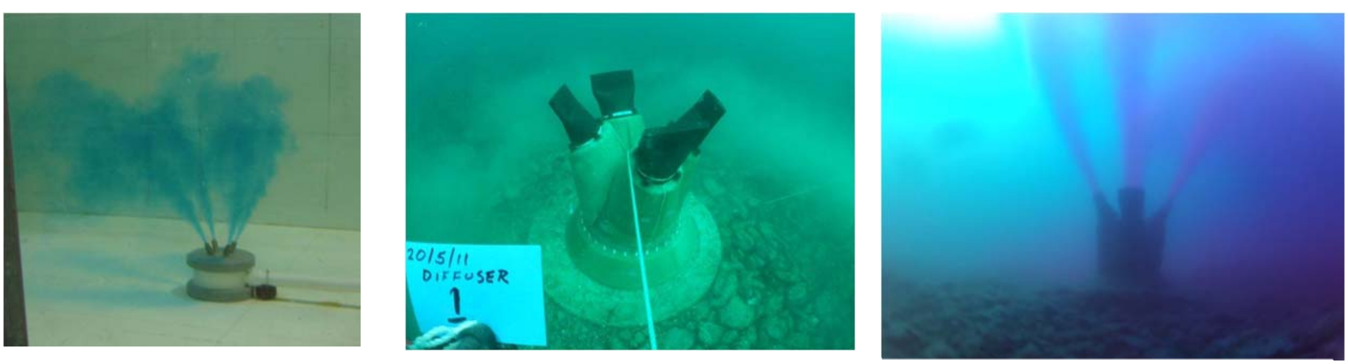

Figure 7 – Dilution scale modeling, (4) 250mm Tideflex nozzles, in-situ tracer study
Adelaide Desalination Outfall, Australia (courtesy Adelaide Aqua)

buoyant and discharge at an inclined angle to maximize the jet trajectory thereby maximizing dilution. The jet initially discharges at an inclined angle, reaches a terminal rise height, then falls back to the seabed where it spreads as a density current. Most regulatory agencies establish a criterion of a minimum dilution when the jet impacts the seabed. DBNs are commonly used on outfalls with dense jets, even when backflow prevention is not needed, as the variable orifice maximizes jet velocity at all flow rates which maximizes the jet trajectory and dilution. This has the potential to save significant cost if it prevents the need for additional treatment processes at the plant (Ayala 2014).

3 GUIDANCE FOR DESIGNERS IMPLEMENTING DUCKBILL NOZZLES

3.1 *Sizing of Duckbill Nozzles*

The quantity, nominal size, geometry, and relative stiffness of DBNs can all be iterated to provide a multiport diffuser design that will achieve the required jet velocity and headloss. Given the size variation and 50+ possible hydraulic variations per size, outfall designers should contact qualified DBN manufacturers to size and provide hydraulic analyses of the DBNs based on the criteria. At a minimum, the hydraulic analyses should provide the headloss, jet velocity, and effective diameter at all flows of interest.

3.2 *Determining the Maximum Backpressure*

Outfall designers should determine the maximum backpressure in which the DBNs will be exposed taking into account waves, currents, tides, and hydraulics transients due to pump start and stop. Realize just because the DBNs are submerged in 30 meters of water, for example, that rarely results in a maximum backpressure of 30 meters. The outfall pipe would have to be at atmospheric pressure for the DBNs to be exposed to 30 meters backpressure which is rare given the construction techniques of outfalls (Roberts 2010). The maximum backpressure is usually much less than the depth of the receiving waterbody and is commonly just the maximum rise in tide (including wave height) or river level if flow from the effluent source is halted.

3.3 *Mixing Zone Modeling*

In order to accurately predict dilution of duckbill-fitted diffusers using Computational Fluid Dynamics (CFD) or commercially available mixing zone modeling software such as CORMIX, Visual Plumes, and VISJET, the effective diameter of the DBNs must be used at each flow rate. Although it would be conservative, it would be incorrect to use a DBN effective diameter of 150mm, for example, at all flow rates when that effective diameter is only applicable at the peak flow.

