AIR-ACTUATED PUMPING TECHNOLOGY IN URBAN DRAINAGE

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ABSTRACT

Airlift Pump technology is briefly summarized and the potential application of airlift technology to low-lift, low-submergence, high-flow applications such as open channel flow in urban storm drainage, is explored. Four experimental setups are described, including one prototype urban storm drainage installation. Three descriptive models for airlift pump operation are developed and one adopted for application in low-lift, low-submergence, high-flow applications. The model allows a simple design procedure for airlift pumps in this regime. A simple design hand-calculations procedure is developed, and two personal computer-based implementations are described. A simple design example is presented and recommendations for further research and development directions are made.

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CHAPTER 1

1.1 – Introduction to Airlift Pumps

Airlift pumps are commonly considered to be part of a unique class of "alternate" pumping technologies. These alternate pumping technologies are required when common rotodynamic pumps are unsuitable for a given project or application. Some applications that commonly benefit from alternate pumping technologies involve fluid/solid mixtures, very viscous fluids, hazardous fluids, live organisms suspended in fluids, low-head or low-submergence situations, scenarios with variable inlet water surface levels, etc. Airlift and other alternate pumping technologies provide a means for engineers to approach these scenarios.

Despite the success of the airlift pump in several other areas, the airlift pump has not gained acceptance in civil engineering applications. Specifically it has not been used for management of storm waters, pumping fluids in open channels, nor in any other high discharge, low lift, low head applications despite the fact that in some cases it may promise some advantages in these settings. In fact, an extensive literature search on airlift pump research and development found no references at all to airlift pumps used in high-discharge, low-head, low-lift capacities in civil engineering applications or otherwise. Nevertheless, there are potential applications for low head, high capacity pumping of water in open channels, and specifically of storm runoff in drainage conduits. This research program is focused on investigating those possibilities.

The main feature of an airlift pump is a vertical tube with the lower end submerged in water and a supply of compressed air provided to the lower end. As the compressed air flows into the lower end of this tube bubbles are formed and a mixture of water and air bubbles results. Since this mixture of air and water is less dense and thus lighter than water, the level of the air and water mixture in the vertical tube rises above that of the surrounding water surface. With a suitable physical arrangement, this results in continuous "lifting" of the water to a higher level than the original water surface - in effect creating an "airlift pump".

Carl Loëscher, a German mining engineer, reportedly developed the original airlift pump concept in 1797 and the technology began to gain widespread acceptance in the middle 1800's (Ward 1924). By the early 1900's several patents had been issued for various arrangements of airlift pumps and they were widely used for pumping water, often from quite deep wells, until being superceded by reliable electrically-driven submersible rotodynamic pumps. There was a considerable amount of early research into the airlift concept, but broad interest on the topic waned as airlift pumps were superceded in the early 1900's. Despite having been replaced in common use, airlift pumps have continued to be used in several specialized applications, which are described in more detail later in this chapter.

The city of Richmond in British Columbia, Canada is situated in the mouth of the Fraser River and experiences an average 1100 mm of rainfall per year[1]. The average elevation of the city is approximately one metre above mean sea level. Because of this very low elevation, much of the city would be submerged under tidal or river water during various parts of the year were it not for the extensive system of levees protecting Richmond from the Fraser River and the ocean waters of Georgia Strait. Recent initiatives to further improve the city's protection from river and sea flood waters have been to plan for the installation of a so-called mid-island dike to help prevent Fraser River waters from inundating central Richmond in the event of a levee breach in the Eastern region of the municipality.

The average ground slope in Richmond is zero and thus the municipal stormwater management system is constrained to very low slopes in its' main conduits. The problem of low slopes is compounded by the necessary levee system used to protect the city. The levees create a need to pump stormwater out of Richmond when tides are unfavorable, particularly in the winter when the tides are relatively high and constant. The stormwater management system in Richmond relies on low tides to allow the outfall flapgates to open. In the winter months the tides tend to be high and constant, with the daily second low tide still very high. This is unfortunate timing since the winter months are often very rainy in the Lower Mainland. These factors result in a real and ongoing danger of winter flooding in the city of Richmond.

[1] City of Richmond Engineering staff graciously provided the background information on their stormwater drainage system as presented in this brief section during various site visits, meetings and conversations that took place from 1997 to 1999 throughout the development of this research project.

During heavy rains, pumping stations at the perimeter outfalls of the system can pull the local water levels down to shutoff but there can still be flooding in central Richmond because of the inability to move storm water quickly enough to the outfalls. Recent experience has shown that Richmond experiences unacceptable storm water levels and flooding in some areas as frequently as once every two or three years.

Because of these concerns and increasing high-density development in the urbanized core of Richmond, the city has been considering options for improving the capacity of their stormwater management system. Concentration times are short so either faster removal of runoff or detention and storage is required. Detention and storage is problematic given the high water table in Richmond, so the approach has been to consider options focused on increasing the rate of runoff removal.

The first option presented was to introduce more and larger conduits. Unfortunately this strategy would be extremely expensive and very problematic in public inconvenience since many of the main stormwater conduits are installed in built-up areas and under main city roads. Additionally, installation of large concrete box culverts has become very unattractive since British Columbia worker's protection legislation concerning the conditions required for their maintenance is so strict that it makes the upkeep of such conduits impractical and very expensive.

The second alternative was to investigate means of increasing the effective slope of the system by increasing the water surface grade within the conduits by pumping. This second approach would accelerate the mean flow velocities and thus remove stormwater from the city core at an increased rate.

A need for high capacity, low head pumps that could be installed in storm drainage conduits to lift storm water between 1 and three feet (0.3 to 1.0 m) had developed. Such pumps would increase the effective slope and hence the discharge capacity of the existing storm drainage infrastructure. These pumps would only be required for short durations under the combination of heavy rainfalls and high tides.

Common rotodynamic pumps do not conform to this high-flow, low-head requirement and if pump units could be found to satisfy these requirements they would still be expensive to install and house in the Richmond system. This is because of their need for minimum submergence levels at their inlets, necessitating substantial excavation and placement of infrastructure in an area with sandy soils and a high watertable.

The difficulties and impracticalities in both of the proposed solution strategies have effectively stopped Richmond's progress towards an improved stormwater management system. Despite the impasse however, the danger of flooding in central Richmond is real and increasing as urban development continues.

Realizing the need for a way forward, an alternative pumping technology was sought and this requirement spurred Richmond into sponsoring the applied research program that is described in this thesis.

1.2 - Description of an Airlift Pump

An airlift pump itself is comprised of five major components, namely the air supply apparatus, the air injection or aeration system, the water intake, the riser pipe and the pump outlet. Figure 1 shows the main elements of an airlift pump. Nomenclature used in that figure and other variables of interest are defined in Table 1.

An airlift pump may also feature a so-called "foot piece", a lengthened section of the main riser pipe located below the aeration point and in which only single-phase water flows. A foot piece allows an airlift pump to entrain water from a depth greater than its' aeration depth. This allows a means for pump units with low head air-supply apparatus to successfully pump liquid from much deeper levels than they would otherwise be capable of. Since foot pieces are required only in scenarios in which the water to be pumped is to rise from a great depth not all airlift pumps feature foot pieces. In fact, most short airlift pumps such as those in this study, do not use foot pieces.

FIGURE 1 - Schematic Airlift Pump Layout

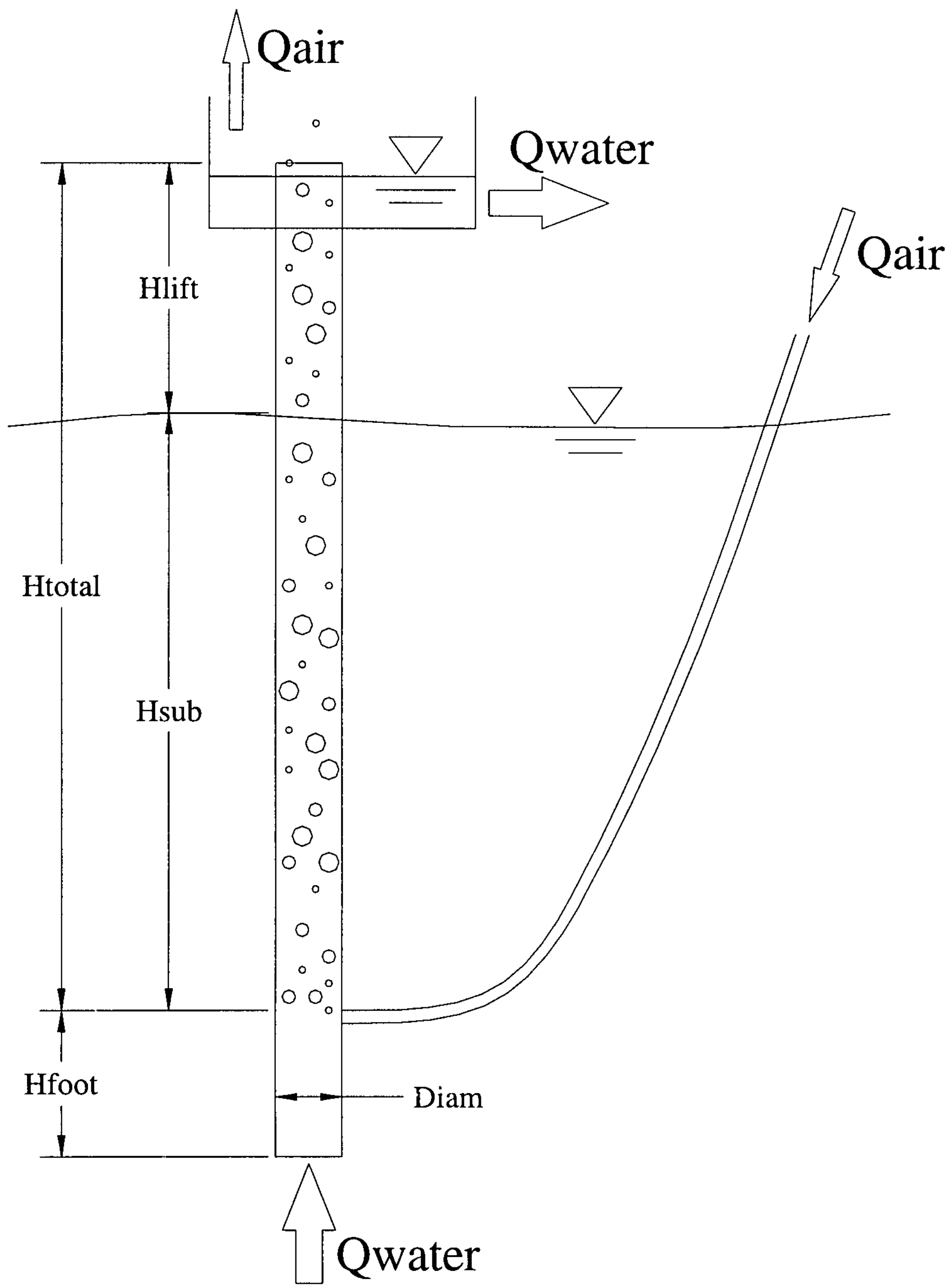


TABLE 1 – Airlift Pump Nomenclature and Variables

Area	= cross-sectional area of airlift pump tube
b	= tuning parameter in air phase velocity/mixture velocity relationship
A_{air}	= area of flow mixture cross section occupied by air
A_w	= area of flow mixture cross section occupied by water
c	= tuning parameter in air phase velocity/mixture velocity relationship
d	= tuning parameter in head loss equation
Diam	= diameter of airlift pump tube
Dens	= relative density of the air-water mixture in the airlift pump tube
e	= tuning parameter in head loss equation
g	= acceleration due to gravity
H_{drive}	= driving head applied to airlift pump
H_{lift}	= lift height of air-water mixture in airlift pump tube
H_{loss}	= head loss in airlift pump tube
H_{tota}	= height of pump lift above aeration point
H_{foot}	= height of pump tube footpiece below aeration point
H_{sub}	= height of standing water surface above aeration point
K_{ent}	= pump tube entrance loss factor
K_{exit}	= pump tube exit loss factor
K_{pipe}	= pump tube pipe loss factor
K_{total}	= total pump loss factor
Q_{air}	= volume flow rate of air in airlift pump tube
Q_{mix}	= volume flow rate of the air-water mixture in airlift pump tube
Q_{water}	= volume flow rate of water in the airlift pump tube
V_{air}	= velocity of the air fraction in the air-water mixture in airlift pump tube
V_{mix}	= velocity of the air-water mixture in airlift pump tube
V_{rel}	= relative velocity of the air phase to the water phase in the airlift pump tube
V_{water}	= velocity of the water fraction in the air-water mixture in airlift pump tube
η_{system}	= airlift pump system efficiency
$\eta_{airdelivery}$	= airlift pump air delivery subsystem efficiency
η_{riser}	= airlift pump riser tube subsystem efficiency
ρ_{air}	= density of gas phase
ρ_{water}	= density of liquid phase

As mentioned previously, in this study only airlift pumps with zero-length footpieces are considered, so $H_{foot} = 0$ and the total length of the pump riser tube is equal to the sum of the submerged and unsubmerged lengths, H_{sub} and H_{lift}.

1.3 - Applications of Airlift Pumps

Despite having been superceded by submersible rotodynamic pumps in most common applications, airlift pumps are still used in several specialized settings. Typical modern applications of existing airlift pump technology include use of these pumps in deep water wells, where a related system known as a "geyser pump" is also becoming increasingly common where small-diameter pump tubes are feasible. Airlift pumps also still frequently serve deep shaft and well drilling applications.

Airlift pumps are also used in modern windmill-driven pneumatically-operated water-well pumping applications, such as those available as turnkey systems from Airlift Technologies of Redlands, CA.

Despite the fact that mining technology has developed dramatically, airlift pumps are still a staple in mine dewatering, and modern examples are remarkably similar to the original system developed by Loëscher in 1797. Airlift pumps are also often used in process applications in which corrosive or viscous liquids such as sand-water slurries, salt solution, oils and various other waste products make traditional rotodynamic pumps less suitable. (Giot, 1982) The oil industry uses airlift pumps in retrieving crude oil from dead wells. The nuclear industry uses carefully calibrated small diameter airlift units to pump fluids in nuclear fuel retreatment (Clark & Dabolt 1986).

Wastewater treatment plants are currently the most common application for airlift pumps, where excellent aeration and subsequent oxygenation of the pumped mixture that is derived from the injected air is a strong benefit. The Sanitaire company of Brown Deer, WI builds stainless steel airlift pumps for this application.

Airlift pumps are often used in aquaculture and fish farming operations where their lack of moving parts provides necessary safety for fish and the air introduced into the water column improves oxygenation (Wurts, McNeill & Overhults, 1994). The Aquacare company of Bellingham, WA manufactures airlift pumps for fish farming applications. The competing technologies used in fish farming, namely geyser pumps and propeller pumps, have the respective disadvantages of noise and possible damage to fish safety in aquaculture applications.

Offshore mineral excavation and diamond mining is an emerging application for airlift pumps, where the lack of moving parts and ability to handle particulates make them particularly suitable. Airlift pumps are also sometimes used in a similar manner for underwater recovery and salvage operations, where an airlift tube may be rigged and powered from the surface, allowing divers to place small items at the intake of the pump and have the items carried to the surface. Airlift pumps for use in deepwater salvage often feature tapered riser pipes, presumably so that as air bubbles increase in size during their rise from the aeration point towards the surface the void ratio of the mixture in the pump tube does not increase too much and reduce efficiency. The airlift pump is very well suited to underwater recovery purposes since compressed air is a staple aboard salvage vessels and the turbulent nature of the flow in the airlift pump tube as well as the upwards-opening shape of the commonly-used airlift pump barrels in this application are doubtless helpful in avoiding any potential jamming irregularly shaped items may experience in the pump risers.

The final common application of airlift pumps is in lake turnover, where these pumps are used to counter the effects of lake stratification (Parker & Suttle 1987). In lake destratification applications airlift pumps often float on small buoys with their outlets at the water surface and compressed air delivered by floating supply lines (Wurts, McNeill & Overhults 1994).

1.4 - Project Scope and Rationale

This research project aims to investigate the suitability and behaviour of airlift pumps in a new class of applications – namely low-lift, high-flow, low-submergence scenarios such as pumping in open channels and management of urban storm drainage. Despite the unorthodox concept, airlift pumps promise many advantages in such applications. Installed costs are low since the pumps are simple, composed primarily of commonly available PVC or steel pipe fittings. Airlift pumps are very robust and nearly maintenance-free since they have no underwater moving parts (de Cachard & Delhaye 1996). Additionally, their air supply systems can be located conveniently above ground to minimize installation costs and facilitate inspection and maintenance.

The following discussion of airlift pump efficiency suggests that the low-head, low-submergence, high-flow, necessarily large diameter airlift pumps that would be required in open-channel and urban storm drainage applications would be energy inefficient units. Despite this inefficiency, the author believes that airlift pumps may offer enough other cost and service advantages to offset the operational inefficiency of the airlift pumps that would be applied in these settings.

Some of the advantages airlift pumps may offer to urban drainage applications include low installation cost and maintenance cost, very low supporting infrastructure cost, and a possibly huge placement benefit in the potential option for portable pump units and/or portable power units, thus potentially eliminating entirely the need for a pump house or similar infrastructure.

The aeration of storm runoff may also be a reason to consider the application of airlift pumps to urban drainage applications. Urban storm runoff often contain high levels of heavy metals, petrocarbons, chemicals from spills, and other roadwash pollutants and tend to create potentially significant environmental impacts to the bodies of water into which they discharge. (Turer, Maynard & Sansalone, 1996). Airlift pumps are used routinely in aquaculture and wastewater treatment because of their significant benefit in aerating the pumped liquid. Using airlift pumps for urban drainage could provide the additional benefit of aerating the storm runoff, thereby mimicking the aeration process used in many municipal mixed-sewage treatment plants, potentially accelerating oxidation of the roadwash and other stormwater pollutants, and allowing for a decrease in resulting environmental impacts.

This compelling array of advantages, particularly the very low cost of installation and maintenance of airlift pumps, the lack of a need for permanently installed power and control systems with their attendant housing infrastructure, and the potential benefit of aerating the runoff waters make the investigation of airlift pumps for these applications very attractive.

1.5 - Two-Phase Flow Regimes

Airlift pumps are two-phase fluid flow devices. Gas and liquid (in most cases air and water) flow upwards together in a vertical pipe. This two-phase fluid mixture can take several different forms, and the various flow patterns of the two phases in these forms have significantly differing hydraulic behaviours. This is significant to the science and design of airlift pumping systems since any of these forms of air-water mixtures are possible, and the form found in the system of interest is a very important variable since physical relationships and derived mathematical relationships are unique for each form. The exact descriptions of the flow patterns vary somewhat by author, terminology is not always common, and some flows are described as combinations of patterns (Shelton & Stewart, 2002).

A summary of the five basic forms observed in the two-phase flow of water and air in vertical pipes, along with their most common names are shown in Figure 2. (modified from Taitel, Bornea & Buckler, 1980). Figure 3 shows the same flow regimes characterized by gas flux and mixture velocity.

