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Physical Modelling to Minimise Air Entrainment Over an Industrial Weir and into a Discharge Pipeline

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Abstract: *Physical modelling was used to simulate cooling water flow entering a chamber over an industrial weir and exiting through long discharge pipelines. The weir was required to maintain a backwater for condensers, but also resulted in significant aeration of the flow. The objectives were to minimise the air entrained to the discharge pipeline and to ensure de-aeration of any air within the pipeline was fully effective. Physical modelling was selected as the most reliable means of investigation as the complex air entrainment and free surface interactions would require highly complex CFD numerical modelling, with limited confidence in the results. The physical modelling study concentrated on flow patterns, air entrainment and the amount of air released within the chamber, discharge pipes and air release structures. A suite of flow and entrainment characterisations by dimensionless numbers have been assembled from the literature and used to scale the model of this complex system. The study highlights the need for careful consideration of geometry to minimise aeration and how relatively simple changes to flow asymmetry can reduce the air entrainment. The solution is relevant to other entrainment problems.*

Keywords: *Physical Modelling, Aeration, De-aeration, Weir*

1. INTRODUCTION

The Water Research Laboratory (WRL) of the University of New South Wales undertook physical modelling of the discharge components of the saltwater cooling system in the proposed Port Kembla Steelworks cogeneration plant. The cogeneration plant proposed to use salt water from the nearby harbour for turbine condenser cooling. The cooling water discharge from the condensers would enter a chamber, where it would flow over a weir and exit through dual outlet concrete pipes. The weir was required to maintain a minimum back-pressure onto the condensers. The pipes would convey the cooling water approximately 800m to a discharge structure in the tidal harbor which varied the tailwater conditions.

Air entrainment and air pockets within the pipeline would have serious negative impacts on system operation, which was expected at certain flow rates and tidal conditions. Hence the study objectives were to minimize air entrainment from the plunging jet over the weir and maximise the performance of de-aeration, air release structures. Opportunities for changes in the prototype design were limited due to space. Physical modelling was selected as the most reliable means of investigation as the complex air entrainment and free surface interactions would require highly complex CFD numerical modelling, with limited confidence in the results. The physical modelling study concentrated on flow patterns, air entrainment and the amount of air released within the chamber, discharge pipes and air release structures. The results are specific to this particular study, but the solution is relevant to other entrainment problems.

1.1. The Original Chamber Design

The flow within the chamber was the primary focus of the investigation. A design was required that would maintain back-pressure on the upstream condensers while avoiding the negative impacts of air entrainment to the discharge pipeline. The originally chamber design is shown in Figure 1. The available space for the chamber was approximately 10m x 6m and 9m deep. The inflow pipelines were oriented vertically into a benched chamber behind the weir. The weir was a trapezoidal layout around the inlet pipes with the intention to maximise the weir length. The invert of the discharge pipelines were located approximately 3.5m below the weir height and water level downstream of the weir was influenced by the backwater of the harbour tides. The obvious solution to minimise air entrainment to the discharge pipes would be increasing the area downstream of the weir or lowering the elevation of the pipes. However these solutions were not possible within the available space of the existing industrial site.

Dual outlet pipes of 1530 mm ID conveyed discharge from the chamber with a very flat slope of 0.2%. Pipe A exited perpendicular to the chamber whereas Pipe B exited at an 85^o angle. At a location approximately 33m downstream, the pipes turned by 121 and 117 degrees respectively before travelling parallel to each other for the remaining 800m to the harbour. This layout is presented in Figure 2 (noting that the physical model did not represent the 800m to the harbour but rather had a tail-water box approximately 25m downstream of the bend). At the bend in the pipes, vertical air release structures were included. These vertical stand pipes were the same diameter as the main pipes and located in the mid-point of the bend. Placing these air releases on a bend was not hydraulically optimal, but was the preferred location within the existing industrial site. Further they could be cast into the thrust block to be located on the bend.