3.4 *Elliptically-Shaped Jet*

Duckbill Nozzles discharge an elliptically-shaped jet which independent scale modeling has shown results in faster initial dilution (Lee 1997). The reason is that ambient water can reach the centerline of the jet faster than a hydraulically equivalent circular jet. While this may be of less importance with deep marine outfalls whose dilution is dominated by buoyancy flux, it can especially be advantageous in shallow inland discharges to rivers, streams, and lakes. None of the commercially available mixing zone modeling software accounts for the enhanced improvement in dilution, so the predicted dilutions can be considered conservative when DBNs are installed. Computational Fluid Dynamics (CFD) does have the potential to capture the effect of the elliptical jet but would rely heavily on mesh density, turbulence model, relaxation criteria, etc.

3.5 *Configurations and Mounting Styles and Methods*

A qualified DBN manufacturer should be consulted on the available mounting styles, configurations, materials, and installation procedures. Even small issues could be overlooked. For example, HDPE flange adapters do not have full-faced flanges. They are raised face and with certain size DBNs, a reinforcing ring is recommended to be installed between the rubber flange and face of the HDPE flange adapter. Other project-specific topics include the capability to clamp the bill of the DBNs closed for a float and sink operation, and the use of breakaway flanges or fasteners.

4 SPECIFICATION GUIDANCE FOR DUCKBILL NOZZLES

The number of duckbill valve manufacturers has increased in recent years and there are varying degrees of elastomer knowledge and manufacturing experience, amount of independent hydraulic testing and modeling, long-term performance validation, etc. Considering the discussion in Sections 1.4 and 1.5 on DBN construction, it is erroneous to consider one manufacturer's duckbill nozzle to have the same hydraulics as another even when the same size and operating conditions are specified. The associated risks of having DBNs that do not meet performance expectations are the outfall has reduced hydraulic capacity, does not meet the required dilution, and the DBNs fail to prevent backflow. Replacement of failing DBNs is time consuming and expensive.

Until an international standard is established governing the design and construction of duckbill nozzles, the following specification guidance can be considered by the designer, owner, and contractor as a method to vet DBN manufacturers and to achieve a satisfactory level of confidence in the supplied hydraulic data and performance claims.

4.1 *Verification of Independent Hydraulic Testing*

Independent hydraulic tests shall have been conducted on a sufficient number, including size, geometry, and stiffness variations, of DBNs as determined acceptable by the engineer or owner. Testing shall include at least one stiffness variation of the same size DBN for the specific project. Or, testing shall have been conducted on smaller and larger DBNs. If the project-specific DBN is larger than 1350mm, testing shall have been conducted on at least one 1200mm DBN.

4.2 *Verification of Independent Testing for Manufacturing Consistency*

Independent hydraulic testing shall have been conducted verifying that a minimum of four DBNs of the same size and stiffness were tested consecutively to prove the repeatability and consistency of the manufacturing process by confirming the headloss was within a +/- 10% variance from target.

4.3 *Finite Element Analysis*

Finite Element Analysis (FEA) shall have been conducted to analyze the stress, strain, and deflection characteristic of DBNs for flowing and backpressure conditions.

4.4 *Backpressure Testing*

Backpressure testing of DBNs for at least the same size and stiffness DBN for the specific project shall have been conducted.

4.5 *Experience*

DBN manufacturers should have a sufficient number of years of experience in fabrication of similar size and style DBNs as determined acceptable by the engineer or owner.

4.6 *Project References*

DBN manufacturers shall submit numerous references for DBN installations that have been in service for a minimum of 5 years and have been tested or inspected at least once to confirm long-term satisfactory operation. DBNs shall be of similar size and style.

4.7 *Quality Control Documentation*

DBN manufacturers shall have a comprehensive quality control program covering processes from receipt of raw material, thru the fabrication, vulcanization, and finishing processes of DBNs.

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