FIGURE 2 - Two-Phase Air-Water Flow Regimes

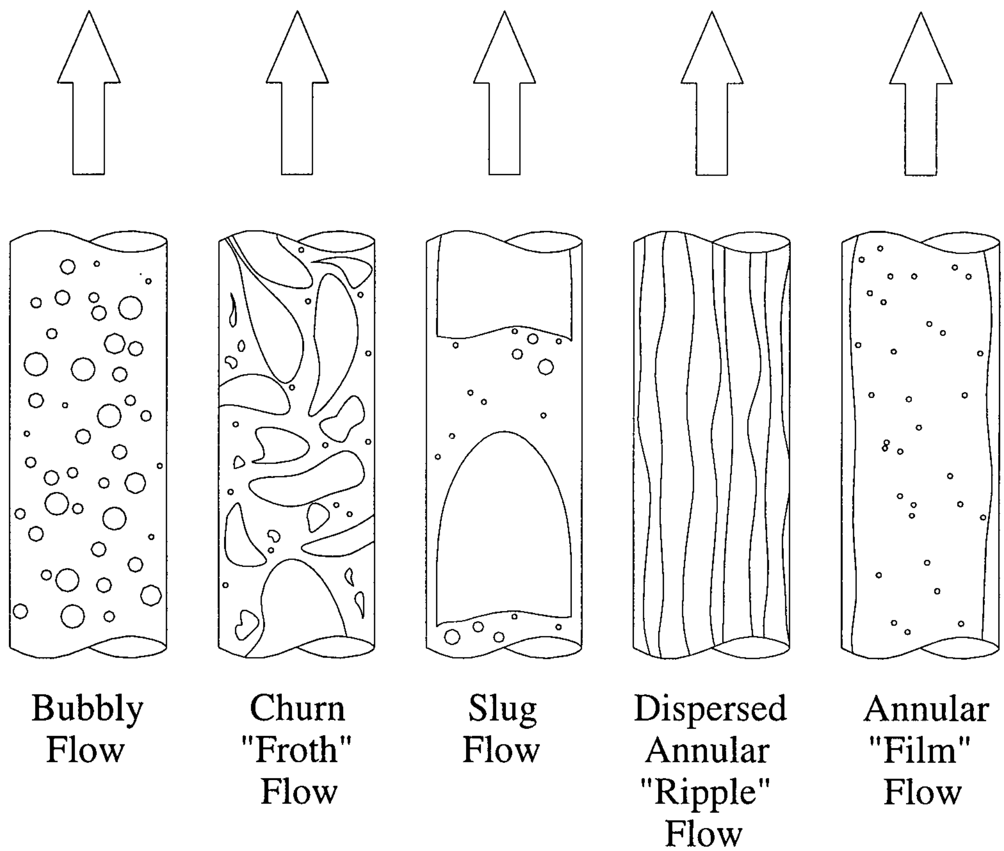
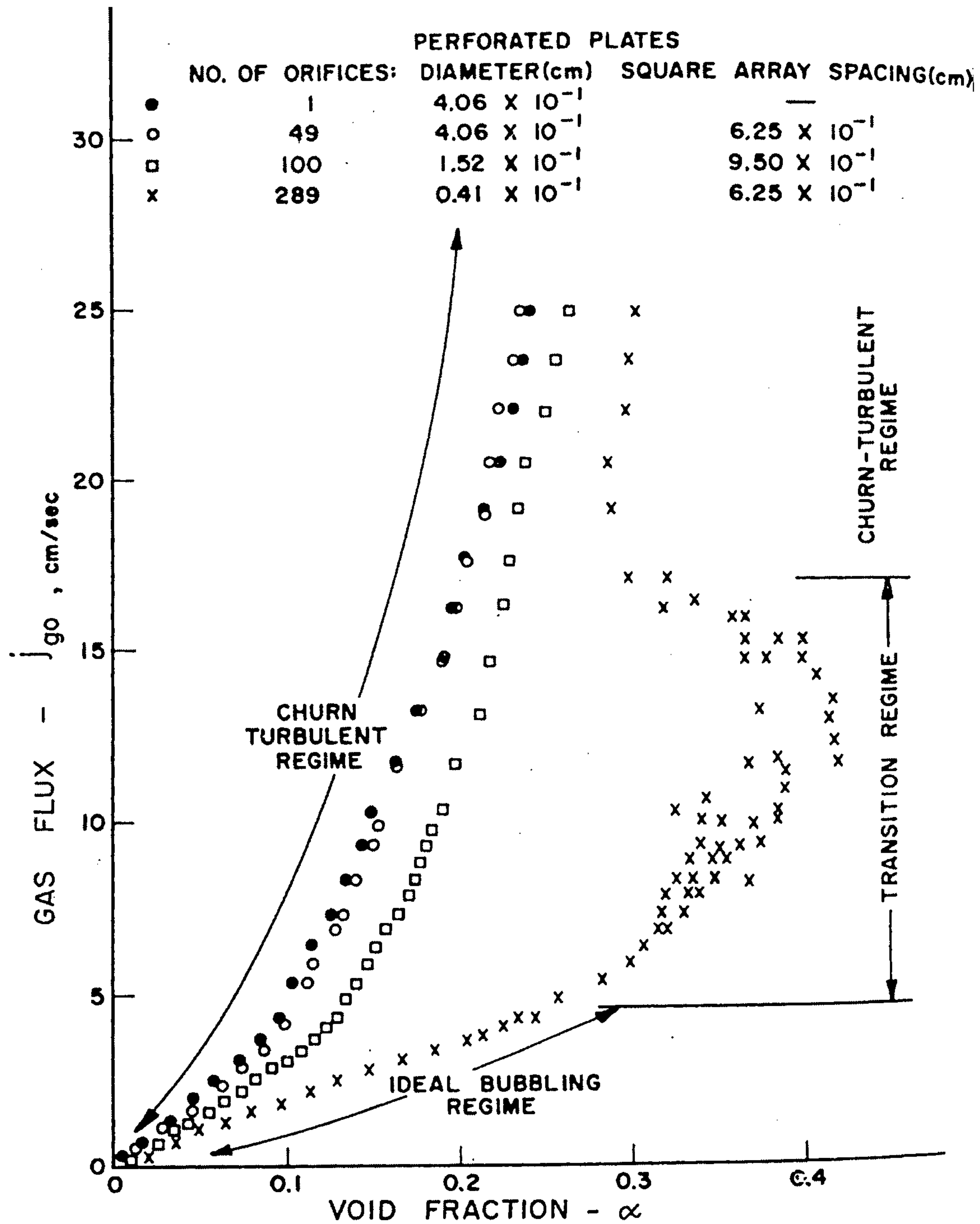


FIGURE 3 – Two Phase Flow Regimes characterized by Gas Flux and Mixture Void Fraction, adapted from Wallis (1969)



1.6 - Operational Efficiency of Airlift Pumps

Airlift pump efficiency can be defined as the ratio of energy delivered to the pump unit to the unit energy output in the form of velocity and head of the pumped liquid. The overall system efficiency can be considered a product of the air delivery and airlift riser subsystem efficiencies. The efficiency of the air delivery subsystem depends on the type and configuration of the air supply equipment, piping, conduits and controls. Efficient delivery of air through installed conduits at desired pressures and flow rates is a well-explored and mature branch of mechanical engineering.

Common wisdom in the design and use of airlift pumps suggests the efficiency of an airlift pump riser subsystem is maximized when deep submergence is available, the lift height is low, and liquid and air flow rates are low. De Cachard & Delhaye (1995) and De Cachard (1989) also suggest a very strong contributing effect in the length-to-diameter ratio, namely that slender pumps with high length-to-diameter ratios are greatly more efficient than their low length-to-diameter ratio counterparts.

The most efficient airlift pumps feature a situation in which the air and water phases have very similar velocities, air bubbles are either spherical and very small or are large, dart-shaped Taylor bubbles with a cross section near the entire pipe diameter. In both of these maximally efficient cases, the slip velocity between the air bubbles and water is minimized.

Airlift pump efficiency is further enhanced by use of the smallest possible stable void fraction – thus pumping the maximum amount of water per amount of air injected. Aeration efficiency is also an important factor in determining the efficiency of short airlift pumps although it matters less in long pumps (Wallis 1968). This phenomenon appears to occur because the long airlift pumps tend to operate in slug flow. Slug flow occurs in pumps long enough that small bubbles can accrete together to form homogeneously spaced large Taylor bubbles close in cross section to the pipe diameter (Taitel & al. 1980). In this flow regime the fluid flows continuously in contact with the pipe walls creating losses directly dependent on the fluid velocity.

At the entrance of long pumps (and in shorter airlift pumps in which small bubbles do not have the opportunity to accrete into Taylor bubbles before exiting the pump riser) the air and water mixture flow is turbulent and recirculatory. Taitel & al (1980) characterize this flow regime as "froth" or "churn" flow and identify it by the oscillatory nature of the liquid's upward and downward motion between and around bubbles. An aerator assembly that diffuses many small evenly distributed bubbles into the flow field helps reduce this turbulence and recirculation, reducing losses and increasing efficiency. Morrison & al. (1987) suggest that this is also true for the bubbly flow regime where "multiport injection is more efficient".

Despite early and contradictory observations such as those by Ward (1924) and Bauer & Pollard (1945) on large diameter airlift pump systems, riser diameter also plays a role in airlift pump efficiency for a given lift height since larger diameter airlift pumps tend to be less efficient than their smaller counterparts. This is because the larger diameter pumps must be very long before the efficient Taylor bubble-induced slug flow regime can stabilize (De Cachard & Delhaye 1995). In fact, as the pipe diameter increases the cross sectional area increases even more rapidly, thus diminishing the ability of surface tension forces to hold large bubbles intact against the influence of a complex turbulent shear field in the air/water mixture column. De Cachard & Delhaye (1995) also suggest that surface tension forces in bubbles reduce slip velocities between the air water phases. In that case since bubble surface tension forces are increased in small diameter pipes, the reduced efficiency of large diameter pumps may be due to greater slip velocities, themselves due to the reduced relative effect of surface tension forces.

Observation suggests that as the pipe diameter increases above a maximum feasible bubble diameter the thickness of the film in the annular region surrounding the Taylor bubbles in the slug flow mixture may begin to thicken rapidly. This rapidly thickening film could then provide a dramatically increased flow path area for liquid from the region ahead of any Taylor bubble to slip downwards through the annular-shaped region, past the Taylor bubble and into the region behind the bubble. As the flow rate of the downward-traveling fluid in the annulus regions increases, the overall frictional shear on the pipe tube may become downward (Wallis 1968). In such cases the overall lift efficiency falls rapidly. Thus, increasing pipe diameter above the stable bubble diameter for a given flow field may reduce efficiencies for long airlift pumps operating in the slug flow regime.

1.7 - Summary

The motivation for this work is "Can apply airlift pump technology be practically applied to civil engineering works such as open channel drainage of urban stormwater?"

An airlift pump is a deceptively simple two-phase flow device than can operate in several flow regimes, depending on several geometric and flow parameters. Airlift pumps have been the subject of a small amount of research since their invention in 1797 by Carl Loëscher. Since then they have been applied extensively in a small number of specialized applications but not to high-flow, low-lift, low-submergence civil engineering applications such as open-channel drainage and storm water management. Airlift pump efficiency is maximized in scenarios in which submergence is high, gas and liquid flow rates are low and aeration efficiency is high. Despite the fact that low-head high-flow applications do not promise very efficient operation of airlift pumps there are significant reasons such as low installed cost, ease of maintenance, reduction of environmental impact of runoff water, etc. to investigate them for these uses.

This thesis considers the application of airlift pumps to these civil engineering applications and outlines a four-stage experimental program undertaken at the University of British Columbia and the City of Richmond, British Columbia. This study had several objectives. These were namely: to first evaluate the potential for airlift pumps in urban drainage and other low-slope open-channel applications, to create a mathematical descriptive model of low-head, high discharge airlift pump systems, to develop a practical design method for such pumps using the mathematical model above, and to illustrate the use of that method. To these ends, small-scale and full-scale models were built and tested. Water and air flows and levels were recorded. A broad literature study was undertaken. From this theoretical background and experimental observations, three mathematical models for predicting airlift pump behaviour in these settings are developed. One is suggested as representative. A simple hand-calculator design procedure is explained and two personal computer-based solutions are suggested. A practical design example is presented, and conclusions and recommendations for further development are made.

CHAPTER 2

2.1 - Introduction - Literature Review

This chapter describes a brief history of the open literature on airlift pumps, providing an overview of the development and theory behind their operation as well as an overview of airlift theory development to the present day. This literature search first investigated the historical use of airlift pumps in civil engineering applications. No mention was found. Broadening the scope of the search revealed a niche body of literature concerning airlift pumps in the process engineering field, documented mainly in the disciplines of Aquaculture and Chemical Engineering.

2.2 - Development of Airlift Pump Theory, 1797 to Present

As noted in Chapter 1, Carl Loëscher, a German mining engineer, is thought to have been first invented the airlift pump in 1797 (Giot 1982). Loëscher's invention was an attempt to simplify the pumping tasks in deep mines. Submersible rotomàchinery was not available in the late 1700's and the benefits of a pneumatically-operated system are immediately evident in that context.

Airlift pumps became popular several decades after Loëscher's first models, during the middle 1800's (Ward 1924). At this time direct pneumatic power was widely available in the form of boiler steam which was easily generated at high pressure. Pneumatic power was also available from steam-powered compressors. Faraday's discovery of electromagnetic induction in 1831 led the way to the invention of the electric motor. This and the appearance of the internal combustion engine pioneered by Rudolf Diesel and others at the end of the same century made compressed air a viable source of power.

Shaw (1920) first suggested a volume ratio for the gas and liquid phases in a long airlift pump riser tube operating at 100% efficiency:

$$\frac{Volume_{air}}{Volume_{water}} = \frac{Q_{water} \cdot g \cdot H_t}{P_{discharge} \cdot \ln\left(\frac{P_{aerationdepth}}{P_{discharge}}\right)} \tag{1}$$

Shaw's is the first attempt found in the open literature to quantify airlift pump behaviour on a physical basis. Evidently his relationship was successfully used in design with an efficiency multiplier added, on the order of 50% (Zenz 1993).

Ward at the University of Wisconsin did the first serious experimental study of airlift pumps found in 1924. This study focused on the behaviour of long airlift pumps and attempted to create functional relationships between the air and water phase flow rates, efficiency and pump riser geometry such as pump length and diameter. Ward developed an elaborate curve-fitting algorithm for use in design but was only moderately satisfied with the results and qualified the technique's application to the long pump risers in his study.

Ward presented sixteen summary conclusions in his study. Many of Ward's results and suggestions form the ongoing common basis for subsequent use and understanding of airlift pumping systems. Here is a summary of Ward's eight most salient conclusions:

1. The efficiency of long airlift pumps depends primarily on flow conditions in the riser pipe, and thus great refinement in aeration and foot piece design beyond ensuring minimum flow restriction at the entrance are not necessary in most cases.
2. There is a maximum efficiency for every combination of pump geometry and submergence that depends on water flow rate.
3. Maximum efficiency occurs at submergence ratios of greater than 70% in most cases, (ie: when over 70% of the total length of the riser tube is submerged) although very small diameter pumps can operate with relatively high efficiency at lower submergence ratios.
4. High efficiency is possible at lower submergence ratios if the aeration depth is deep.
5. The combined friction and slip losses due to the flow in airlift riser pipes follow a different law than those that govern the flow of water or air in a pipe.
6. There is a relatively simple relation between frictional losses and velocity of flow in an airlift riser pipe for any particular mixture of air and water.
7. Smooth joints in airlift riser pipes are necessary to avoid unnecessary losses. Sudden expansion or contraction is very detrimental to efficient operation.
8. Air lift pumps of less than forty feet in length are likely to give results much different to those encountered in long pumps. Losses that are relatively insignificant in large pumps become important in short airlift pumps.

Eight years later in 1932, Pickert published "The Theory of the Airlift Pump" in an attempt to elaborate on the mechanics of the flow in these units. His study did not present results greatly contributory to the behaviour of the large diameter, low lift, low submergence high flow pumps of interest in this study.

More than 25 years passed until Govier, Radford & Dunn's "The Upwards Vertical Flow of Air-Water Mixtures" appeared in 1957. Their experimental study was based on a 1.025" diameter pump riser 30' long (ie: length-to-diameter ratio approximately 350:1). They were able to accurately predict flow pattern, head loss and slip velocity but restricted the application of their results to the behaviour of pump units of similar riser tube diameters when pumping mixtures of similar gas and liquid properties.

DJ Nicklin's "The Airlift Pump: Theory and Optimization" of 1963 presented the first satisfactory explanation of the behaviour of small-diameter airlift pumps in the bubbly and more importantly, the slug-flow regimes. Nicklin's momentum balance, 2-phase drift flux model based on mass flow forms the basis of the bulk of subsequent research into airlift pumps and slug flow theory and behaviour. The most broadly used of Nicklin's conclusions (recast here in consistent terminology for this study) is used to characterize the velocity of Taylor bubbles in the slug flow regime in still water:

$$V_{taylorbubble} = 0.35 \cdot \sqrt{\frac{g \cdot (\rho_{water} - \rho_{air}) \cdot Diam}{\rho_{water}}}$$

$$V_{taylorbubble} \approx 0.35 \cdot \sqrt{g \cdot Diam} \qquad (2)$$

Nicklin also observed (like Ward) that although many aerators have been designed to minimize bubble size and maximize bubble distribution, none were successful in long airlift pumps. He also first clarified the one-to-one relationship between the submergence ratio and the average pressure gradient in the pump riser tube.

Multiphase flow was still a nascent field in the 1960's and developments in this area were happening rapidly. In 1964, Duckler, Wicks & Cleveland published a two-part study "Frictional pressure drop in two-phase flow". Their results are illustrative of the still-developing nature of two-phase flow theory at that time. They found the existing correlations for pressure loss in two-phase pipe flow to be inadequate and asserted that "There is not even a phenomenological understanding of this type of flow."

As two-phase flow theory was further developed, and due possibly to the explicit solution for slug flow operation as suggested by Nicklin, the study of airlift pumps continued to focus increasingly on the mechanics of Taylor bubbles in the slug flow regime, and to an increasingly lesser degree on the bubbly flow, churning flow and annular flow regimes.

Wallis' definitive work, *One Dimensional Two-Phase Flow,* appeared in 1969. Wallis' text is still one of the best sources for a broadly-focused collection of most of the open theory of one-dimensional two-phase flow. Wallis' work exposes the tremendous complexity in multiphase flow behaviour and provides much of the foundation for two-phase flow as used today. Many frictional and velocity relationships developed by Wallis are still state of the art in modern two-phase flow theory.

Todoroski, Sato and Honda followed Nicklin ten years later in 1973 with "Performance of Airlift Pumps", which elaborated slightly on Nicklin's approach to the slug-flow regime flow of these devices. Todoroski, Sato and Honda modified Nicklin's experimental basis for determination of the slip velocities in slug flow.

The interpretation of the various regimes of vertical two-phase flow was mainly descriptive in nature until 1980 when Taitel, Barnea & Duckler published "Modeling Flow Pattern Transitions for Steady Upward Gas-Liquid Flow in Vertical Tubes". Their study undertook mathematically predicting the transitions between these patterns. They were able to predict which pattern or regime of two-phase flow would occur under a given set of conditions, and their approach is still used today. Taitel, Barnea & Duckler also provide the best of the visual descriptions of two-phase flow regimes (which supplied the basis for Figure 2 in chapter 1). Their most useful finding for this current study suggests that (in cases in which slug flow can develop) the length of the turbulent entrance or transition zone region from the aeration point to the point where slug flow can develop depends on the mixture velocity and pipe diameter:

$$L_{entrance} = 40.6 \cdot Diam \cdot \left(\frac{V_{mix}}{\sqrt{g \cdot Diam}} + 0.22 \right) \tag{3}$$

In 1982, Markatos & Singhal produced a numerical analysis process for two-phase flow. This study was focused on bubbly and slug flow, much the same as those that had preceded it. It appears that in the bubbly and particularly the slug flow regimes the mathematical formulation for the friction and loss terms is easier to accomplish since the relatively fixed geometry of the round or Taylor bubbles allow a solution that requires less experimental data for correlation. Markatos & Singhal's technique was developed for use in deep water wells and depends on the breakdown of long vertical risers into smaller contiguous segments, in effect creating a "gradually varying flow" formulation. It is suitable only to long riser pipes.

Long, small diameter airlift pumps are widely used in nuclear fuel reprocessing. Very accurate estimates of flow rates are required in those settings. In 1986 Clark & Dabolt developed a general set of design equations for airlift pumps in slug flow for use in the nuclear industry. They focused primarily on accurately predicting the flow rate behaviour in their applications. Despite their admitted inability to accurately calculate the overall frictional losses in pipes of 38 mm diameter they did provide an accurate design model for such pumps in the slug flow regime. Interestingly they also attempted to apply Nicklin's model to a short pump and found that Nicklin's model overpredicted the pump efficiency, unlike its' better agreement when applied to longer units. Clark & Dabolt's general design equation for long, small-diameter pumps does not address pump efficiency in great detail but does provide an accurate and practical means of design for very long slender airlift pumps.

In 1993 Zenz produced "Explore Potential of Airlift Pumps and Multiphase Systems" primarily exploring airlift pumps in three-phase scenarios. Zenz' study was concerned mainly with slug flow and particulate entrainment, again in long pipes. Airlift pump riser pipes are generally considered long when length to diameter ratios are 50:1 or more.

Wurts, McNeill and Overhults (1994) provided a simple curve-fitting approach to airlift pump performance for near-100% submergence in aquaculture and destratification applications.

In 1995 Tramba, Topalidou, Kastrinakis, Nycas, Francois & Scrivener completed their "Visual Study of an Airlift Pump Operating at Low Submergence Ratios" which is not particularly helpful for this present study since it is mainly concerned with bubble formation at a jet inlet and includes no performance data for non-slug flows.