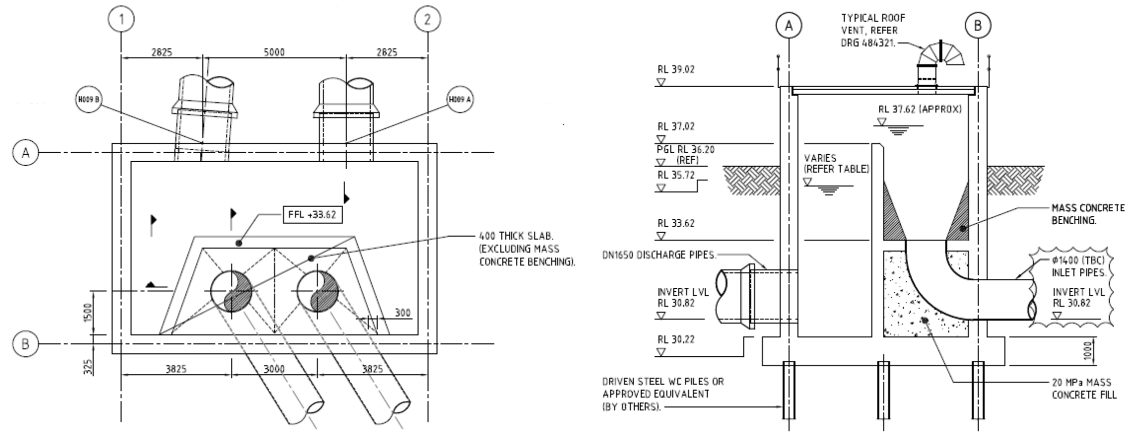

Figure 1 – Original Design of Weir Chamber

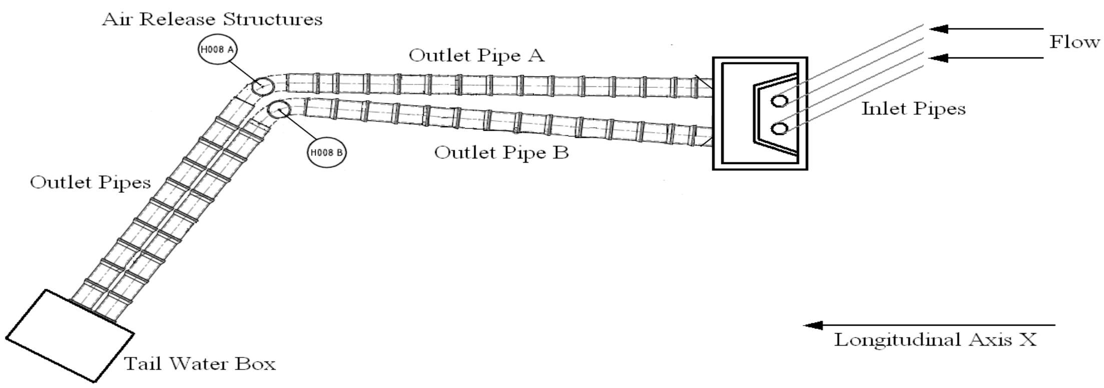

Figure 2 – Layout of the Components Investigated showing Chamber, Pipelines and Air Release Structures.

1.2. Flow Rates and Tidal Ranges

The design cooling water flow was 33,000 m^3/hour (9.16m^3/s). Investigations were undertaken at 60%, 100% and 120% of the design discharge to represent the range of flows expected during operation.

The tidal range in the harbour was 1.8m and tail-water conditions considered low and high tides. These tidal levels were dampened and elevated by the pipe friction over the 800m to the harbour. The tail-water levels applied at the model tail-water box were between 1.6m and 3.3m above the pipe invert depending on the flow rate and tide.

2. PHYSICAL MODELLING

2.1. Model Scaling

Flows in the model were scaled according to the Froudian similitude criterion. This essentially requires that the ratio of inertia forces to gravity forces be the same in model and prototype, knowing that the model was subject to the same gravitational field that prevails at full prototype scale. The Froude number similarity prescribes that the Froude number at full prototype scale is equal to the Froude number at model scale. Hence the relationships in length (d), velocity (V) and discharge (Q) are between the model (m) and the prototype (p) are:

$$L_R = \frac{d_p}{d_m} \qquad V_m = \frac{V_p}{L_R^{1/2}} \qquad Q_m = \frac{Q_p}{L_R^{5/2}}$$

Turbulence is quantified by the Reynolds number while surface tension is quantified by the Weber number. While these numbers in the model will be smaller than those in the prototype, the model will adequately reproduce the prototype conditions provided these numbers meet certain criteria. Hence, the maximum acceptable scale ratio (L_R) was determined from several published guidelines as discussed below.