Following Clark & Dabolt in the nuclear fuel reprocessing industry, De Cachard & Calhaye created a steady-state model for very small diameter, long lift pumps in 1995. De Cachard & Calhaye's is certainly the most extensive study found. It is concerned primarily with creating an accurate model for gravitational and frictional components of the airlift pump riser pressure gradient. Like Clark & Dabolt's work, it is focused on very long "slender" airlift pumps in the slug flow regime. De Cachard & Delhaye are not concerned with optimization of energy efficiency since energy inputs are very small in their cases of interest. De Cachard & Delhaye observed churning flow in the lower sections of their study pump units and concur with previous researchers that churn flow is a development phase for the slug flow pattern. However, they also found that churn flow could exist as a stable flow pattern at high gas flow rates. De Cachard & Delhaye developed the most detailed and accurate analysis framework available for airlift pumps of under 40 mm diameter and with length-to-diameter ratios above 250:1.

Most recently Nenes, Assimacopulos, Markatos, & Mitsoulis completed "Simulation of Airlift Pumps for Deep Water Wells" in 1998. Their analytical framework involves an interspersed continua model and solves a system of differential equations per Markatos (1982). Results from their system are very accurate but unfortunately suitable only for very tall pipe units in which the pump riser tube may be broken into tens of internally contiguous discrete elements.

2.3 - Summary of Literature Review

Airlift pumps have been a niche interest area in process, chemical and mechanical engineering as well as aquaculture. Publication on the topic has been sparse and the literature has tended towards attempts to explain the behaviour of these devices in two distinct flow regimes. Nicklin's model (1963) continues as the base for almost all theoretical development whereas the numerical techniques of Markatos, Nenes et al. (1992) promise a powerful toolset for evaluating the behaviour of long airlift units.

There has been little reason to evaluate the high-flow, low-head, low-submergence airlift systems and subsequently those applications are still unexplored from theoretical and design standpoints. This has not stopped such pumps from being used sporadically and often unintentionally since in a practical sense, simplicity in field use has tended towards installing a pipe at an appropriate depth, adding air in an appropriate volume and at an appropriate depth to produce the desired results if possible. In a research sense, the inability to accurately measure the relative velocities of the air and water phases except in the bubbly and slug flow regimes have tended towards tuning a theory focused on those regimes alone. High submergence, small diameter, short lifts have been traditionally investigated since low-submergence, high-lift units provide decreasing efficiencies.

As Ward (1924) concluded, there remain inherent gaps in our understanding of theory that mainly arise from the fact that the sizes, speeds and distribution of the air bubbles are not known, yet the size and the rate of ascent of the bubbles through the air-water mixture are critical variables.

Recent research work on air entrainment in fast flowing water using laser optical probe technology with the ability to measure the behaviour of the air fraction in a two-phase air-water flow mixture as distinct from the overall air-water fluid mixture has recently become available. This technique was employed first by Cartellier (1992) and later refined by Serdula & Loewen (1998), whose techniques might seem to promise a more rigorous approach to air lift pump design by the direct measurement of gas and liquid phase velocities and void ratio. Unfortunately, investigation of the experimental equipment and personal conversations with Loewen suggest that since the laser system employed is a point measurement system it is not suitable for air-water mixtures with recirculatory movement. It cannot resolve differences between upward-moving and recirculating air bubbles and does not function well without distinct boundaries between the air and water phases at the bubble boundaries such as are found in bubbly and slug flow. Unfortunately this means that at least currently the laser measurement technology is inapplicable to the study of airlift pumps in the churn flow regime.

CHAPTER 3

3.1 - Overview of the experimental program

For airlift pumps to be used effectively in short lift, high flow applications such as storm drainage conduits, the airlift pump must be able to "lift" large volumes of water through a height of about 0.3 to 0.6 m. For example, such an increase in head over a run of 5000 feet in relatively flat terrain such as exists in Richmond, B.C in the 5' by 9' concrete box culvert leading from Granville Street to the Gilbert Road outfall could easily result in a doubled water surface slope and subsequent dramatic improvements in water flow velocity, and subsequent reduction of local flooding during extreme rainfall events.

A pump system for occasional use in emergency situations such as might be experienced by Richmond during the 10-year design flow should ideally be inexpensive and maintenance-friendly. Since the pump units would run only during extreme conditions, and since operating costs in extreme conditions are often accounted for differently than ongoing costs, efficiency is only important in so much as it affects the first cost of the installation. Running costs are less important as the pumps are only used during extreme storm events - in the order of once every two or three years. However, installed cost is important - of course less expensive is preferred. Airlift pumps promise a very attractive match to these criteria. The compressed air supply can be dry and out of the way, in fact there is no need for the supply apparatus to be permanently located since air can be supplied through a flexible pipe. This means that a permanent pumphouse need not necessarily be used with an airlift system. The pumps themselves can be built quite inexpensively as they only consist of sets of tubes and aerators with an air supply. Because airlift pumps are notoriously inefficient compared with their rotodynamic counterparts and air compressors are expensive, it is very desirable to have the ratio of water lifted to compressed air used be as high as possible.

These design considerations and potential benefits were investigated, motivating the current study. Preliminary calculations were made and two series of preliminary qualitative experiments were run at the University of British Columbia Civil Engineering Hydraulics Laboratory to check the concept. Classical airlift pump components and layouts were considered and adapted for use in a low-lift situation. Since the desire was to determine whether a viable airlift pump could be developed for these applications it was reasonable to start with a system that was configured similarly to what a working unit might be.

First a small-scale airlift unit was built using the full width of a 6 inch wide undergraduate student hydraulics lab flume, exploring the conceptual layout for a full-width box culvert installation.

Subsequently a similar larger-scale airlift unit was built using the full 20-inch width of a large hydraulics lab flume to check if the system would be functional on a larger scale.

The laboratory experiments provided some valuable insights into the nature of airlift performance at low lifts, low submergence and low void ratios. They also showed that airlift pumps of this type could be practical.

Next a sequence of full-scale prototype experiments was carried out at the Gilbert Road storm drainage outfall in Richmond. Several full-scale experimental prototype layouts and systems were planned and tried. Various combinations of upstream and downstream water levels were investigated with varying rates of air injection. Riser pipe diameter was investigated, as was aerator geometry.

Since evaluating and maximizing water flow for these pump systems was the end goal of this study, in all cases it was attempted to determine the water flowrate possible for a given upstream and downstream depth, rate of air injection, pump riser diameter and aerator geometry.

There were many practical difficulties such as unusually low flows and water levels in the drainage conduit that was used as the site. However, these experiments produced several very useful results. They demonstrated that low-head, high-flow, low-submergence airlift systems did provide a viable and practical alternative in an installed storm drainage system. However, they also showed that there was considerable circulation in the pump tubes and as a result, the water was being lifted several times with resulting low overall efficiency. They also showed that there was never a steady state situation such as is usually assumed in deriving theory and formulae. The air-water mixture was very turbulent and the air bubbles were increasing and decreasing in size by shearing and coalescence as they rose, in effect always in a transient condition.

Having identified the major problem of circulation and re-cycling, a final set of experiments were set up at the Richmond Public Works Yard, using banks of tubes 75 to 200 mm in diameter, as opposed to the 250 and 300 mm tubes used in the Gilbert Road prototype experiments. Theory suggested that smaller diameter pipes would allow less circulation due to a more evenly distributed air phase. Also, the riser pipe walls would have a much greater influence over a larger cross-sectional flow area. Trials were also made with the tubes inclined instead of vertical, as inclined tubes would be easier to install and could be potentially less costly due to a reduced number of fittings required for construction.

The results from the fourth experimental setup were successful and showed little circulation, although there was still considerable uncertainty as a result of the transient nature of the underlying phenomenon of the air bubbles rising, expanding, shearing and coalescing. Since the experimental "pumps" were similar to the proposed final design the results were considered acceptably accurate. The design concept was thus considered proven and the relationships developed sufficient for design of a practical operating airlift pump.

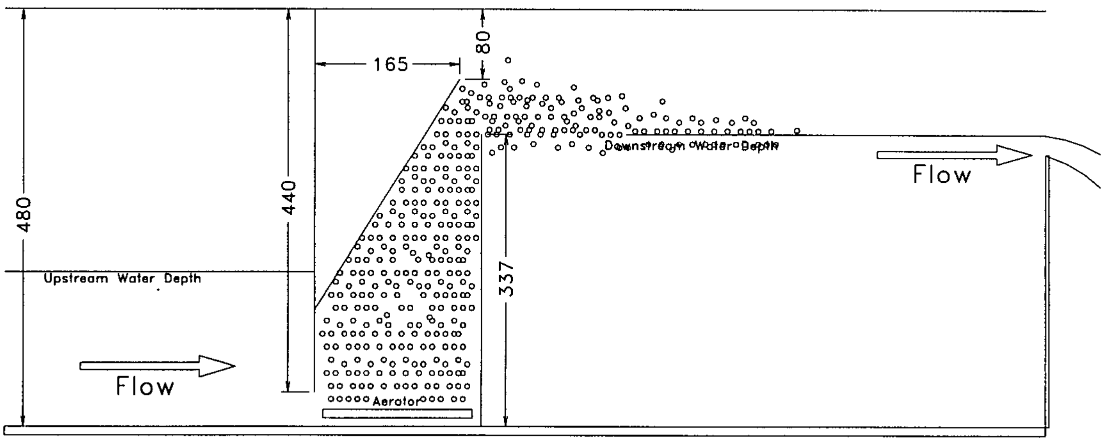
3.2 - The Experimental Setups

The first experimental laboratory setup is shown in Figure 4. The purpose of this first setup was to build a visual model of the airlift pump as a full-width element in a storm drain scenario. Because of known limitations in width, discharge rate, flow rate measurement equipment and theoretical knowledge, this first setup was intended to serve as a base for experimentation to aid in understanding airlift pump behaviour, rather than as an instrumented data collection experiment. This system was designed to simulate on a very small scale the original proposed layout of an in-culvert airlift pumping system. Upstream water flowed into the system under a baffle. An aerator installed on the base of the channel supplied bubbles to the water column. The air-water mixture then flowed between the upstream baffle and a downstream baffle, exiting the pump unit at the higher downstream level.

The small-scale system was installed in a six-inch wide student hydraulics lab flume to test the concept of a full-width airlift system in a rectangular channel. Various combinations of upstream and downstream water levels and air volume inputs were tried in order to maximize the water flowrate given any combination of upstream and downstream levels. Several geometries were tried since all of the various system elements were modular. The most effective layout found is shown in Figure 4.

FIGURE 4 – First Laboratory Airlift Pumping System

Preliminary Lab Airlift Pumping System



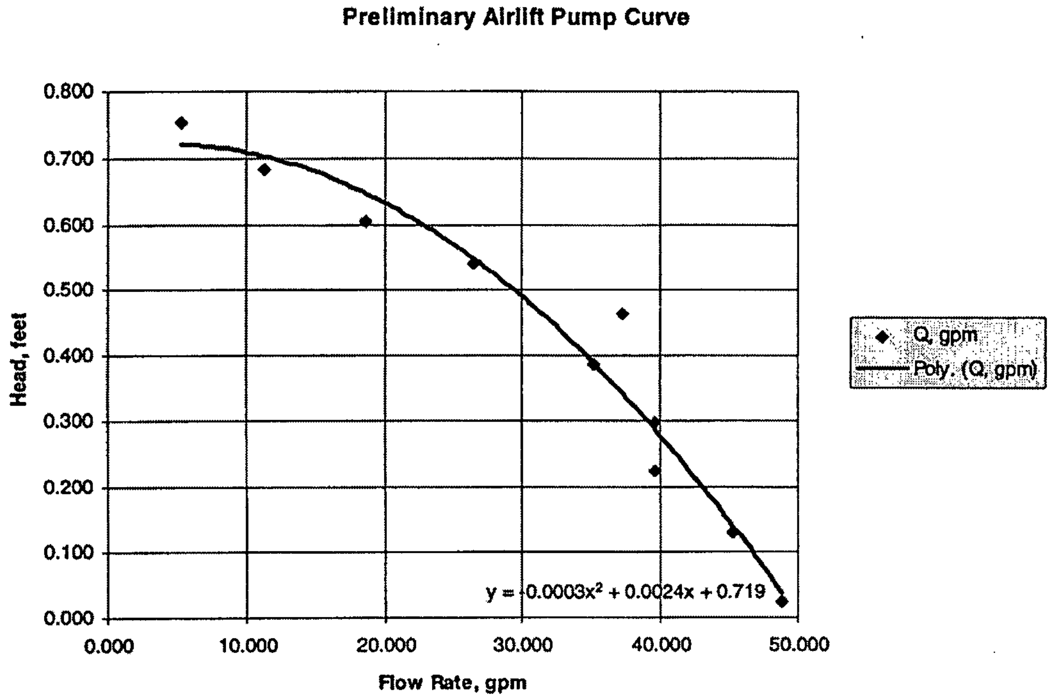
all dimensions in mm

Several aerator designs were also tried, with little improvement in efficiency. Circulation was evident as a very important (and previously much under-estimated) effect in these high-flow, low-submergence scenarios.

The best performing setup in the preliminary experiment was measured for performance and provided the first clues to the shapes of pump discharge curves for systems of this nature. Figure 5 shows the sample data set and resulting discharge curve for this system.

The second experimental setup was a simple test intended to determine the possibility of a larger-scale system based on the same conceptual layout as the first small-scale system. The larger scale system built in a large 20-inch wide hydraulics flume at the University of British Columbia Department of Civil Engineering. This system was designed to determine the feasibility of airlift pump technology at prototype scale for very shallow

FIGURE 5 – First Laboratory Airlift Pumping System Results

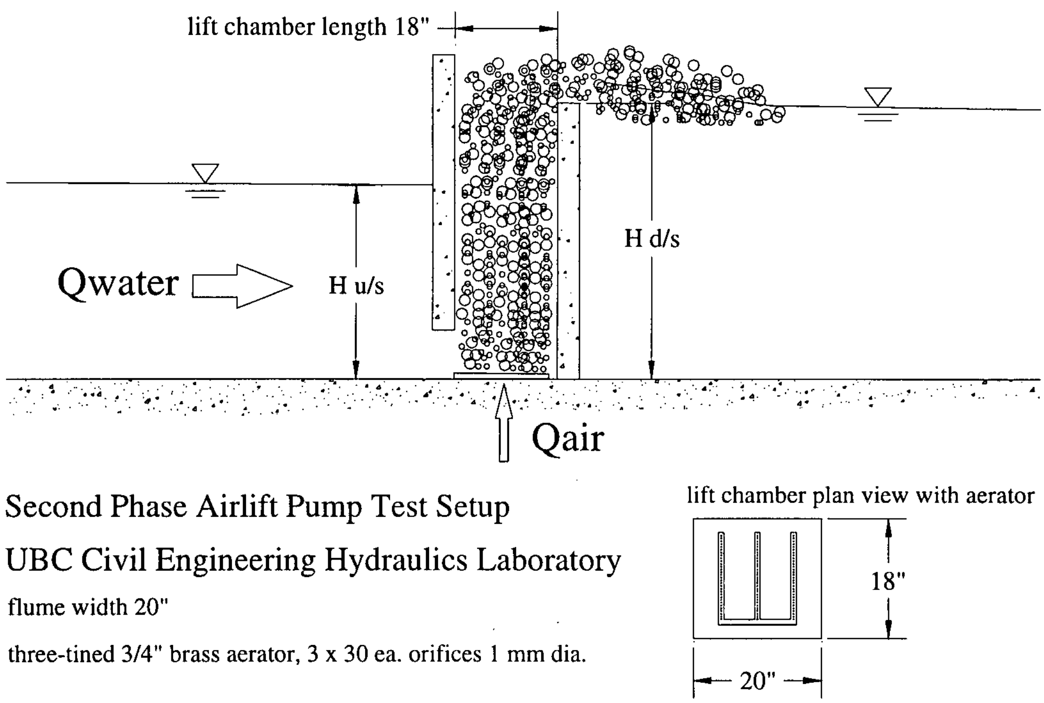


These operating characteristics are for the model pump which has a width of 156mm and hence an operational lift chamber plan area of 29640 mm^2.

Lift, mm	Q, l/s	Lift, feet	Q, gpm
226.000	0.333	0.753	5.283
205.000	0.714	0.683	11.321
182.000	1.176	0.607	18.647
162.000	1.667	0.540	26.417
116.000	2.222	0.387	35.222
139.000	2.353	0.463	37.294
67.000	2.500	0.223	39.625
89.000	2.500	0.297	39.625
39.000	2.857	0.130	45.286
7.000	3.077	0.023	48.769

insertion depths. Several tests were run and results were promising. Circulation was very strongly evident in the large 18" x 20" lift chamber. Accurate instruments for measuring the airflow in the system were not available and therefore direct numerical results for airflow were not collected. This was not considered a drawback because the larger scale laboratory airlift unit did prove the concept at the prototype scale despite serious submergence limitations and limitations in the air flow rate possible from the installed screw compressor-based air delivery system. Figure 6 shows the second experimental setup and Table 2 shows numerical results of this phase of the study.

FIGURE 6 – Prototype Scale Laboratory Airlift Pumping System



Second Phase Airlift Pump Test Setup

UBC Civil Engineering Hydraulics Laboratory

flume width 20"

three-tined 3/4" brass aerator, 3 x 30 ea. orifices 1 mm dia.

TABLE 2 – Prototype Scale Laboratory Airlift Pumping System Results

Airlift Flow Test 2
Aaron Bohnen
UBC Civil Engineering Hydraulics Lab

Flow baffle height	Hds	25.5 in	0.65 m
Weir crest height	Pweir	23 in	0.59 m
Weir crest width	Wweir	19.5 in	0.50 m

Coefficient of Discharge = 0.63 for this test.

Q=Cd*(2/3)*L*H^(3/2)*SQRT(2*g)

Head d/s (Hds, in)	Head u/s (Hus, in)	Weir head (Hweir, in)	lift (delta H, in)	Flow (m^3/s)	Flow (l/s)	Flow (cfs)
25.5	26.0	5.5	-0.5	0.050	49.5	1.75
25.5	24.5	5.3	1.0	0.046	46.2	1.63
25.5	24.0	5.0	1.5	0.043	42.9	1.52
25.5	23.0	4.5	2.5	0.037	36.6	1.29
25.5	22.5	4.3	3.0	0.034	33.6	1.19
25.5	22.0	4.3	3.5	0.034	33.6	1.19
25.5	21.5	4.0	4.0	0.031	30.7	1.09
25.5	20.3	3.5	5.3	0.025	25.1	0.89
25.5	18.5	2.8	7.0	0.018	17.5	0.62
25.5	17.0	2.0	8.5	0.011	10.9	0.38
25.5	16.0	1.5	9.5	0.007	7.1	0.25
25.5	15.0	1.0	10.5	0.004	3.8	0.14
25.5	14.5	0.5	11.0	0.001	1.4	0.05
25.5	14.0	0.3	11.5	0.000	0.5	0.02

Notes:
Pressure at 100 psi delivered, approx. 4 psi at aerator
20" wide in 39" tall flume
four-tined 3/4" diam aerator - 1mm holes

The limited airflow available from the screw-based compressor slowed development until a four horsepower gasoline engine-powered centrifugal blower was obtained from the university equipment salvage program. The blower was overhauled, performance was evaluated and fittings were designed to adapt it to the experimental setup. The centrifugal blower was not installed in the second laboratory experimental setup since at this time a full-scale prototype location was selected in the City of Richmond and the experimental program shifted focus to that location.

The third set of prototype experimental equipment was developed, assembled and installed just upstream of one of the flood boxes at the outlet of a drainage conduit at the Gilbert Road storm water outfall in Richmond. The experimental setup was installed over the winter of 1997 to 1998. It originally consisted of three different pump designs aimed at investigating key features of the proposed pumps. The original equipment was comprised of two, ten-inch diameter pump units and one, twelve-inch diameter unit. One of the ten-inch diameter pump units was constructed from clear acrylic pipe, allowing visual inspection of the mixture flow regime within the pump riser pipe.

Water was introduced from an upstream chamber over a V-notch weir and pumped by the experimental airlift units into a downstream chamber. Another V-notch weir at the output of the downstream chamber enabled the water pumping flowrate to be measured. Water levels were read from staff gauges.

Tests were run until the system had stabilized, at which point measurements of all the water levels and airflow rates were taken. The water levels were used to find the flowrates by conventional V-notch weir analysis. Figures 7 and 8 show the original prototype layout at the Gilbert Road location. Additional large-scale system and site drawings can be found in Appendix 1.

FIGURE 7 – Gilbert Road Prototype Airlift System Layout

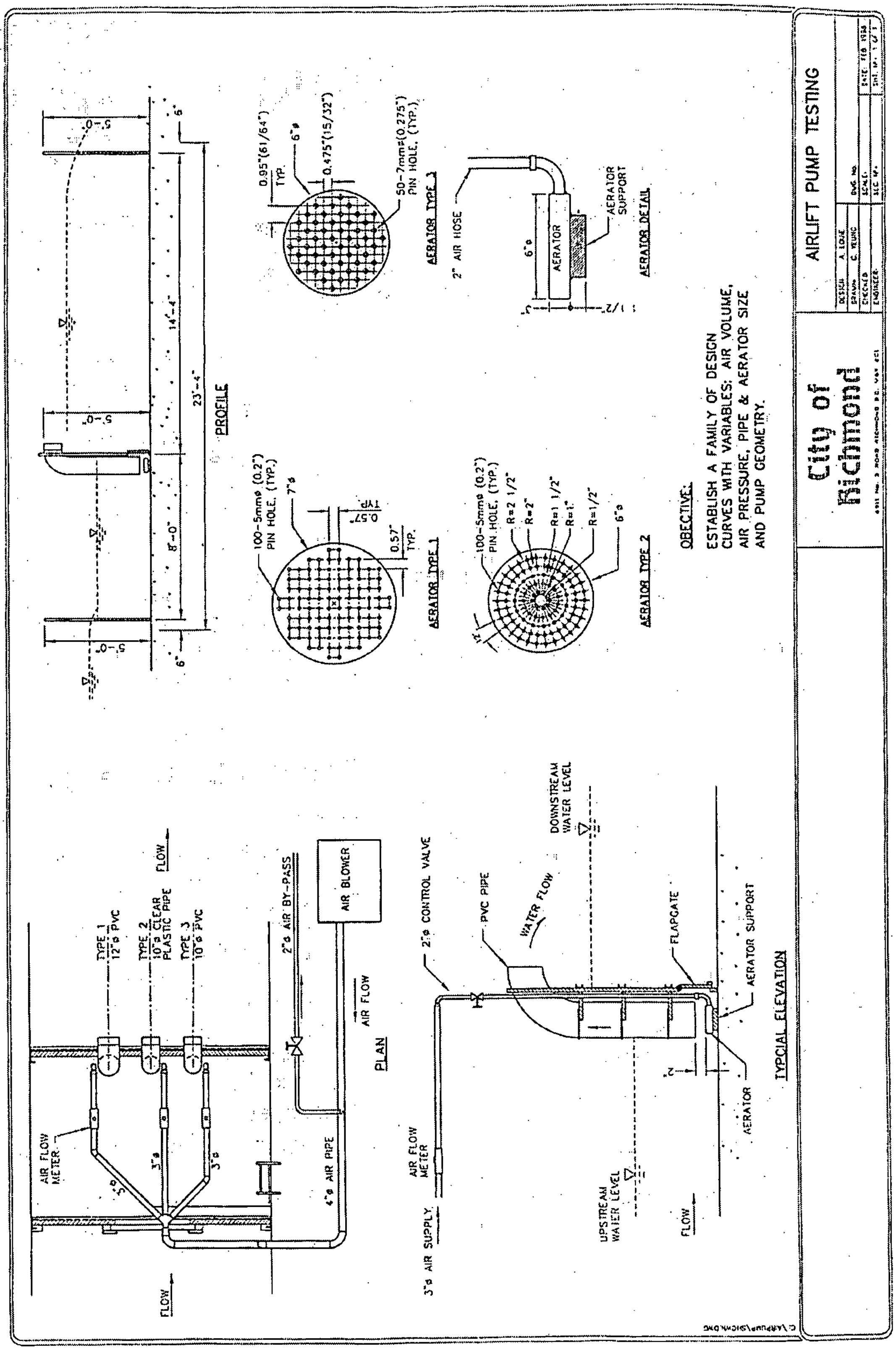
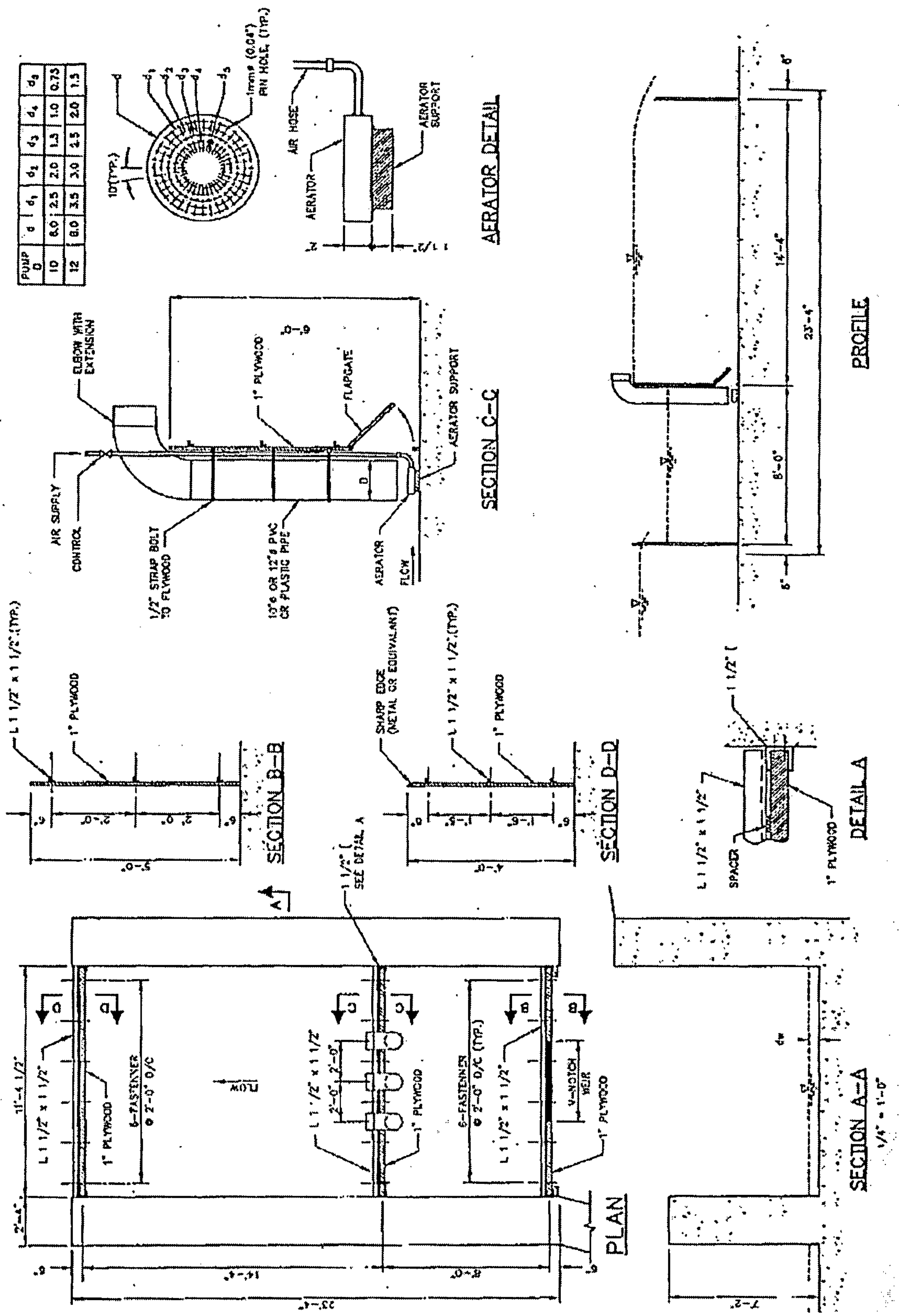


FIGURE 8 – Gilbert Road Prototype Airlift System Components



Compressed air was supplied to diffusers located beneath each pump unit by a 28 horsepower Comair-Rotron positive displacement blower unit and pipe distribution system. This unit was installed in a soundproofed shed and equipped with intake and discharge filters and silencers. Since positive displacement blowers provide a constant rate of airflow, individual valves were installed at each pump unit and a bypass added. In this way each pump unit could be tested individually. Venturi-style air velocity meters were also installed to allow air flow to each pump unit to be individually monitored. Figure 9 shows the air supply system at the Gilbert Road site. Figure 10 shows the prototype system in operation. Large-scale site drawings in Appendix 2 show the installation of the air supply subsystem at the Gilbert Road location.

FIGURE 9 – Gilbert Road Compressed Air Supply Subsystem

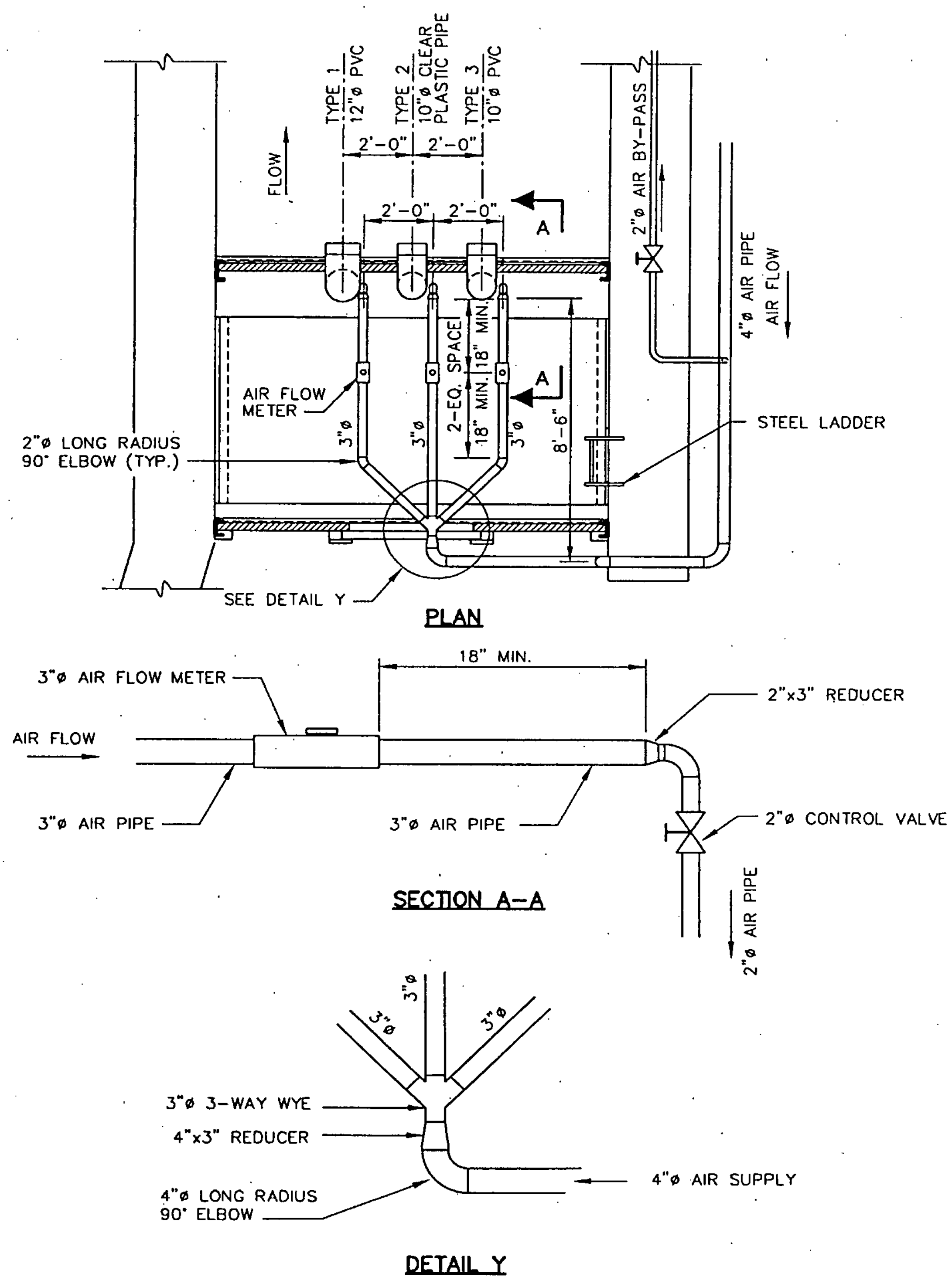
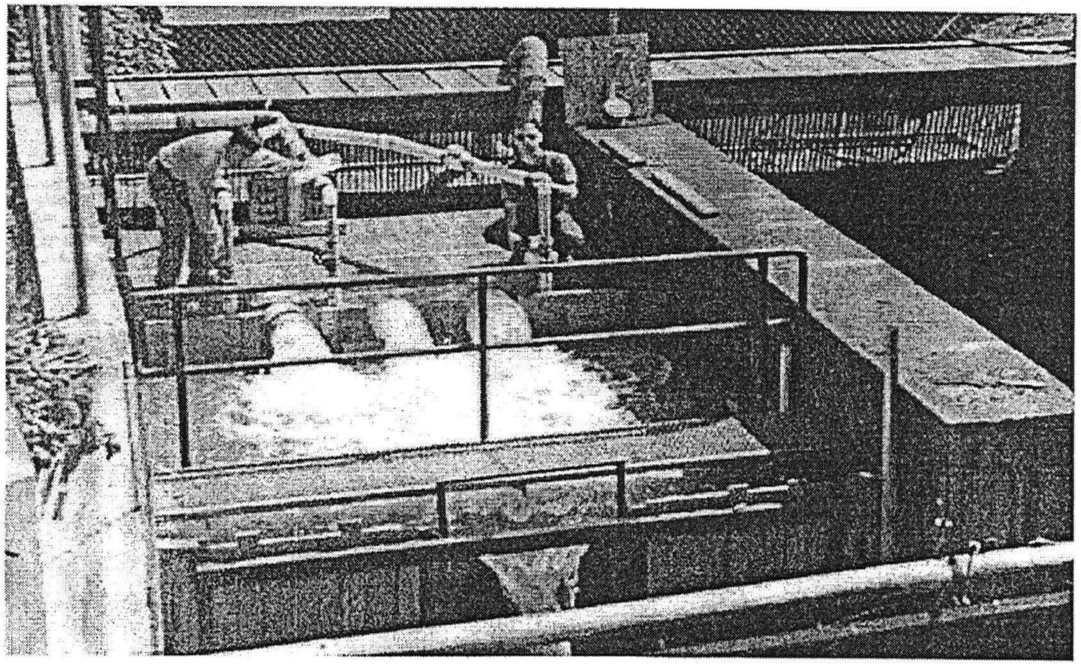


FIGURE 10 – Gilbert Road Prototype Airlift System in Operation



The original system as tested was moderately successful at pumping water and provided tremendous insight into the operation of the pump units, particularly by the ability to observe the mixture flow pattern in the acrylic ten-inch diameter unit (the centre unit shown in Figures 9 and 10). The original prototype setup identified several weaknesses in the physical layout and construction of the layout at the prototype site. Leakage between upstream and downstream chambers was found to be particularly problematic. Additionally, the abnormally low levels of water in the drainage conduit leading to the site over the winter of 1997/1998 made testing at only one level of upstream flow possible. A portable pump was introduced to increase the level in the upstream conduit but this had only limited success.

These difficulties led to delay in this phase of the program as several revisions to the site system layout and air distribution layout were developed, drafted and implemented. This work progressed over much of the Spring of 1998.

The results from the tests of these prototype units were more scattered than expected but clearly showed the importance of design details. Although reduced, leakage between chambers continued to be problematic despite the system revisions, and a breakdown of the compressed air delivery system created further difficulties.

Some of the data and calculations from the third experimental setup are shown in Table 3. Table 4 shows sample velocity and loss calculations for the data shown in Table 3. Table 5 shows the leakage test data collected at this site. Table 6 shows a sample of later data and also calculations for the loss coefficients of the three original prototype pump systems at the Gilbert Road site.

When analyzed, the results of this phase of testing indicated systemic problems with the alternatives being investigated. The large diameters pipes had very low packing density in the space-constrained storm drain scenario. Also no aerator geometry was found to be highly successful in sharply maximizing efficiency. This was likely due to several factors, primarily the practical issue of leakage and the prevalent recirculating flow patterns in the pump risers.

TABLE 3 – Gilbert Road Prototype Airlift System Sample Experimental Data

Results march 9, 1998

Outside wl = 33 Vee notch = 34

Pump	U/ wl	d/s wl	air cfm	Flow	pipe dia	area	qmix	vmix	inches head loss	Mix density	vwat	vair	vrel
									2.5	8			
2	35.000	40.25	250	0.676762	0.833	0.54498	4.843429	8.887344	36.7942	0.391054	0.485614	12.55535	12.06974
	34.500	39.75	250	0.578271	0.833	0.54498	4.744937	8.70662	35.313	0.395151	0.419289	12.6404	12.22111
	34.500	39	250	0.450973	0.833	0.54498	4.617639	8.473037	33.44365	0.411212	0.340279	12.98521	12.64493
	39.000	41.5	250	0.974318	0.833	0.54498	5.140985	9.433339	41.45398	0.413587	0.739413	13.0378	12.29839
2	38.750	41.25	200	0.908704	0.833	0.54498	4.242037	7.783834	28.22426	0.500209	0.834052	12.23798	11.40393
	35.250	40.75	200	0.786746	0.833	0.54498	4.120079	7.56005	26.6247	0.45895	0.66255	11.30473	10.64218
	35.000	40.5	200	0.730287	0.833	0.54498	4.06362	7.456452	25.9	0.462329	0.619532	11.37578	10.75624
2	35.000	40.5	150	0.730287	0.833	0.54498	3.230287	5.927345	16.3665	0.552526	0.740398	10.25159	9.511189
	35.000	40.75	150	0.786746	0.833	0.54498	3.286746	6.030943	16.94361	0.543329	0.784363	10.04514	9.26078
	37.750	41.62	150	1.006934	0.833	0.54498	3.506934	6.434972	19.28984	0.562277	1.038892	10.47997	9.441076
2	38.000	41.5	100	0.974318	0.833	0.54498	2.640985	4.846018	10.9397	0.675072	1.206897	9.411976	8.205079
	34.500	40	100	0.626111	0.833	0.54498	2.292777	4.207082	8.245128	0.658465	0.756489	8.954315	8.197826
1	40.250	41	250	0.846199	0.833	0.54498	5.012866	9.198249	39.41356	0.406102	0.63056	12.87348	12.24292
	33.500	38	250	0.316525	0.833	0.54498	4.483191	8.226335	31.5245	0.356521	0.207068	11.88156	11.6745
	35.000	38	200	0.316525	0.833	0.54498	3.649858	6.697228	20.89419	0.443392	0.257522	10.98875	10.73123
	39.750	41	200	0.846199	0.833	0.54498	4.179532	7.669142	27.39864	0.471078	0.731449	11.56395	10.8325
	37.000	40	150	0.626111	0.833	0.54498	3.126111	5.736189	15.32789	0.524148	0.602177	9.640225	9.038048
	35.500	39	150	0.450973	0.833	0.54498	2.950973	5.414823	13.65853	0.5125	0.424095	9.40989	8.985795

TABLE 4 – Gilbert Road Prototype Airlift System Sample Experimental Results

Results March 9, 1998

1	2	3	4	5	6	7	8	9	10	11	12	13
Pump	Us/ wl	d/s wl	Air	Water	Vmix	Dens	Vw	Head loss	L/Vm^2	Vm^2*Den	L/Vw^2	-exit/vw^2
	ins.	ins.	cfs	cfs	ft/sec		ft/sec	feet				
2	35.00	57.75	4.17	0.68	8.96	0.23	5.53	1.44	1.16	5.12	3.03	2.44
	34.50	57.75	4.17	0.58	8.78	0.21	5.05	1.46	1.22	5.78	3.69	3.05
	34.50	57.75	4.17	0.45	8.54	0.19	4.34	1.55	1.36	7.10	5.29	4.55
	39.00	57.75	4.17	0.97	9.51	0.27	6.76	1.60	1.14	4.28	2.26	1.73
						1.00						
2	38.75	57.75	3.33	0.91	7.83	0.30	5.54	1.42	1.49	4.92	2.98	2.38
	35.25	57.75	3.33	0.79	7.61	0.29	5.10	1.21	1.34	4.71	2.99	2.36
	35.00	57.75	3.33	0.73	7.51	0.28	4.89	1.23	1.40	5.07	3.31	2.65
						1.00						
2	35.00	57.75	2.5	0.73	5.97	0.34	4.00	0.96	1.74	5.16	3.87	3.12
	35.00	57.75	2.5	0.79	6.08	0.35	4.19	0.92	1.61	4.63	3.37	2.65
	37.75	57.75	2.5	1.01	6.48	0.38	4.87	1.00	1.53	3.99	2.71	2.03
						1.00						
2	38.00	57.75	1.67	0.97	4.89	0.48	3.79	0.62	1.66	3.49	2.76	1.97
	34.50	57.75	1.67	0.63	4.24	0.41	2.81	0.60	2.15	5.22	4.89	3.95
						1.00						
1	40.25	54.5	4.17	0.85	9.27	0.25	6.27	1.85	1.38	5.54	3.03	2.48
	33.50	54.5	4.17	0.32	8.29	0.17	3.43	1.60	1.50	8.80	8.77	7.77
	35.00	54.5	3.33	0.32	6.74	0.20	2.86	1.59	2.25	11.00	12.54	11.40
	39.75	54.5	3.33	0.85	7.72	0.29	5.32	1.62	1.76	5.97	3.70	3.08
	37.00	54.5	2.5	0.63	5.78	0.32	3.64	1.30	2.50	7.86	6.32	5.51
	35.50	54.5	2.5	0.45	5.45	0.28	2.93	1.31	2.84	9.98	9.80	8.82
	Outside wl = 33		Vee notch = 34				Average #2		1.48	4.96	3.43	2.74
							Av. #1		2.04	8.19	7.36	6.51
							Sdev #2		0.28	0.91	0.89	0.82
							Sdev #1		0.58	2.17	3.69	3.46
							CV #2		0.19	0.18	0.26	0.30
							CV #1		0.29	0.26	0.50	0.53