The fluid properties of concern are velocity, depths, density, kinematic viscosity and surface tension. Definitions of terms, along with the relevant guideline criteria are presented in Table 1.

The surface tension effects start to become important and cannot be neglected if the Weber number, W_e, is of order of 120 or less (Jain *et al.*, 1978).

Swirls and vortices at pipe inlets can be reproduced in scale physical modelling provided the viscous effects are minimised. The Reynolds number in the pipe based on velocity (R_e) and the Reynolds number based on flow discharge (R_d) should be higher than 30000 and 25000 respectively (Daggett et Keulegan, 1974). Further, the radial Reynolds number (R_r) representing the ratio of discharge to depth of submergence should be higher than 20000 (Anwar *et al.*, 1978). Finally, Jain *et al.* (1978) showed a minimum pipe diameter (d) required to ensure negligible viscous effects.

At a fundamental level, air entrainment is determined by an interaction of surface normal motions (turbulence or impacting flows) with free-surfaces and bubble buoyancy. Recently, Wu et al. (2012, Figure 2) reconciled microphysical characterisations of aerated flow (Brocchini and Peregrine, 2001) with conventional engineering approaches based on dimensional analysis of large-scale, fresh water test data (Kobus and Koschitzky, 1991). This lends further support to Kobus and Koschitzky's threshold Reynolds number (5×10^4) for air concentration independence of Froude scale (See also, Peirson and Cameron, 2006 and Peirson et al., 2008). To estimate an appropriate Reynolds number, the flow depth in the chamber was adopted as the known minimum tailwater (3m) and the velocity was assumed averaged across the chamber.

The above parameters were calculated for different flow rates and the worst conditions for model representation of the prototype air entrainment being the maximum submergence h_m = 5 m (prototype). The model scale was adopted as 1:10.93, being hydraulically acceptable and ensuring internal diameter of the discharge pipes would match a standard diameter of available clear acrylic tubing at model scale, (i.e.1530 mm internal diameter of the prototype scaled to an available 140 mm internal diameter acrylic section).

Values for this model scale are presented in Table 1. The guideline values for swirls and vortices were all met except the radial Reynolds number at 60% of the design flow rate. With either lower depths of submergence or with greater flow rates the criteria was met, however model results from the lower flow rates should be considered with caution. The guideline values for air entrained due to the plunging jet were not met. As such, it is acknowledged that the model cannot provide exact quantification of the air volumes, but can be relied upon for an accurate representation of the air/water flow behavior. Meeting the air entrainment criteria would require a model almost twice the size, which was not possible with budget and timeframe limitations.

The model used fresh water at approximately 20^{o}C, whereas the prototype cooling water was saline at approximately 40^{o}C. The values presented in Table 1 were calculated with the density, surface tension and kinematic viscosity of fresh water. These were compared to values if hot, salt water had been used. As the values all remained above the guideline values (where scaling effects were assumed to have been minimised), it was acceptable to use fresh water.

Table 1 – Swirl and Vortices Scaling Guidelines and Values for the 1:10.93 Scale Model

Scale Numbers	Value for Different Flow-rates Percentage of Design Flow			Guideline	Reference
	60 %	100 %	120 %		
Weber Number $W_e = \frac{\rho.d.V^2}{\sigma}$	390	1,090	1,580	> 120	Jain *et al.* (1978)
Reynolds Number in Pipe $R_e = \frac{V.d}{\nu}$	63,300	105,600	126,700	> 30,000	Daggett et Keulegan (1974)
Reynolds Number Based on Flow Discharge in Pipe $R_d = \frac{Q}{\nu.d}$	49,800	82,900	99,500	> 25,000	Daggett et Keulegan (1974)
Radial Reynolds Number at Pipe approach $R_r = \frac{Q}{\nu.h}$	15,200	25,400	30,400	> 20,000	Anwar *et al.* (1978)
$\frac{g^{1/2}d^{3/2}}{\nu}$	164,000	164,000	164,000	> 50,000	Jain *et al.* (1978)
Reynolds Number (for plunging air entraiment) $R_e = \frac{V.d}{\nu}$	14,300	23,900	28,600	>50,000	Kobus and Koschitzky, (1991)