TABLE 5 – Gilbert Road Prototype Airlift System Leakage Tests

Pump Data from May 1 tests

Air	U/s W.L	D/S W.L	Weir	Weir flow	Leaks	Total
No 3 pump - 12"						
250	46.5	50.5	41.75	1.127673	0.33775	1.465423
250	44.5	50	41.75	0.974561	0.334608	1.309169
250	37.5	48	41.75	0.489537	0.321734	0.811271
250	38	48.75	41.25	0.769405	0.326621	1.096026
250	46	50	41.25	1.127673	0.334608	1.462281
250	42.5	49.5	41.25	0.974561	0.331436	1.305998
200	45	50	41.75	0.974561	0.334608	1.309169
200	38.25	48	41.75	0.489537	0.321734	0.811271
150	47	50	41.75	0.974561	0.334608	1.309169
150	44.5	50	41.75	0.974561	0.334608	1.309169
150	38	48	41.75	0.489537	0.321734	0.811271
100	45.5	49	41.75	0.707362	0.328234	1.035596
No 2 pump						
250	48	49	41.75	0.707362	0.328234	1.035596
250	45	48	41.75	0.489537	0.321734	0.811271
250	37.5	47	41.75	0.317686	0.315099	0.632785
220	39	48	41.25	0.592484	0.321734	0.914218
200	45.5	48.5	41.75	0.592484	0.325	0.917484
150	48.5	49	41.75	0.707362	0.328234	1.035596
150	45.5	48.5	41.75	0.592484	0.325	0.917484
150	39	47	41.75	0.317686	0.315099	0.632785
100	45.5	48	41.75	0.489537	0.321734	0.811271
No 1 pump						
250	48	49	41.75	0.707362	0.328234	1.035596
250	45	48	41.75	0.489537	0.321734	0.811271
250	38.5	47	41.75	0.317686	0.315099	0.632785
200	46	48.5	41.75	0.592484	0.325	0.917484
200	38	47	41.75	0.317686	0.315099	0.632785
150	49	49	41.75	0.707362	0.328234	1.035596
150	46	49	41.75	0.707362	0.328234	1.035596
150	39.5	47	41.75	0.317686	0.315099	0.632785
100	46.5	48.5	41.75	0.592484	0.325	0.917484

TABLE 6 – Gilbert Road Prototype Airlift System Sample Experimental Results 2

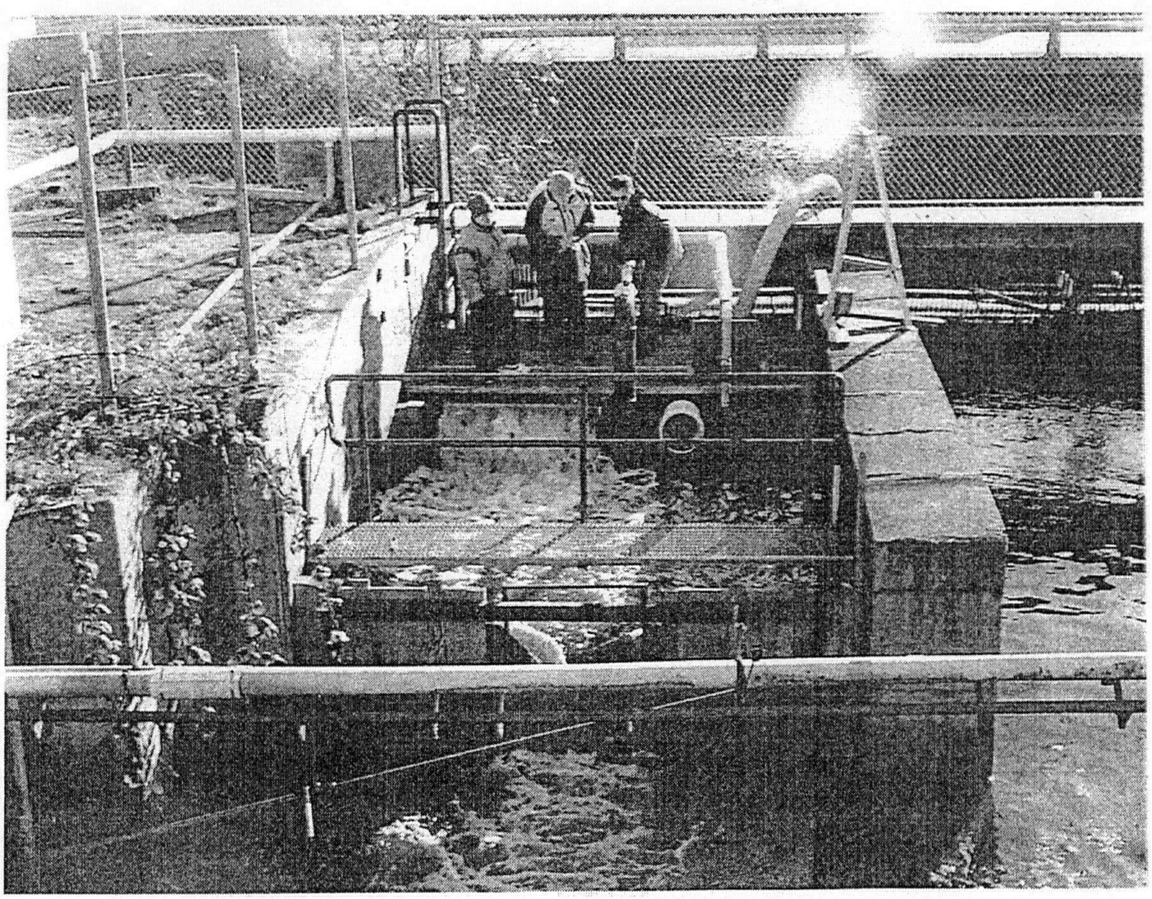
Tests May 1, 1998

1	2	3	4	5	6	7	8	9	10	11	12	13
Pump	U/S wl ins.	d/s wl ins.	Air cfs	Water cfs	Pipe area sq. ft.	V mix ft/sec	Dens	Vw ft/sec	Head loss feet	L/Vm^2	L/d*Vm^2	L/Vw^2
3	46.50	53.50	4.17	1.80	0.79	7.60	0.38	5.99	1.86	2.07	5.42	3.34
3	44.50	53.50	4.17	1.31	0.79	6.97	0.33	4.98	1.88	2.50	7.46	4.89
3	37.50	53.50	4.17	0.81	0.79	6.34	0.28	3.73	1.53	2.45	8.84	7.08
3	38.00	53.50	4.17	1.10	0.79	6.70	0.31	4.49	1.44	2.06	6.62	4.59
3	46.00	53.50	4.17	1.46	0.79	7.17	0.35	5.31	1.95	2.44	6.96	4.44
3	42.50	53.50	4.17	1.31	0.79	6.97	0.33	4.98	1.72	2.28	6.82	4.47
3	45.00	53.50	3.33	1.70	0.79	6.41	0.43	5.07	1.56	2.44	5.72	3.91
3	38.25	53.50	3.33	1.20	0.79	5.77	0.37	4.09	1.21	2.34	6.27	4.65
3	47.00	53.50	2.50	1.31	0.79	4.85	0.46	3.66	1.61	4.41	9.68	7.77
3	44.50	53.50	2.50	1.31	0.79	4.85	0.46	3.66	1.40	3.84	8.43	6.76
3	38.00	53.50	2.50	0.81	0.79	4.22	0.39	2.65	1.12	4.07	10.45	10.30
3	45.50	53.50	1.67	1.04	0.79	3.44	0.52	2.53	1.22	6.66	12.76	12.37
2	48.00	57.75	4.17	1.04	0.55	9.55	0.28	6.91	2.31	1.64	5.95	3.12
2	45.00	57.75	4.17	0.81	0.55	9.13	0.25	6.06	2.19	1.69	6.89	3.84
2	37.50	57.75	4.17	0.63	0.55	8.81	0.22	5.27	1.67	1.39	6.31	3.89
2	39.00	57.75	3.67	0.91	0.55	8.41	0.28	5.89	1.52	1.39	4.87	2.82
2	45.50	57.75	3.33	0.92	0.55	7.80	0.30	5.52	1.98	2.09	6.86	4.18
2	48.50	57.75	2.50	1.04	0.55	6.49	0.39	4.91	1.87	2.86	7.39	5.01
2	45.50	57.75	2.50	0.92	0.55	6.27	0.37	4.56	1.70	2.78	7.54	5.26
2	39.00	57.75	2.50	0.63	0.55	5.75	0.32	3.63	1.37	2.67	8.33	6.71
2	45.50	57.75	1.67	0.81	0.55	4.55	0.45	3.32	1.36	4.23	9.42	7.94
1	48.00	54.50	4.17	1.04	0.55	9.55	0.28	6.91	2.39	1.69	6.14	3.22
1	45.00	54.50	4.17	0.81	0.55	9.13	0.25	6.06	2.26	1.74	7.10	3.96
1	38.50	54.50	4.17	0.63	0.55	8.81	0.22	5.27	1.82	1.51	6.85	4.22
1	46.00	54.50	3.33	0.92	0.55	7.80	0.30	5.52	2.10	2.22	7.29	4.44
1	38.00	54.50	3.33	0.63	0.55	7.28	0.26	4.45	1.61	1.96	7.51	5.25
1	49.00	54.50	2.50	1.04	0.55	6.49	0.39	4.91	2.02	3.09	7.97	5.40
1	46.00	54.50	2.50	1.04	0.55	6.49	0.39	4.91	1.77	2.71	6.98	4.73
1	39.50	54.50	2.50	0.63	0.55	5.75	0.32	3.63	1.50	2.92	9.11	7.34
1	46.50	54.50	1.67	0.92	0.55	4.74	0.47	3.60	1.49	4.26	9.11	7.38
								Average #3		3.13	7.95	6.21
								Stdev #3		1.38	2.17	2.77
								CV #3		0.44	0.27	0.45
								Average #2		2.30	7.06	4.75
								Std #2		0.93	1.33	1.68
								CV #2		0.40	0.19	0.35
								Average #1		2.45	7.56	5.10
								Std #1		0.88	1.01	1.44
								CV #1		0.36	0.13	0.28

A second prototype concept was then designed and built at the Gilbert Road location. This system was conceived in an attempt to maximize the use of the available plan area in the constrained space of a drainage conduit. The concept was based on the original lab model that used the full width of a small flume. A full-width built-in pump assembly was designed. It formed a continuous side-to-side element in the base of the drainage conduit.

Such a unit would have superior aeration density and make maximally-efficient use of the limited plan area in the base of the conduit. The result was a lateral slot-based pump and aerator. This unit was built in the form of a slot four feet long by one foot wide for the air-water mixture. A horizontally oriented cylindrical aerator was designed and installed at the base of the unit. If this proved successful the intention was to adopt the design concept and build airlift pump units that could span across the entire width of rectangular box culvert. Large-scale drawings of the slot-configured airlift pump system can be found in Appendix 2. Figure 11 shows the slot-configured airlift pump in operation.

Figure 11 – Slot-Configured Airlift Pump in Operation



This system was tested under adverse conditions with very little upstream depth available. Nevertheless, it identified an unanticipated and major problem with the "slot" design. Water tended to "slosh" from side to side in the pump unit body, but very little was effectively lifted. It was observed that when the water was high at one end of the slot it gave a large enough back pressure to the orifices there to create an increased flow of air from the orifices at the other end. In this way the air tended to escape from the system. When the water sloshed back to the other end of the system the air escaped from the first end. Thus, although a considerable amount of spray was created very little water was pumped. The immediate failure of this design showed convincingly that large capacity airlift pump systems must be designed to prevent this sloshing behaviour, effectively a one-dimensional recirculation effect analogous to that which had been observed in the cylindrical units. This test confirmed the findings of the first test, namely that circulation could easily develop within the pump riser pipes, greatly reducing pump efficiency.

The third experimental phase was successful in pointing the way forward. The design concept was revised to minimize the two most severe problems encountered at the Gilbert Road site, namely circulation within the riser pipes and leakage between the test chambers. The large ten and twelve-inch diameter pump barrels were replaced with eight, six, four, and three-inch units. This was considered a useful means of reducing circulation and turned out to be very effective. It was also decided to test the effect of inclining the pump tubes. Wallis (1969) asserts that inclination up to approximately 40 degrees from the vertical does not adversely affect bubble velocity, and inclining the pump riser tubes in this way promised reduced construction costs by requiring fewer pipe fittings.

This fourth phase of the experimental program was carried out over the course of several months at the Richmond Public Works Yard. Plastic pipes were set up in a tank with a metered water supply and metered compressed air supplied from a single jet at the bottom of each pump's riser tube. Since aerator configuration had little discernible effect in previous phases of the project, aerator designs were not tested in this phase. The pipes were inclined from zero to thirty degrees from the vertical. The flow of air and water were set and when the water level stabilized in the tank, the stable depth of water in the tank was read. Figure 12 shows the experimental setup for this phase of the project.

Various combinations of air and water flow and pipe diameters were tested in an "evolutionary" manner – starting with one pipe at one upstream water level and varying downstream water levels for a given air flow rate. The tests showed that for a given flow of air the inclination away from the vertical of the pump riser pipes within the range of zero to thirty degrees did not seem to affect the water flow rates. The overall results still evidenced some scatter but this was at least partly due to unavoidable variations in the position of the air jets in the bottom of each pipe riser tube and other minor factors such as the resolution of the meters used, etc.

Data from this experimental phase was far more consistent than that from the third experimental setup since upstream and downstream water levels could be precisely controlled and there was no leakage from the sealed tanks. Table 7 shows sample experimental data from this series of experimental tests.

FIGURE 12 – Richmond Public Works Experimental Setup

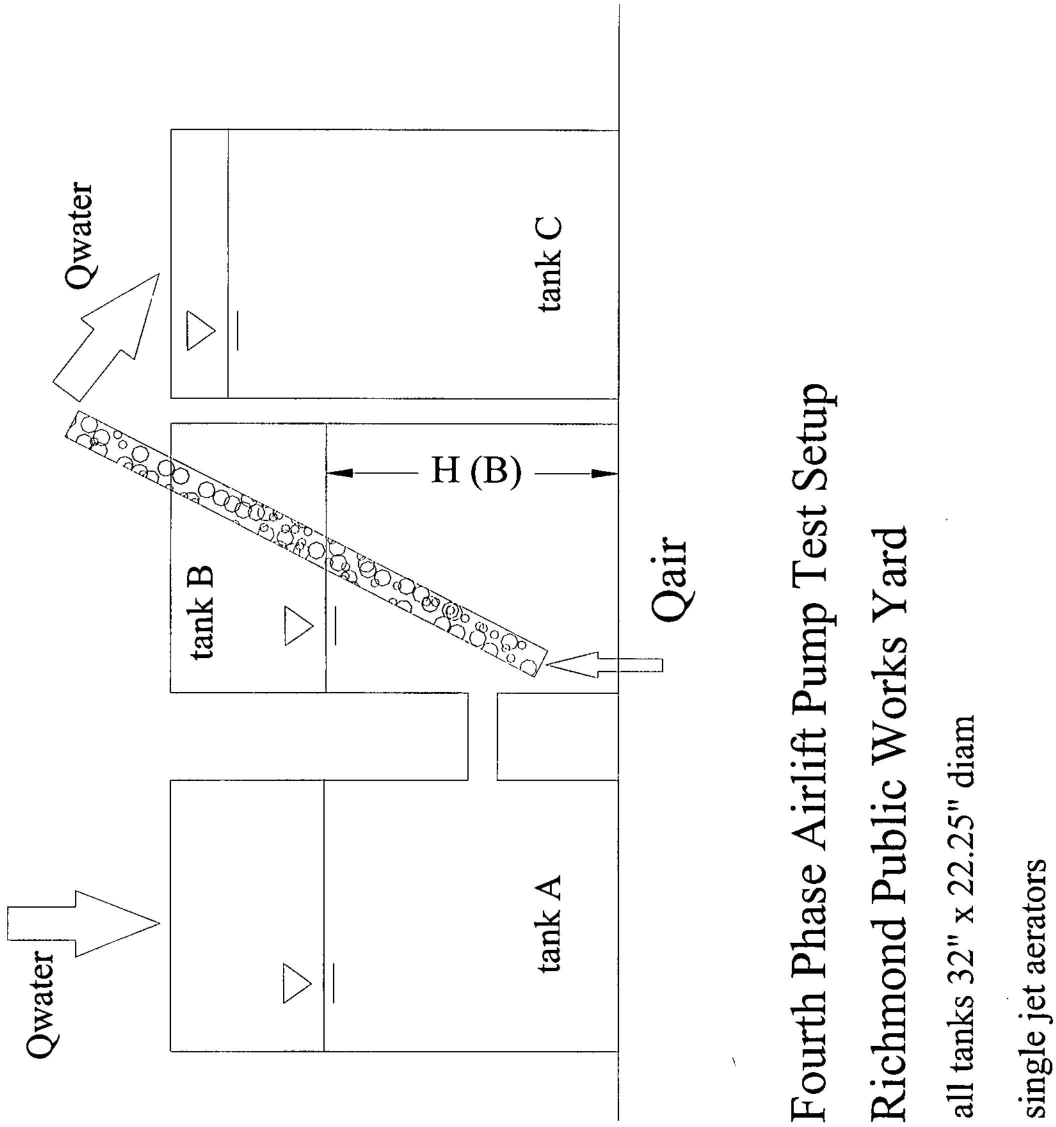


TABLE 7 – Richmond Public Works Sample Experimental Data

Dia. Inches	Water flow m^3/min	Air flow cfm	W.L cm	Height above noz inches	True dia inches	Dia feet	Area sq. feet	Water flow	Air flow	Mix v	Air vel	Air %	Density	Water v	U/s water	D/s water	Loss - feet
Made up pipe sections						Calcs											
3	0.16	60	81.8	38.75	2.875	0.239583	0.045059	0.094133	1	24.28216	30.1386	0.736367	0.263633	7.924288	2.060367	3.229167	1.209051
3	0.16	80	77.5	38.75	2.875	0.239583	0.045059	0.094133	1.333333	31.67985	39.01582	0.758429	0.241571	8.648015	1.919291	3.229167	1.139219
3	0.16	100	77.5	38.75	2.875	0.239583	0.045059	0.094133	1.666667	39.07754	47.89304	0.772313	0.227687	9.175352	1.919291	3.229167	1.184053
3	0.16	120	76.5	38.75	2.875	0.239583	0.045059	0.094133	2	46.47522	56.77027	0.781855	0.218145	9.576687	1.886483	3.229167	1.182056
																	0
4	0.25	60	76	35.75	3.75	0.3125	0.07666	0.147083	1	14.96323	18.95587	0.688155	0.311845	6.152555	1.870079	2.979167	0.941042
4	0.26	80	78	35.75	3.75	0.3125	0.07666	0.152967	1.333333	19.38817	24.2658	0.716761	0.283239	7.044888	1.935696	2.979167	1.091879
4	0.27	60	78.5	35.75	3.75	0.3125	0.07666	0.15885	1	15.11672	19.14006	0.681533	0.318467	6.506587	1.9521	2.979167	1.003334
4	0.26	120	77.5	35.75	3.75	0.3125	0.07666	0.152967	2	28.08456	34.70147	0.751817	0.248183	8.039997	1.919291	2.979167	1.179914
4	0.26	120	74	35.75	3.75	0.3125	0.07666	0.152967	2	28.08456	34.70147	0.751817	0.248183	8.039997	1.804462	2.979167	1.065085
4	0.26	100	75	35.75	3.75	0.3125	0.07666	0.152967	1.666667	23.73636	29.48364	0.737391	0.262609	7.598327	1.83727	2.979167	1.054915
																	0
6	0.4	120	74	36.15	5.75	0.479167	0.180237	0.235333	2	12.40222	15.88266	0.698657	0.301343	4.332903	1.804462	3.0125	0.896665
6	0.48	60	75.7	36.15	5.75	0.479167	0.180237	0.2824	1	7.115094	9.538113	0.581694	0.418306	3.745656	1.860236	3.0125	0.60009
6	0.45	100	74.5	36.15	5.75	0.479167	0.180237	0.26475	1.666667	10.71601	13.85921	0.667217	0.332783	4.414001	1.820866	3.0125	0.818358
6	0.46	80	76.5	36.15	5.75	0.479167	0.180237	0.270633	1.333333	8.899231	11.67908	0.633414	0.366586	4.09602	1.886483	3.0125	0.782141
6	0.45	150	71	36.15	5.75	0.479167	0.180237	0.26475	2.5	15.33956	19.40748	0.714707	0.285293	5.148754	1.706037	3.0125	0.846592
																	0
8	0.26	120	63.5	35.05	7.75	0.645833	0.327424	0.152967	2	6.575469	8.890563	0.687053	0.312947	1.492847	1.459974	2.920833	0.545907
8	0.26	150	57.5	35.05	7.75	0.645833	0.327424	0.152967	2.5	8.102541	10.72305	0.712051	0.287949	1.622448	1.263123	2.920833	0.422073
8	0.26	80	67.5	35.05	7.75	0.645833	0.327424	0.152967	1.333333	4.539373	6.447248	0.631617	0.368383	1.268197	1.591207	2.920833	0.515222
8	0.53	80	78	35.05	7.75	0.645833	0.327424	0.311817	1.333333	5.024524	7.029429	0.579306	0.420694	2.263719	1.935696	2.920833	0.706918
8	0.53	150	68	35.05	7.75	0.645833	0.327424	0.311817	2.5	8.587691	11.30523	0.675383	0.324617	2.933711	1.607612	2.920833	0.659459
8	0.61	150	78	35.05	7.75	0.645833	0.327424	0.358883	2.5	8.73144	11.47773	0.665233	0.334767	3.274157	1.935696	2.920833	0.957896
																	0
Straight pipes																	0
4	0.26	60	78	40	4.25	0.354167	0.098466	0.152967	1	11.70932	15.05119	0.674752	0.325248	4.776363	1.935696	3.333333	0.851536
	0.31	90	77.5	40	4.25	0.354167	0.098466	0.182383	1.5	17.08598	21.50318	0.708441	0.291559	6.352921	1.919291	3.333333	0.947427
	0.37	120	76	40	4.25	0.354167	0.098466	0.217683	2	22.52239	28.02687	0.72472	0.27528	8.03093	1.870079	3.333333	0.952478
																	0
6	0.32	60	79	41.1	5.75	0.479167	0.180237	0.188267	1	6.592818	8.911381	0.622604	0.377396	2.767793	1.968504	3.425	0.675924
	0.4	90	79	41.1	5.75	0.479167	0.180237	0.235333	1.5	9.628088	12.55371	0.662943	0.337057	3.873805	1.968504	3.425	0.814085
	0.43	120	77	41.1	5.75	0.479167	0.180237	0.252983	2	12.50015	16.00018	0.693525	0.306475	4.579885	1.902887	3.425	0.853212
	0.43	140	73.5	41.1	5.75	0.479167	0.180237	0.252983	2.333333	14.34957	18.21948	0.710555	0.289445	4.84935	1.788058	3.425	0.79671
	0.46	140	78	41.1	5.75	0.479167	0.180237	0.270633	2.333333	14.4475	18.33699	0.706002	0.293998	5.107327	1.935696	3.425	0.928752
	0.46	148	78.5	41.1	5.75	0.479167	0.180237	0.270633	2.466667	15.18726	19.22472	0.711881	0.288119	5.211553	1.9521	3.425	0.965294
																	0
8	0.22	120	74	48.8	7.75	0.645833	0.327424	0.129433	2	6.503595	8.804314	0.693783	0.306217	1.290942	1.804462	4.066667	0.559181
	0.22	150	73	48.8	7.75	0.645833	0.327424	0.129433	2.5	8.030667	10.6368	0.717825	0.282175	1.400931	1.771654	4.066667	0.624141

At this point the head loss relationships described in equation s (35) and (36) in chapter 3 were created and used to characterize the system behaviour. A final set of tests were made with a bundle of nine, four-inch diameter plastic pipes at an inclination of 0 to 40 degrees from the vertical. Compressed air was supplied through a manifold of pipes with a one inch jet at the centre of each pump riser pipe.

Although some practical problems remained, the performance of this experimental setup confirmed that the relationships developed in the model for turbulent mixing formed a reasonable basis for airlift pump design in the churn turbulent regime. This successful phase of the program resulted in a reliable data set, providing the basis for calibration of the theoretical model and pointed the way towards a viable airlift pump design for the situation in Richmond.

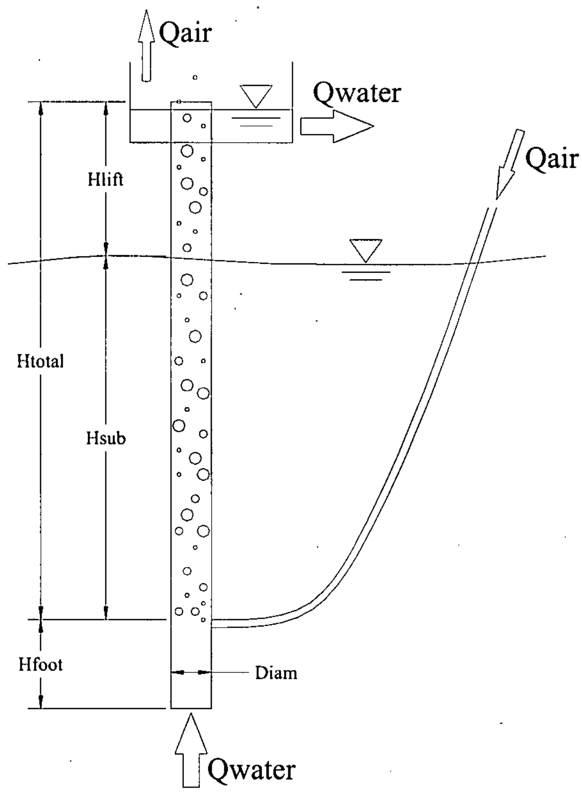
3.3 - Results of the Experimental Program

The lessons from the first two laboratory-based phases of the experimental program indicated the viability of the concept of low-lift high-flow low-submergence airlift pumps for urban storm drainage. The Gilbert Road prototype system suggested several practical considerations for full-scale applications and led the way to the final experimental phase. The final phase produced the reliable data set used to calibrate the head loss relationships developed in the third theoretical model. This experimental program also led to a viable practical design. The results were also used to verify the theoretical model developed to explain low-lift, low-submergence, high-flow airlift pump behaviour in these scenarios, which in turn led to a viable practical engineering design procedure.

CHAPTER 4

4.1 - Airlift Pump Model for Fixed Bubble Slip Velocities

Refer again to Figure 1, reproduced here for convenience:



In static conditions, the pressures inside and outside of the airlift pump tube are equal at the point of aeration.

$$H_{sub} = H_{total} \cdot Dens \qquad (4)$$

Under dynamic conditions air bubbles are rising through the water column within the airlift pump tube and a driving head must be added to the system as described in (4) to maintain the pumping action:

$$H_{sub} = H_{total} \cdot Dens + H_{drive}$$ which can be rearranged to form

$$H_{drive} = H_{sub} - H_{total} \cdot Dens \tag{5}$$

For equilibrium, the driving head must be equal to the losses in the system.

$$H_{drive} = H_{loss} \tag{6}$$

Fluid flow losses are commonly expressed in the form of:

$$headloss = K \cdot \frac{V^2}{2g} \tag{7}$$

so for the case of entrance, pipe and exit losses in the airlift pump system, and assuming that the entrance, pipe and exit losses due to viscosity and fluid friction due to air will be much less than those due to water:

$$H_{loss} = K_{entrance} \cdot \frac{V_{water}^{\ 2}}{2g} + K_{pipe} \cdot \frac{V_{water}^{\ 2}}{2g} + K_{exit} \cdot \frac{V_{water}^{\ 2}}{2g} \tag{8}$$

or for the case in which loss factors for various entrance, pipe and exit geometries are not explicitly considered separately, a combined loss factor can be used:

$$H_{loss} = K_{total} \cdot \frac{V_{water}^{\ 2}}{2g} \tag{9}$$

Combining (3) and (2) and rearranging, get

$$H_{sub} - H_{total} \cdot Dens = K_{total} \cdot \frac{V_{water}^2}{2g} \tag{10}$$

The goal is to determine the combined loss factors K_{total} for representative geometries so that airlift pump performance can be modeled simply by (7). We want to determine the loss factor, so rearrange:

$$K_{total} = 2g \cdot \frac{H_{sub} - H_{total} \cdot Dens}{V_{water}^2} \tag{11}$$

Equation (11) provides the total loss factor for the airlift pump, dependent on the submergence and total pump length, as well as the density of the air-water mixture and the velocity of the water phase.

To solve (11) for the total loss factor we need the density of the air-water mixture in the airlift pump tube and the velocity of the water phase in the airlift pump tube. Considering a representative cross-section of the air-water mixture flowing in the airlift pump tube, the relative density of the air-water mixture in the airlift pump tube is given by:

$$Dens = \frac{A_{water}}{Area} \tag{12}$$

To solve (11), the area of the pump cross section occupied by the water phase is also needed. To obtain the area occupied by the water phase, the velocity of the water phase and the velocity and area occupied by the air phase are required.

To get the velocity of the water fraction of the mixture, consider continuity of the volume flow rates of the mixture and of each phase in the airlift pump tube:

$$Q_{mix} = V_{mix} \cdot A_{mix} \tag{13}$$

$$Q_{air} = V_{air} \cdot A_{air} \tag{14}$$

$$Q_{water} = V_{water} \cdot A_{water} \tag{15}$$

also the volume flow rate of the mixture is composed of the sum of the volume flow rates of the air and water phases:

$$Q_{mix} = V_{mix} \cdot A_{mix} + V_{water} \cdot A_{water} \tag{16}$$

and the total cross-sectional area in the airlift pump tube is simply composed of the sum of the areas occupied by the air and water phases:

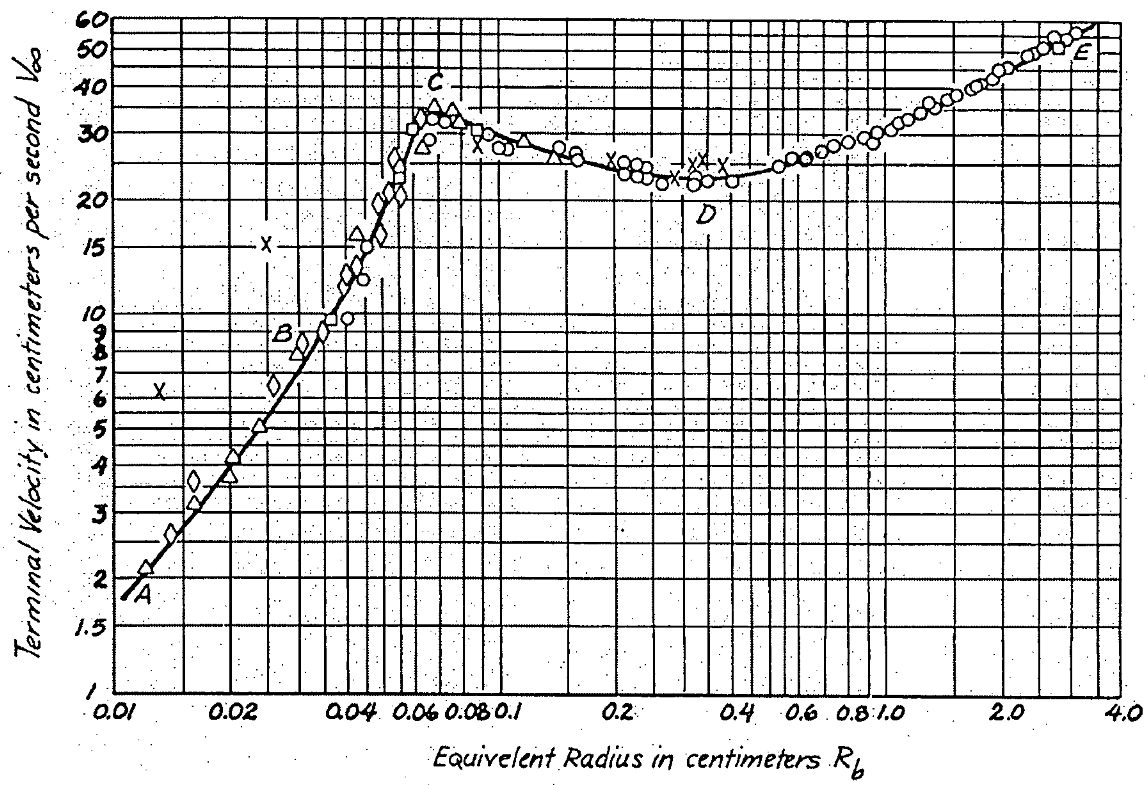
$$A_{mix} = A_{water} + A_{air} \tag{17}$$

Nicklin (1962) suggests that in the slug flow regime for still water and where Taylor bubble diameter and pipe diameter are very similar,

$$V_{bubble} = 0.35\sqrt{g \cdot Diam} \qquad (2)$$

If Taylor bubbles were to be found in the 3 to 12-inch diameter airlift pump riser tubes in this study, Nicklin (1962)'s equation (2) would suggest their rise velocities to be within the 1.1 to 2 foot per second range. Classical observations of bubble rise speeds outside the slug flow regime (i.e.: smaller bubbles not constrained directly by pipe boundaries) suggest the terminal velocity of a single bubble is relatively constant between 25 to 45 cm/s over a broad range of bubble diameters, as shown in Figure 12, here reproduced from Wallis (1969):

FIGURE 13 – Bubble Rise Velocities in Still Water, from Wallis (1969)



Taitel & al.(1980) suggest that above a critical diameter (approximately 1.5 mm) air bubbles tend to deform and adopt an erratic path. Thus the slightly slower effective bubble rise speeds of the unconstrained non-Taylor bubbles may be explained by the irregularity of the smaller bubbles' rise trajectories compared with the constrained-vertical rise trajectories of the Taylor bubbles in the slug flow regime.

Using the concept of a constant terminal rise velocity for bubbles in still water, we introduce the relative velocity of the air phase to the water phase in the airlift pump tube,

$$V_{air} = V_{water} + V_{rel} \tag{18}$$

substituting (18) into (14) results in:

$$Q_{air} = \left(V_{water} + V_{rel}\right) \cdot A_{air} \tag{19}$$

substituting (17) into (19) results in:

$$Q_{air} = \left(V_{water} + V_{rel}\right)\left(Area - A_{water}\right) \tag{20}$$

rearranging (15) and substituting into (20):

$$Q_{air} = \left(V_{water} + V_{rel}\right)\left(Area - \frac{Q_{water}}{V_{water}}\right) \tag{21}$$

Equation (21) provides a functional relationship between the measured flow rates of the air and water phases Q_{air} and Q_{water}, the known cross-sectional area of the airlift pump tube *Area*, the known relative velocity of the air phase to the water phase V_{rel}, and the unknown velocity V_{water} of the water phase. Therefore, under these assumptions the velocity of the water phase in the airlift pump tube can be calculated for any combination of the measured values. This water phase velocity can then be used to solve (11) for the desired overall loss factor K_{total}.

However, to solve (11) we also need the density of the air-water mixture in the airlift pump tube. Rearranging (15) and substituting into (12):

$$Dens = \frac{Q_{water}}{V_{water} \cdot Area} \tag{22}$$

substituting (22) into (11) and rearranging, get:

$$K_{total} = \frac{2g}{V_{water}^2}\left(H_{sub} - \frac{H_{total} \cdot Q_{water}}{V_{water} \cdot Area} \right) \tag{23}$$

Equation (23) gives the pump loss factor as a function of the water phase velocity, diameter, total length and submergence of the pump tube, volume flow rate of water and velocity of the water phase in the airlift pump tube. The velocity of the water phase can be determined from (21) and thus the pump loss factor determined for a variety of flow and submergence conditions.

In this way it was hoped the characteristic behaviour of the airlift pump system could be determined from the pump loss coefficient, enabling a clear understanding of the pump system operation and as well creating a simple design procedure.

When the experimental data was compared with this model it became apparent that losses found in the pump units in this study were not accurately predicted. The summary values in column 13 of Table 6 correlate the measured system losses with the water phase velocity. The wide spread in the derived loss factors as well as the large coefficients of variation indicate clearly that this model is not applicable to the pumps in this study.

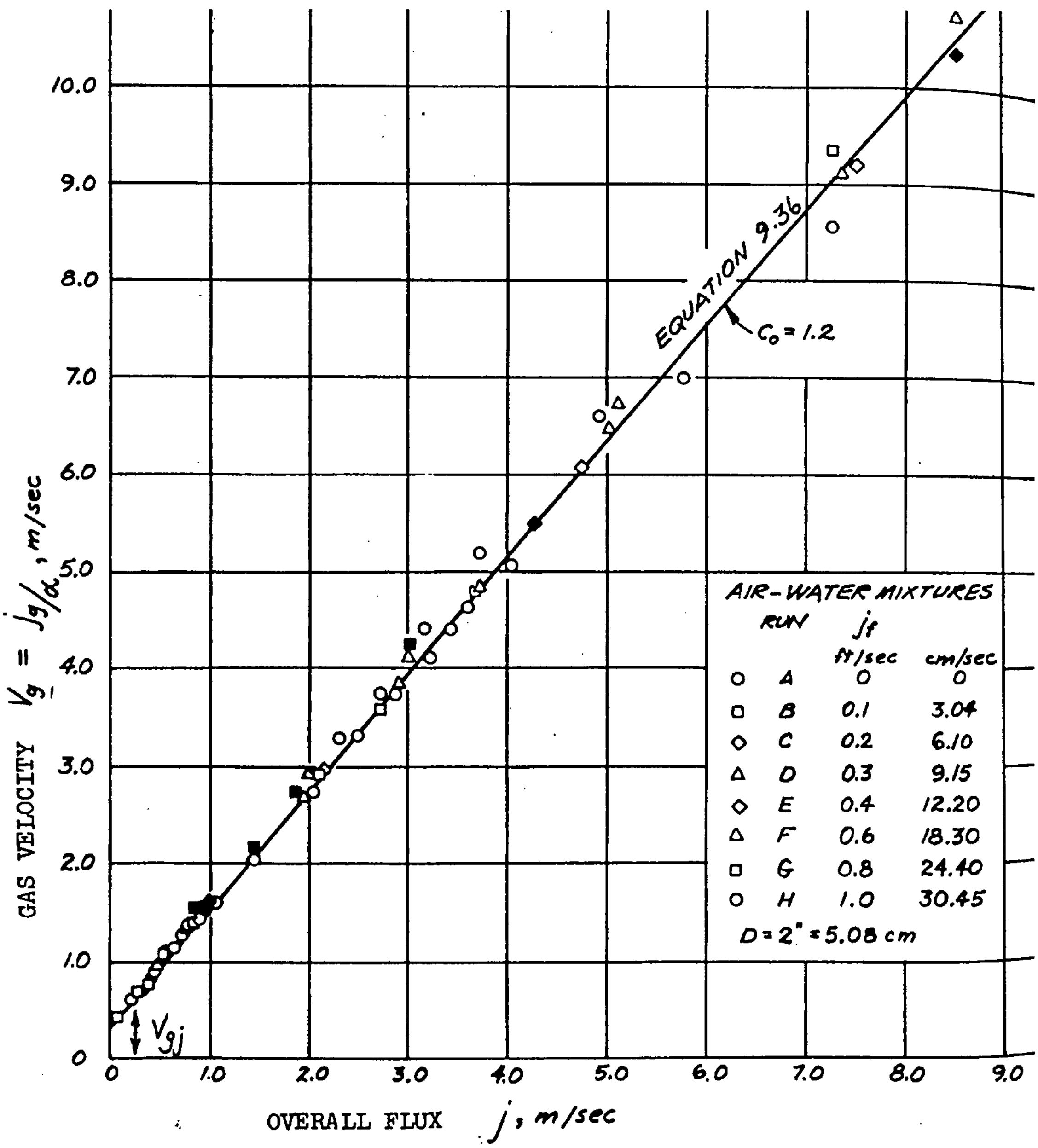
Further observations of the experimental units in operation and more research suggested that the assumption of a terminal bubble velocity as explained by Figure 13 was not applicable in this case.