2.2. Construction and Instrumentation

The physical model comprised the inlet pipes entering the weir chamber, the chamber, the outlet pipes exiting the chamber, the air release structures and a tail-water box maintaining downstream head levels (Figure 3). Water was supplied from a constant head tank, controlled by a valve on each inlet pipeline and measured by electromagnetic flow meters. The twin inlet pipes entered vertically into the chamber. The chamber components were constructed accurately according to the prototype dimensions, respecting the geometrical scale exactly. The chamber was 916 mm wide, 548 mm long and 805 mm high. The internal features of the chamber comprised two vertical expander cones located at the exit of the twin inlet pipes allowing for water to overflow a trapezoidal-shaped weir, 622 mm high and 36 mm thick. All the panels and internal features of the chamber were built in 19 mm thick marine Plywood panels except the two side walls which were made of 15 mm thick clear acrylic Perspex panels. This improved inspection through the water column and allowed photo/video recordings of flow patterns and air entrainment within the chamber.

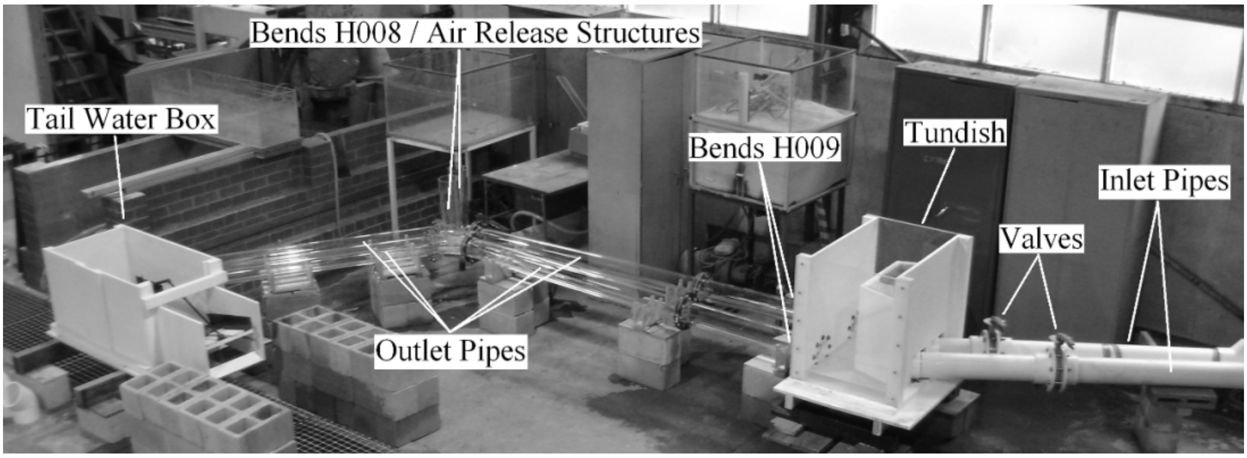

Figure 3 - Photograph of Model Overview

The twin outlet pipes, the twin curved pipes forming the bends and the two air release structures were made of 140 mm internal diameter clear acrylic Perspex tubing allowing photo/video recordings of air entrainment within the straight pipes, the bends and the air release structures. Each bend was made of six identical wedges glued together. At the top of each bend, the air release structure was added through the horizontal outlet pipes and glued as a single vertical pipe of internal diameter 140 mm and 547 mm high. All the constituents were glued as appropriate ensuring no internal hydraulics effects.

The twin outlet pipes discharged into a tail-water box built in 19 mm thick marine Plywood panels, with an adjustable weir modifying the backwater levels. The backwater levels applied at the tail-water box were calculated using straightforward pipe hydraulics from the levels in the harbor with expected pipeline friction under both clean and marine fouled conditions. At model scale the tail-water was between 100 mm and 210 mm above the pipe invert depending on the conditions.

A reducer was installed on top of the air release structures to connect a calibrated TSI Air Velocity Meter Model 8347 VelociCalc (a bulb instrument). Air velocities (and calculated air flow rates) were measured with a determined accuracy of 3% within the range of 0 to 30 m/s. All air flow rates were averaged over 20 seconds.

3. RESULTS AND IMPROVEMENTS TO CHAMBER DESIGN

3.1. Flow Patterns and Air Entrainment for the Original Design

Scenarios were modeled for three different flow rates being 100%, 120% and 60% of the 33,000 m^3/h design flow, and for high and low tide levels which were applied at the tailwater box as levels between 1.18m and 2.29m above the invert of the chamber exit pipe (shown on Figure 1) depending on backwater calculations.

Visual observations of flow and air patterns within the chamber, outlet pipes and air release structures were made and photographic records taken. Inflow conditions behind the weir were observed to be highly unsteady, due to the high velocity of inflows, the vertical entrance pattern (via the vertically oriented expander cones) and the limited flow area behind the weir. Water then plunged over the trapezoidal weir into the chamber generating a strong agitation of the free surface and creating a large and strong horizontal swirl/eddy along the side walls. The large height of the weir, the small length of the chamber and the small flow area did not provide conditions for the dissipation of unsteady, high velocity flows. Turbulence and aeration within the chamber could be clearly observed with a high density of large air bubbles being maintained at the top of the water column and along the side walls.

Although the higher flow rates had greater energy and turbulence, they also corresponded with higher tail-water levels below the weir. The degree of air entrainment was observed to increase for lower water levels in the chamber. This was expected with a larger plunge of the weir overflow.

The flow within the chamber was not symmetrical for the larger flow conditions. The density of air bubbles in the right side of the chamber was higher than the density of air bubbles in the left side. This asymmetry was attributed to the oblique angle of the inlet pipes and led to more air being entrained in the outlet Pipe A than in the outlet Pipe B.

The flow patterns and air entrainment within the outlet pipes reflected conditions within the chamber. At the design flow, significantly less discharge was observed in pipe A than in pipe B. Pipe B was almost full of water, except the small upper part of the pipe just downstream of the chamber exit where some large air bubbles were entrained. Pipe A contained a very large air pocket, due to strong air entrainment from the chamber.

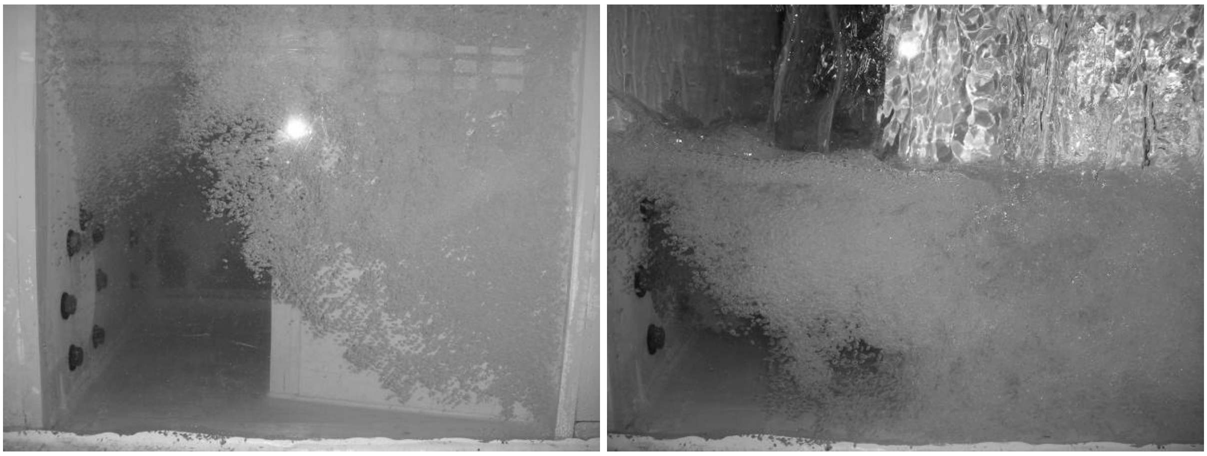

Figure 4 – Flow patterns in the Chamber. Left shows high flow rate, high tail-water. Right shows low flow rate, low tail-water.