The assumption of a terminal bubble speed relative to still water makes this model possibly more suitable for low void -ratio flows and low mixture flow velocities, such as might be encountered in a long, large diameter riser such as used in lake aeration or destratification or harbour de-icing. Although this model for airlift pump performance is not helpful in the case of low-lift, low-head high flow pumps such as are considered here it does have promise and may prove useful in analysis of cases such as those mentioned above.

4.2 - Airlift Pump Model for Variable Bubble Slip Velocities

Wallis (1968)'s Figure (9.5) in the section concerning churning flow presents the mixture and gas phase mass flux rates in terms of the mixture mass flux rate and a gas phase "drift flux" rate *relative to the mixture flux.* Wallis' figure is reproduced as Figure 13 here.

FIGURE 14 - Mixture and Gas Flux Rates, Wallis (1969



It indicates the relationship between the mass flow rate of the gas and the mass flow rate of the mixture, expressed as a mass flux rate per unit area for the mixture and a relative, or "drift" mass flux rate per unit area for the gas phase. Inspection of Figure 13 suggests that the gas phase average velocity is dependent on the flux rate of the mixture.

Consider a case such as ours in which the densities of the gas and liquid phases are known fixed quantities, the pump geometry is known and the density of the gas phase is negligible compared to that of both the liquid phase and that of the mixture. In such a case Figure 9 suggests that the drift flux rate and mixture flux rate are dependent on the mix ratio and component phase velocities only. So for any given mix ratio the straight-line relationship in the ratio of the gas drift flux and mixture flux rate should be equally representative of the gas and mixture fraction velocities. In that case for known fixed densities of liquid (water) and gas (air) phases, and for a known void fraction, the velocity of the gas phase of the mixture in a churn-turbulent two-phase flow depends not on the velocity of the water phase as suggested by Figure 8 and as found in low void-fraction still water and bubbly flow, but rather depends on the velocity of the mixture instead.

Wallis' equation 9.36 suggests a different form of this relationship. That is expected since his flow analysis was momentum-based and did not require the relative velocities of the component mixture phases.

Nevertheless, the conclusion is powerful – namely that in cases where the gas density is negligibly low in comparison with the mixture density the gas phase velocity is greater than, and rises linearly with the mixture velocity. This provides a valuable component missing so far in the analysis of these short-lift systems. It is reassuring to note that De Cachard & Delhaye (1995) also found a similar result for mixture and gas phase velocities up to approximately 6 m/s in small diameter, long lift pump risers.

So, expressing the air phase velocity as a linear function of the mixture velocity:

$$V_{air} = b + cV_{mix} \tag{24}$$

and fitting the linear relationship in (25) to Wallis' data in Figure 13 suggests:

$$V_{air} = 1.0 + 1.2V_{mix} \tag{25}$$

Equation (25) models Figure 13 to remarkably good agreement in units of feet per second. This equation fit corresponds with the bubble terminal velocity of approximately 30 cm/s, which is approximately equal to 1 foot per second as in Figure 12 and suggested by Wallis for still water and used in the first model. The $1.2V_{mix}$ term is also familiar since it represents the ratio of the centreline velocity to the average velocity in the fully developed turbulent flow field within a closed pipe.

The form and values of (25) as interpreted here from Wallis' data are very similar to those suggested by Nicklin (1962) before his work on airlift pumps. Nicklin suggested for the velocity of a slug bubble rising in a two-phase mixture at Reynold's numbers under 8000:

$$V_{air} = 1.2V_{mix} + 0.35\sqrt{g \cdot Diam} \tag{26}$$

In consistent units for a representative pump riser tube of six-inch internal diameter, equation (26) becomes

$$V_{air} = 1.2V_{mix} + 1.38 \tag{27}$$

Nicklin (1962) qualifies (28) above as being accurate for Reynold's numbers below 8000 and approximate for Reynold's numbers over 8000.

Furthermore, Fernandes, Semiat & Duckler (1983) independently suggest that the Taylor bubble rise velocity in larger diameter pipes than those studied by Taitel et al. (1980) is given by

$$V_{air} = 1.29V_{mix} + 0.35\sqrt{g \cdot Diam} \tag{28}$$

Equations (27) and (28) are very similar to one another and suggest values for the air phase velocity for slug flow just slightly greater than suggested by Wallis' experiments for bubbly flow as given in (25). These findings inspire confidence in this study that the form and values in equation (25) are reliable.

Therefore, substituting (25) into (14):

$$Q_{air} = (1.0 + 1.2V_{mix})A_{air} \tag{29}$$

Substituting (13) into (25):

$$Q_{air} = \left(1.0 + 1.2\frac{Q_{mix}}{V_{mix}}\right)A_{air} \tag{30}$$

Rearranging (30) to solve for the cross sectional area occupied by the air phase,

$$A_{air} = \frac{Q_{air}}{\left(1.0 + 1.2\frac{Q_{mix}}{V_{mix}}\right)} \tag{31}$$

substituting (13) into (28):

$$V_{air} = 1.0 + 1.2\left(\frac{Q_{mix}}{Area}\right) \tag{32}$$

also substituting (32) into (14):

$$A_{water} = Area - \frac{Q_{air}}{1.0 + 1.2\left(\frac{Q_{mix}}{Area}\right)} \tag{33}$$

and substituting (33) into (15) and using (16):

$$V_{water} = Q_{water} \cdot \frac{1}{\left(Area - \frac{Q_{air}}{1.0 + 1.2\left(\frac{Q_{water} + Q_{air}}{Area}\right)}\right)} \tag{34}$$

Equation (34) will then give the velocity of the water phase in the airlift pump tube as a function of the measured flow rates of air and water, and the cross sectional area of the airlift pump tube for churn-turbulent flows, assuming the air and water phase flow velocities are accurately represented by equation (22) which was derived from a fixed-densities and mix ratios analysis of Wallis (1968) data in Figure 14 and bolstered by Nicklin (1962).

Having determined the velocity of the water phase in the airlift pump tube from equation (34), and knowing the water phase volume flow rate and pump geometry, the values can be used to find the value for the pump loss coefficient as determined by equation (23):

$$K_{total} = \frac{2g}{V_{water}^2}\left(H_{sub} - \frac{H_{total} \cdot Q_{water}}{V_{water} \cdot Area}\right) \tag{23}$$

This approach holds more promise than the first for improved and more reliable results.

The experimental data was reanalyzed. However, even with this more reliable approach for calculating the velocity of the water phase and despite good evidence to support equation (29), the head losses were still found not to be proportional to the square of the water phase velocity.

Despite the fact that this model cannot be used to explain the behaviour of the low-submergence, low-lift, high-flow pump units in this study it does hold promise for use in mid-velocity bubbly flow pump units. In such units head losses are primarily due to pipe friction as suggested by Ward (1924) and this model may help provide a simple analysis tool for that class of airlift pump systems.

4.3 - Airlift Pump Model for Turbulent Mixing

Given the inability of the second model to accurately predict the head losses using the improved method for calculating the water phase velocity, a new approach is clearly necessary. Evidently the assumption that the losses are primarily due to pipe friction, entrance and exit losses and are dependent on the velocity of the water phase must be reexamined.

The flow of the mixture in the airlift pump tube is very turbulent with significant visual evidence of churning and recirculation, so the assumption that the influence of the air phase is negligible may be suspect. Wallis (1968) suggests in passing that the majority of energy dissipated in the pipe flow of churning two-phase mixtures results from internal losses rather than pipe-friction-related causes. Clark & Dabolt (1986) also argue that the frictional head losses are a second-order effect within practical lengths for non-slug flows although they do not quantify what the frictional head losses are.

Further research and passing suggestions in several other references provide some clues to the mechanism of these losses. Wallis (1968) mentions that in churning flow the chaotic movement of water in the flow mixture causes the most energy loss, and furthermore, that in the majority of practical cases bubbly flow never becomes fully developed and entrance effects dominate the region before slug flow develops. Ward (1924) mentions that short pumps have losses not important in long pumps. Morrison & al. (1987) suggest that churning flow is in fact a transition regime usually existing from 15 to 35 pipe diameters away from the aeration point, before significant enough bubble accretion can occur to create slug flow. DeCachard & Delhaye (1995) suggest that the length effects from the developmental region of churn flow leading to stabilized slug flow may create higher than predicted head losses up to lengths several hundred times the pipe diameter away from the entrance. Thus a fully stabilized slug flow regime may not develop within a length up to even two hundred times the pipe diameter. Taitel & al (1980) quantified a minimum length for the turbulent entrance transition zone as

$$L_{entrance} = 40.6 \cdot Diam \cdot \left(\frac{V_{mix}}{\sqrt{g \cdot Diam}} + 0.22 \right) \tag{35}$$

It occurs that the short pump losses mentioned by Ward (1924) must be due to the entrance and transition zone turbulence. The pumps in this study are conclusively "short" - substantially shorter than 15 to 35 to several hundred diameters long, and substantially shorter than the entrance lengths suggested by Taital & al. (1980) by equation (35) above.

Therefore it is reasonable to assume that the mixture in the entire pump riser tubes is exclusively experiencing the turbulent transition zone flow regime. In that case, the losses in short airlift pumps such as those in this study must be primarily turbulent in nature - and not pipe friction losses dependent on the water phase velocity as was assumed in the first two models, and as commonly assumed in the primarily slug-flow models developed to date.

In this case the challenge then becomes how to quantify the mixture turbulence and relate the pump head losses to that turbulence.

It was observed in experimental trials that the air-water mixture became increasingly turbulent with increasing mixture velocities, and that very high gas phase velocities at high void fractions resulted in large losses and very little liquid flow. These observations suggest that mixture velocity in the churning regime is a good indicator of mixture turbulence and hence of losses in these short pump units.

Further research discovered Ishii and Zuber's (1979) claim that in turbulent flow regimes the bubbles influence the surrounding fluid and also other bubbles, and that thus bubbles can be entrained in each others' wakes, and therefore the losses in such flows should be considered relative to the mixture velocity rather than that of the liquid phase. Wallis (1968) also suggests a similar general form.

We therefore propose a functional form for the turbulent head losses in these short airlift pumps, dependent on the mixture density and turbulence, and represented by the density and velocity of the entire mixture rather than the velocity of the water phase alone:

$$H_{loss} = d \cdot Dens \cdot V_{mix}^{e} \tag{36}$$

The tuning parameters d and e will be experimentally determined from the research program data.

The form of equation (36) will effectively parameterize the head losses but does not promise a great advancement in terms of the details of the head loss mechanism. This is not entirely surprising since De Cachard & Calhaye (1995) explain that a model for wall friction in churning flow is not yet available, and that the chaotic motion in churning flow makes empirical considerations for wall friction losses a necessity. Govan et al (1991) agree, suggesting that creating a realistic model for churn flow mechanics is "particularly challenging".

De Cachard & Calhaye (1995) recommend a formulation similar to equation (36) for long slender pumps, based on the liquid phase velocity. Following their suggestion and using their equation [48] and Blasius' formula for frictional losses in the boundary layer as given in their equation [11] their solution proposes a friction loss term for churn flow as:

$$H_{loss} = H_{total} \cdot \frac{-0.316 \cdot Dens_{liquid}}{2Diam} \mathrm{Re}_{liquid}^{-0.25} V_{liquid}^{2} \qquad (37)$$

for the Reynold's Number Re based on the velocity of the liquid phase V_{liquid}. The form of equation (37) is reassuringly similar to the form of equation (36), arrived at independently. The primary difference between De Cachard & Delhaye's form and that suggested in this study is that their expression is calibrated for small diameter tall risers and uses the liquid phase velocity as was suggested in the second model above, whereas equation (36) relies on the mixture velocity as an indicator of turbulence.

To use (36), we substitute (6) into (5):

$$H_{loss} = H_{sub} - H_{total} \cdot Dens \qquad (38)$$

and substitute (36) into (38):

$$d \cdot Dens \cdot V_{mix}^{e} = H_{sub} - H_{total} \cdot Dens \qquad (39)$$

now substituting (13) into (38):

$$d\left(\frac{A_{water}}{Area}\right)V_{mix}^{e} = H_{sub} - H_{total}\left(\frac{A_{water}}{Area}\right) \qquad (40)$$

This third model for airlift pumps continues to make use of the relative velocity of the air phase to the velocity of the mixture as given by the experimentally determined equation (26) and suggested from Wallis (1968)'s data and reflected in Figure 13.

So, using (29) for the water phase cross sectional area, and substituting into (40):

$$d\left(Area - \frac{Q_{air}}{1+1.2\dfrac{Qm}{Area}}\right)V_{mix}^{e} = H_{sub} - H_{total}\left(Area - \frac{Q_{air}}{1+1.2\dfrac{Qm}{Area}}\right) \qquad (41)$$

Finally, by substituting (11) into (41), get:

$$d\left(Area - \frac{Q_{air}}{1+1.2\dfrac{Qm}{Area}}\right)\left(\frac{Q_{air}+Q_{water}}{Area}\right)^{e} = H_{sub} - H_{total}\left(Area - \frac{Q_{air}}{1+1.2\dfrac{Qm}{Area}}\right) \qquad (42)$$

By using the measured water and air phase flow rates and pump geometry, equation (42) allows the tuning parameters d and e to be determined from the experimental results.

The summaries of columns 10 and 11 in Table 4 and columns 11 and 12 in Table 6 show good correlation between the head losses in the pumps and the mixture velocity as a measure of turbulence. This correlation was found throughout the experimental results, albeit more convincingly from the last phase of the program in which results were more reliable than those previous due to factors already discussed.

Figure 15 shows a summary of the experimental data and model predictions. The line of best fit for the experimental data leads to the following relationship for the head loss as a function of the mixture flow velocity:

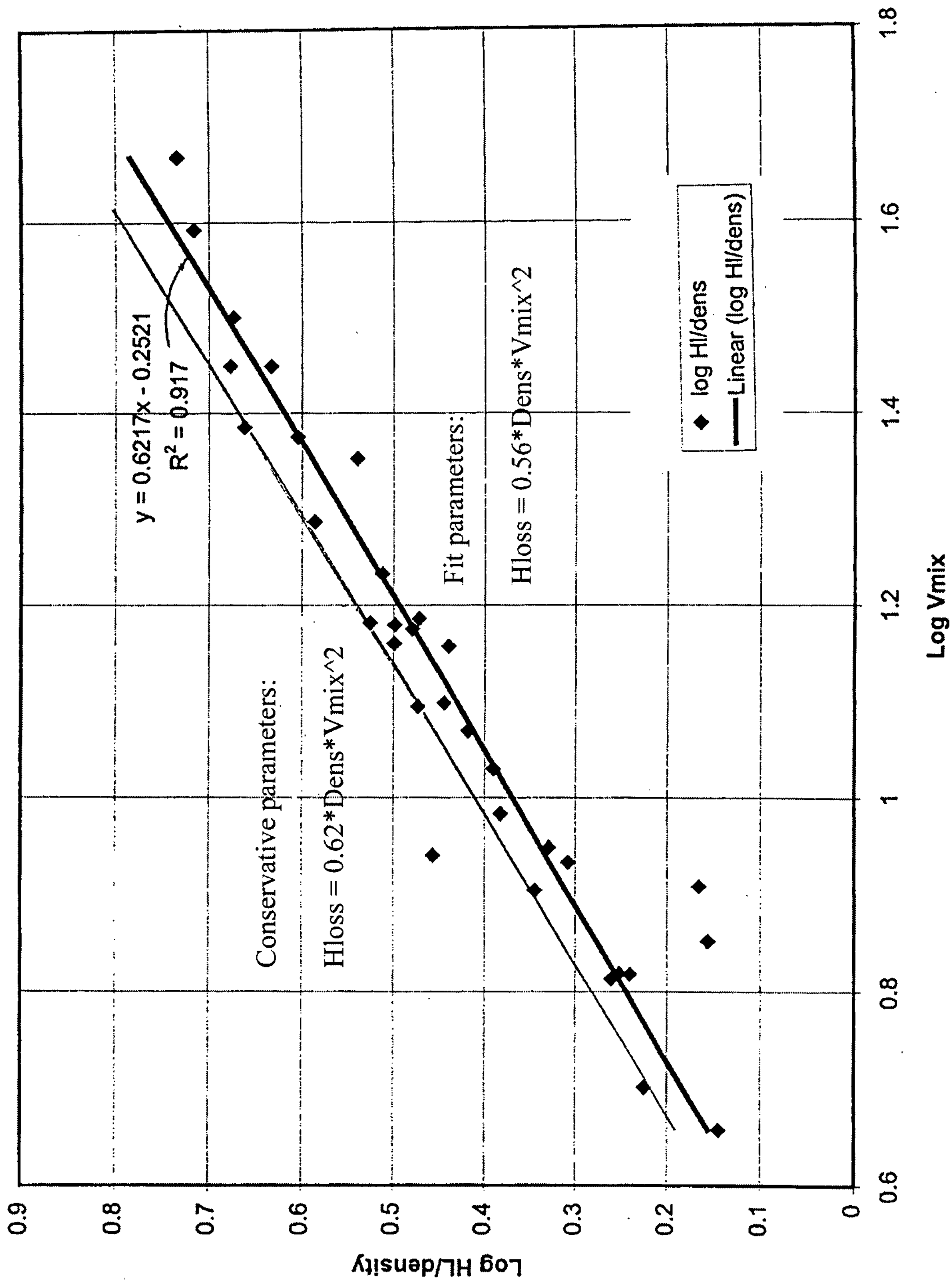
$$H_{loss} = 0.56 \cdot Dens \cdot V_{mix}^{0.62} \tag{43}$$

constructing a slightly more conservative curve fit from the data lead to the following relationship for the head loss as a function of the mixture flow velocity,

$$H_{loss} = 0.62 \cdot dens \cdot V_{mix}^{0.64} \tag{44}$$

Equation (44) could be more suitable for design since it predicts a slightly higher head loss than the line of best fit and would thus be a conservative estimate for pump capacity.

Figure 15 - Comparison of Experimental and Calculated Performance: Log(head loss/density) vs. Log(Mixture velocity)



This model for airlift pump performance performs well in predicting the performance of the low-submergence, low-lift, high-flow units investigated in this project. It also provides the basis for a simple approach to evaluating the behaviour of these units and leads to a reasonably direct and practical design approach.

4.4 - Summarizing the three models

The first model described in **4.1 - Airlift Pump Model for Fixed Bubble Slip Velocities** relies on the assumption of a relatively constant bubble rise speed, and frictional pump losses governed by the velocity of the water phase in the air-water mixture. Investigations of the experimental results and further research indicate that this assumption is not valid in the churn flow regime experienced by the pump units in this study. This model does have promise in applications where the constant bubble rise speed is supported, and may find use in large diameter systems such as are used for lake destratification and harbour de-icing.

The second model described in **4.2 -Airlift Pump Model for Variable Bubble Slip Velocities** also assumes losses governed by the velocity of the water phase in the air-water mixture. It features a refined estimate for the mean bubble velocity as a function of the mixture velocity, a refinement based on the experimental work of several previous researchers. This model does not accurately describe the behaviour of the low-lift, high-flow, low-submergence pumps in this study but does hold promise for use in more energetic bubbly flow regime pumps such as those used in aquaculture and wastewater treatment applications.

The third model as described in **4.3- Airlift Pump Model for Turbulent Mixing** is specific to the churn flow regime. The refinement introduced in the second model is retained, but a new formulation for the nature of the head losses is utilized. Head losses in the third model are assumed to be proportional to the turbulent motion of the air and water phases in the mixture. Mixture velocity is found to be a good indicator for mixture turbulence and is thus used as a basis for calculating the turbulent head losses. This model predicts the behaviour of the pumps in this study with good accuracy and forms the basis of the simple design procedure presented in Chapter 5.

None of the procedures suggested in the open literature are practical for the engineer wishing to design a low-submergence, low-lift, high-flow airlift pump system. Ward's (1924) approach to design of very long airlift pumps by curve matching includes no data for short length pumps and high void fractions. Nicklin's (1963) technique for design of airlift pumps in slug flow, and all of the suggested refinements to Nicklin's work suggested by subsequent researchers do not describe turbulent losses in a churning system. Tramba's (1982) and Nenes & al's (1995) multi-celled simulation-based numerical approaches for deep-well airlift pump analysis relies on dividing the pump pipe riser body into differing contiguous sections, each with individual flow characteristics, a process not feasible for the short pumps described here.