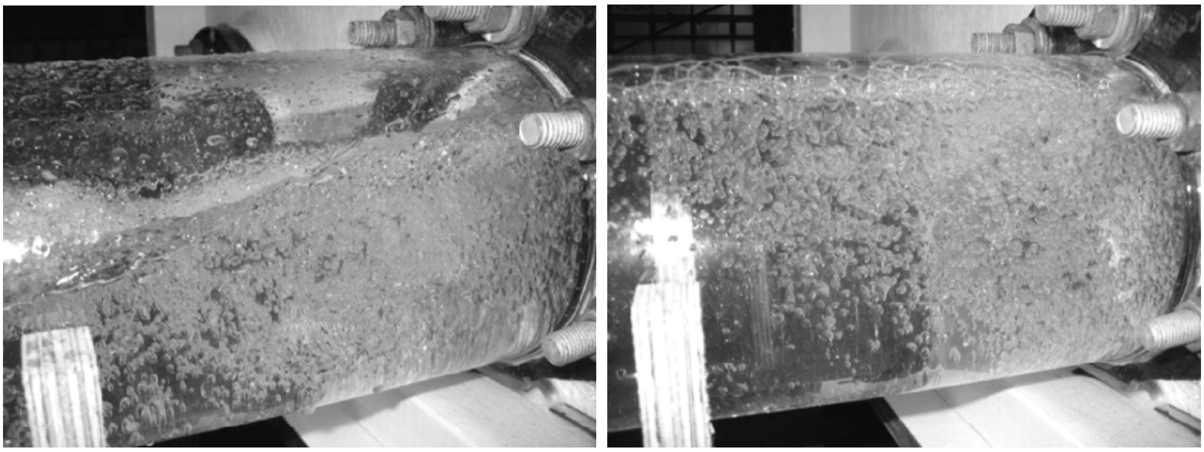

Figure 5 – Flow patterns in Exit Pipes. Left shows high flow rate, high tail-water. Right shows low flow rate, low tail-water.

Figure 6 – Flow in the Air Releases. Left shows high flow rate, high tail-water. Right shows low flow rate, low tail-water.

At the bends, a strong vortex was formed in the air release structures and most of the air was released. Downstream of the bends, remnant air was released unsteadily as bursts of small air bubbles, the frequency and quantity of bursts of bubbles being higher in Pipe A than in Pipe B.
Figure 4, Figure 5 and Figure 6 show photographs of the above described flows.

For conditions of 60 % of design flow, there was less asymmetry but the lower tail-water resulted in large air bubbles entrained within the outlet pipes. These bubbles surfaced to form large air pockets which were transported downstream as an unsteady flow. As the water level within the air release structures was very low, flows downstream of the bends behaved like an almost free surface flow and remnant air was conveyed downstream as unsteady bursts of large air pockets. The vortex within the air release structure was observed to be entraining as much air as it released.

3.2. Modifications to the Chamber

The length of the chamber was increased from 6m to 7m to maximise the volume of water below the weir and to provide slightly more time for bubbles to resurface after the plunging jet. This was the maximum available space.

To remove some more of the inflowing momentum the vertical expander cones were removed and the inlet pipes changed to enter horizontally into the chamber to remove some of the vertical momentum. This resulted in the inflows dissipating more energy against the back of the weir and a somewhat smoother water surface behind the weir.

The asymmetry in flow below the weir was reduced by replacing the trapezoidal-shaped weir with a straight wall which extended over the entire width of the chamber.

The crest of the weir was shaped with an ogee crest and the entrance to the exit pipes given a bellmouth shape to minimise any flow separation, however these last changes were not considered to have a major influence.

As often the case with engineering design, it was not the highest flowrate which created the most problem, but rather the particular combination of flow and tailwater. These modifications did not significantly change the conditions at the high flows when the tail-water was also high. However, the air entrained into the pipelines was significantly less for the design conditions and the 60% of design flows. This was quantified by the measurement of the air flowing from the air release structures. As no air was observed to flow past the air release structures, this was a direct measure of the air entrained. For the 100% and 60% of design flow conditions, the air entrained into the pipe after these relatively simple chamber modifications, was approximately half that of the original chamber.

4. CONCLUSIONS

Physical modeling with correct scaling provides a valuable tool for the assessment of hydraulic problems involving air entrainment. The study highlights the need for careful consideration of geometry to minimise aeration and how relatively simple changes to flow asymmetry can reduce the air entrainment, in this case by approximately half. Physical modelling is of particular advantage in industrial areas were space is limited and chamber design must be optimized within tight constraints.

The characterisation of flow and entrainment by conventional dimensionless parameters changes with position throughout any real physical system. A suite of characterisations have been assembled from the literature and used to design the model of this complex system. All indicate that the model performance was robust although there is some suggestion that the amount of air entrainment at the incoming jet may be slightly underestimated. It is recommended that future work investigate a better understanding of air entrainment/release in the context of assembled knowledge.

5. ACKNOWLEDGMENTS

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