However, **4.3 - Airlift Pump Model for Turbulent Mixing** described in the previous chapter, provides the missing basis for a simple and practical design procedure a low-submergence, low-lift high-flow airlift pump system.

CHAPTER 5

5.1 - A Preliminary Design Procedure for Low-lift, Low-Submergence Airlift Pumps in the Churn Flow Regime

This procedure allows a designer to quickly complete the preliminary calculations for an airlift pump in a low-head, high-flow, low-submergence application for practical pump diameters in the approximately 3 inch to 12 inch range. Since airlift pumps are inexpensive to construct, a prototype unit may then be built and the performance verified.

Because this design approach is simple and based on the friction and velocity correlations developed in this research program it should be used with care in cases of much higher lift and much deeper submergence. In those cases the pipe-fluid friction losses will begin to play a larger part in overall system behaviour as the bubbles in the churn flow begin to coalesce into Taylor bubbles and arrange themselves into a slug flow pattern. The design procedure of Clark & Dabolt (1986) is recommended for use in such cases.

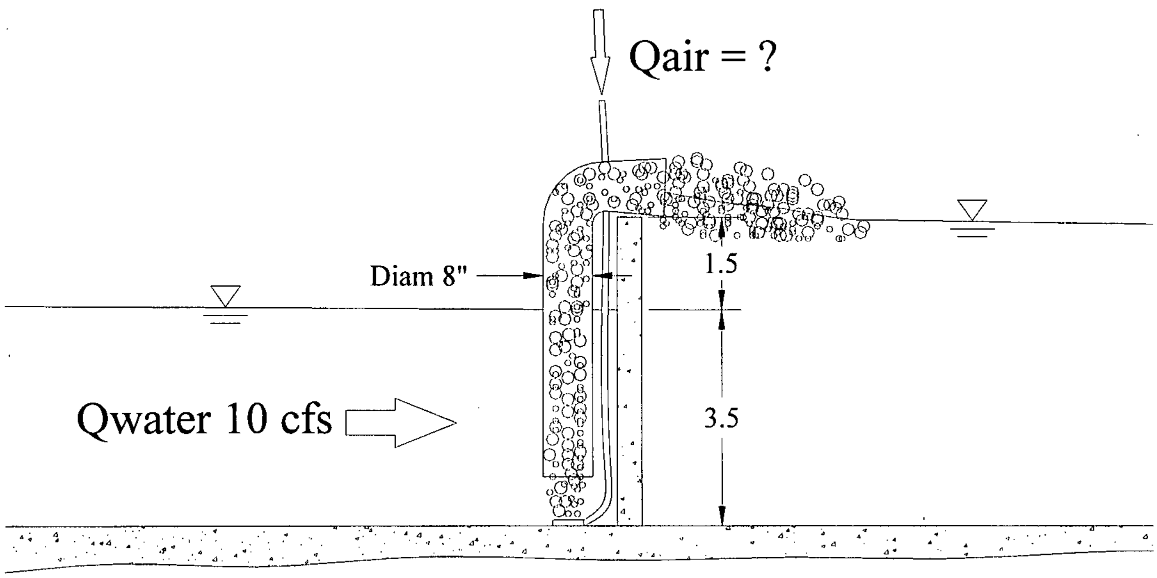
This design procedure is used to predict the volume flow rate of water expected from a low-head, high-flow, low-submergence airlift pump operating in the churn flow regime. The design parameters required are:

- Q_{air} = the intended volume flow rate of air, in cubic feet per second
- Q_{water} = the intended water flow rate, in cubic feet per second

- Upstr = the upstream water level, in feet
- Dnstrdes = the desired downstream water level, in feet

The design procedure will be illustrated by a simple example. In this example an engineer desires to aerate and pump 10 cubic feet per second of water over a 1.5 foot lift using a single or multiple-pipe airlift pump system with 8 inch diameter riser tubes. This pumping system is set in a small concrete drainage channel 8 feet wide by 5 feet deep. Figure 16 shows the proposed layout of the system.

FIGURE 16 - Simple Design Example Layout



A Simple 10-Step Design Process:

1. This design appears to require several pump units to accomplish the required flow rate and lift. In such a case, assume an air flow rate and water flow rate **for a**

single pipe. With no other information available, 50% of the air flow rate is found to be a reasonable starting estimate of the water flow rate. Assuming 2.5 cfs of air, and 1.25 cfs of water:

$$Q_{air} = 2.5 \text{ cfs}, \qquad Q_{water} = 1.25 \text{ cfs} \tag{D1}$$

2. For low insertion depths air can be considered incompressible, so calculate the volume flow rate of the mixture by adding the volume flow rates of the air and water:

$$Q_{mix} = Q_{air} + Q_{water} = (2.5) + (1.25) = 3.75 \text{ cfs} \tag{D2}$$

3. Determine the mixture velocity by dividing the mixture flow rate by the cross-sectional area of the riser pipe:

$$V_{mix} = \frac{Qmix}{\left(\frac{\pi}{4} \cdot Diam^2\right)} = \frac{(3.75 \text{ cfs})}{0.785 \cdot (0.75 \text{ ft})^2} = 10.7 \text{ fps} \tag{D3}$$

4. Determine the velocity of the air phase in the pump riser pipe from equation (25):

$$V_{air} = 1 + 1.2 \cdot V_{mix} = 1 + 1.2 \cdot (10.7) = 13.9 \text{ fps} \tag{D4}$$

5. Determine the sectional area occupied by the air phase in the pump riser pipe:

$$A_{air} = \frac{Q_{air}}{V_{air}} = \frac{(2.5\ \text{cfs})}{(13.9\ \text{fps})} = 0.18\ \text{sf} \tag{D5}$$

6. Determine the relative density of the air-water mixture in the pump riser pipe:

$$Dens = 1 - \left(\frac{A_{air}}{Area}\right) = 1 - \frac{(0.18\ \text{sf})}{(0.35\ \text{sf})} = 0.48 \tag{D6}$$

7. Determine the system head loss from equation (44):

$$H_{loss} = 0.56 \cdot V_{mix}^{0.62} = 0.48 \cdot (10.7\ \text{fps})^2 = 1.18\ \text{ft} \tag{D7}$$

8. Calculate the expected downstream water level from equations (4) and (5):

$$dnstrcalc = \frac{(upstr - Hloss)}{Dens} = \frac{(3.5) - (1.18)}{0.48} = 4.78\ \text{ft} \tag{D8}$$

9. Compare the calculated downstream water depth from equation (D8) in Step 8 to the desired downstream water depth. If the calculated water level from Step 8 is below the desired level the pump unit cannot provide the desired flow rate at the desired lift and given air flow rate. In such a case the water flow rate must be

decreased and/or the air flow rate must be increased. The reverse is true if the calculated downstream level is above the desired height.

10. In this example we select a lower water flow rate, leave the airflow rate as is and re-enter the process at step 1, now decreasing our assumption of the water flow rate to Q_{water} = 1.15 cfs for this pump unit at this airflow. Carry out the steps again starting at step 1 and check the new result for the downstream water level. Once reasonable agreement has been reached the preliminary design is complete. In this case the second trial for the water flow rate was almost exact and thus a preliminary estimate of the pump unit performance has been made.

In this example a practical operating point of 1.15 cfs of water and 2.5 cfs of air in a single 8" diameter pump with a lift of 1.5 feet has been established. Other operating points may be explored using the same technique until a satisfactory operating point is selected. Assuming the preliminary design given above is satisfactory, and given the design requirement for 10 cfs of water, a reasonable suggestion would be to install 9 of the pumps as described, for a total water flowrate of approximately 10.5 cfs of water requiring approximately 23 cfs of air.

Given that step 7 as shown uses the fit values for the parameters in equation (43) rather than the conservative values of equation (44) it is reasonable to build a prototype unit based on these specifications to check performance. A more conservative approach would be to use the "envelope curve" parameters from equation (44) in step 7 instead. Doing so results in a predicted water flow rate for the example pump of 1.05 cfs, indicating that 10 rather than 9 units could be required.

Alternate pipe diameters can be investigated easily, as can the influence of a greater aeration depth, possibly developed through excavating a sump at the site, etc. For example, the model suggests that the same pump could produce a water flowrate of 2.14 cfs if the aerator were placed in a three-foot deep sump. However, this increase in water flowrate at the same air flowrate is not entirely free since the air must be delivered at a consequently higher pressure, and subsequently a possibly higher cost.

This design approach is clearly suitable for hand calculation and can easily be automated by programming into a pocket calculator such as the Hewlett-Packard 48 series or others of similar capability.

5.2 - Design Calculations for Personal Computer

The design procedure outlined above is also suitable for implementation in a common spreadsheet software such as Microsoft Excel©. Figure 17 shows a simple formatted spreadsheet implementation of this design technique. The user enters design values in the boxed cells marked as "Input" and the spreadsheet automates the subsequent calculation steps described above. Simple changes to the system characteristics can be made and effects investigated. Fit parameters for the air phase velocity to mixture velocity relationship can also be adjusted if desired, as can the fit parameters for the head loss to mixture velocity relationship. In this way the performance predictions resulting from the direct fit and conservative parameters can be investigated. The spreadsheet solution also allows for automated fast iteration to accurate solutions by means of the Microsoft Excel© "Solver", "Goal Seek", or equivalent user-implemented system.

Figure 17 - Airlift Pump Churn Flow Worksheet

Sample Airlift Pump Churn Flow Worksheet
AB December 2003

Qair	= volume flow rate of air	=	**2.50**	cfs	Input
Qw	= volume flow rate of water	=	**1.16**	cfs	Input
Diam	= diameter of airlift pump tube	=	**0.67**	ft	Input
Upstr	= upstream water level above aerator	=	**3.50**	ft	Input
Dnstrdes	= desired downstream water level above aerator	=	**5.00**	ft	Input
grav	= acceleration due to gravity	=	**31.90**	fpss	Parameter
a	= curve fitting parameter in Vair=a+b*Vmix	=	**1.00**	fps	Parameter
b	= curve fitting parameter in Vair=a+b*Vmix	=	**1.20**	n/a	Parameter
d	= curve fitting parameter in Hloss = d*Dens*Vmix^e	=	**0.56**	n/a	Parameter
e	= curve fitting parameter in Hloss = d*Dens*Vmix^e	=	**0.62**	n/a	Parameter
athy	theoretical value for a above given slug flow = 0.35*sqrt(grav*Diam)	=	**1.61**	fps	Calculated
Qmix	volume flow rate of the mixture = Qair+Qw	=	**3.660**	cfs	Calculated
Area	cross sectional area of the airlift pump tube = PI()/4*Diam^2	=	**0.349**	sf	Calculated
Vmix	velocity of the mixture = Qmix/Area	=	**10.486**	fps	Calculated
Vair	velocity of the air phase in the airlift pump tube = a+b*Vmix	=	**13.583**	fps	Calculated
Aair	cross sectional area occupied by the air phase = Qair/Vair	=	**0.184**	sf	Calculated
Dens	relative density of the mixture in the airlift pump tube = 1-(Aair/Area)	=	**0.473**	n/a	Calculated
Hloss	head loss from curve fitting experimental data = d*Dens*Vmix^e	=	**1.136**	ft	Calculated
Dnstrcalc	calculated downstream water level = (Upstr-Hloss)/Dens	=	**5.000**	ft	Calculated
Dnstrdiff	difference in calculated and desired downstream water levels = Dnstrcalc-Dnstrdes	=	**0.000**	ft	Calculated

low	high	fit
1	3	**1**
1.2	1.29	**1.2**
0.56	0.62	**0.56**
0.62	0.64	**0.62**

The user selects values for the system inputs and parameters and can explore various aspects of the pump unit's predicted performance. Iteration is simple as the user adjusts the air and/or water flow rate until the desired downstream and calculated downstream depths are equal. The difference in these depths is calculated at the bottom of the worksheet to facilitate the process. A goal-seeking algorithm or system may also be used.

The design procedure can also be coded into a functional form for inclusion in other spreadsheets. This approach makes the calculation of airlift pump behaviour immediate. This approach is also well suited for tabulating predicted airlift pump behaviour and generating predicted performance values for various combinations of design variables.

The design procedure was coded into a set of Microsoft Visual Basic for Applications© functions for use with Microsoft Excel © spreadsheets..

Figures 18 and 19 show the Microsoft Visual Basic for Applications functions.

Figure 18 - VBA© Code for Churn Flow Airlift Pump Design

```
Function Dnstrcalc (ByVal Qair As Single, ByVal Qw As Single, ByVal Diam As Single,
ByVal Upstr As Single) As Single
'This function computes the downstream water level given the flow of water (in cfs),
'flow of air (in cfs), the pipe riser diameter, and the upstream water level (both in feet)


Dim Qmix As Single, Vmix As Single, Vair As Single, Dens As Single
Dim Hloss As Single, Area As Single, Air As Single


Qmix = Qair + Qwater: Area = 0.785 * (Diam) ^ 2
Aair = Qair / Vair: Dens = 1 – (Aair / Area): Hloss = 0.56 * Dens * (Vmix ^ 0.62)
Dnstrcalc = (Upstr – Hloss) / Dens
End Function
```

Figure 19 - VBA© Code for Churn Flow Airlift Pump Design

```
Function Qwater(ByVal Qair As Single, ByVal Diam As Single, ByVal Upstr As Single,
ByVal Dnstr As Single) As Single
'This function computes the flow of water given the flow of air (in cfs), the pump riser
'diameter, the upstream water level and the downstream water level (all in feet). It sets
'the water flow rate to zero and raises it in small steps using Dnstrcalc until the calculated
'and desired downstream levels are equal.

Dim Qw1 As Single, Dnstr1 As Single

Qw1 = 0: Dnstr1 = Dnstrcalc (Qair, Qw, Diam, Upstr)
If Dnstr1 <= Dnstr Then Qwater = 0
        Do Until Dnstr1 <= Dnstr
                Qw1 = Qw1 + 0.01: Dnstr1 = Dnstrcalc(Qair, Qw, Diam, Upstr)
        Loop
Qwater = Qw1
End Function
```

The disadvantage to the functional form described here is that it isolates the user from the intermediate values of mixture density, air, water, and mixture velocity, etc. There is a greater opportunity for the user to trust possibly questionable results because of this disconnect.

5.3 - Practical Considerations for Preliminary Airlift Pump Design.

Mixture Density:

There are several practical considerations when using this approach. It will become evident by using this design technique that the low-lift, low-submergence churn flow airlift pump system is sensitive to the mixture relative density *Dens.* When the mixture relative density falls much below 0.5, diminishing returns set in quickly in terms of increased water flow rate with increased airflow rate. Once the mixture relative density has fallen much below 0.45, increasing the airflow rate even dramatically will produce very little increase in flow of water. In practice, increasing airflow past this level will eventually reduce the flow of water since the air is displacing water in the pipe riser tube. The model presented here does not capture this behaviour at very high air flow rates. However, that is not considered a failing because the phenomenon occurs far outside the practical range of design. If a designer finds him or herself attempting to build an airlift system to operate in such a scenario, prototype testing will be required since the pump unit will likely be operating in the annular or mist flow regimes, which existing airlift pump theory cannot quantify.

Air Pressure Required:

The air pressure required for an airlift pump system is theoretically equal to the static water pressure at the aeration depth and an allowance for losses in the air distribution system. In practice, if using a multi-port aerator the aerator ports should contribute a reasonable head loss themselves. Providing a notable pressure drop across the ports helps ensure that all ports provide equal airflow, thus maximizing the aeration efficiency of the multi-port aerator. Thus the system designer should be prepared to provide airflow at approximately 0.5 to 1 psi greater than predicted by the aerator submergence and air system distribution losses.

Compressor Types

Compressed air at low pressures and high volume flow rates such as is required by an airlift pump system of this type can be obtained by several means. Energy efficiency of these systems is low since much is lost in turbulence and mixing. Because of this energy inefficiency, requirements for power are reasonably high. (Fortunately, portable gas-powered sources are a very viable alternative and can be used only when necessary).

Centrifugal blowers are the most economical means of supplying compressed air to an airlift pump system, producing high rates of flow at low heads, typically below 3 to 4 psi. The Vortron Z40, for example can easily generate 1000 scfm at 3 psi with a 40 hp motor. The centrifugal units operate at very high rotational rates, on the order of 25 000 rpm, and must be muffled appropriately to avoid excessive noise output. Regenerative blowers are somewhat more expensive than centrifugal blowers but have the potential for a multistage design. In such systems operating pressures of up to 9 psi in the 200 to 250 scfm range can be reached. The FPZ SCL-115-DH, for example, can generate 475 scfm at 9 psi with a 40 hp motor. The last type of air supply machinery suitable for use in airlift pumping systems is the positive displacement blower. Because of their design these units deliver a relatively constant supply of air governed by displacement of their internal lobes and the rotational speed of their impellers. Delivery pressures up to 15 psi are possible with single-stage units. For example, the Sutorbilt 8DH can generate 300 scfm at 15 psi with a 36 hp motor. An airlift pump system requiring an air supply with delivery pressure above 15 psi would feature an aerator submergence much greater than those treated in this study. In such a case air supply would likely be supplied by a rotary screw compressor (such as that used in the second experimental phase of this project). In such a case the design procedure of Clark & Dabolt (1986) would be recommended.

CHAPTER 6

6.1 - Conclusions.

Interest in low-head, high-flow, low-submergence airlift pump units has historically been low since such pumps are not particularly energy efficient and have been superceded by submersible electric rotomachinery for many decades.

Despite having been replaced with more modern technology, airlift pumps are still used in several niche applications and offer some promising potential benefits in the field of urban stormwater management and other open-channel civil-engineering applications.

Existing theory was evaluated and found inadequate to describe the behaviour of the low-head, high-flow, low-submergence airlift pumps. A four-stage experimental program was developed and implemented, including a full-scale prototype application in an urban storm drainage application in the city of Richmond, British Columbia. Performance data was collected.

Three theoretical models were developed, with one satisfactorily fitting the experimental data. The model was translated into a practical procedure that an engineer may easily use to develop preliminary designs for airlift pumps operating in the churn flow regime. The design procedure was implemented in two personal-computer-based applications and thus can be quickly and easily completed. Some practical considerations for design of airlift pumps operating in the churn flow regime are given.

6.2 - Research Recommendations

Now that the behaviour of airlift pumps in the churn flow regime has been modeled, the potential for uses of these systems in other low-lift, high-flow, low-submergence applications than those mentioned in this project should be explored. For example, airlift pumps may be useful in irrigation and other pumping in open channels. If so, methods of optimizing their performance in those scenarios must be developed. Additionally, the aquaculture potential of airlift pumping in shrimp and other invertebrate farming drainage applications should be investigated – the range of lift and flow rates are similar to those in urban drainage and aeration of the water may provide additional productivity benefits and cost savings through reducing the need for aeration equipment.

The airlift pump seems to offer many advantages in the urban drainage setting, and the details of those advantages deserve to be investigated. Portable airlift pump units for local flood control may be practical, as might portable or "emergency only" trailer-mounted gasoline-powered air supply subsystems for permanently-installed units. The possibility of reduced environmental impacts in urban drainage subject to aeration as a side effect of airlift pumps should be investigated and subsequent benefits quantified.

More work is also needed to better understand the underlying phenomena of the two-phase churn flow regime. Details such as the turbulent fluid behaviour at high void fractions, the manner in which bubbles accrete at high void fractions and the influence of aeration efficiency on regime stability are all unexplored. The development of high-speed 3-dimensional laser imaging technology may provide the necessary tools.

References

Cartellier, A. "Simultaneous Void Fraction Measurement, Bubble Velocity, and Size Estimate Using a Single Optical Probe in Gas-Liquid Two-Phase Flows", Review of Scientific Instruments 63(11), (1992)

Clark, N.N. & R.J. Dabolt, "A general design equation for air lift pumps operating in slug flow", American Institute of Chemical Engineers Journal 32(1), (1986)

De Cachard, F. & J.M. Delhaye, "A slug-churn model for small-diameter airlift pumps", International Journal of Multiphase Flow 22(4), (1996)

Duckler A.E., M. Wicks & R.G. Cleveland, "Frictional pressure drop in two-phase flow: A. A comparison of existing correlations for pressure loss and holdup", American Institute of Chemical Engineers Journal (1964)

Duckler A.E., M. Wicks & R.G. Cleveland, "Frictional pressure drop in two-phase flow: B. An approach through similarity analysis", American Institute of Chemical Engineers Journal (1964)

El-Kamash, M.K., M.R. Loewen & N Rajaratnam, "Measurements of bubble properties and void fraction on a stepped chute", Proceedings of the 15th Canadian Hydrotechnical Converence of the Canadian Society for Civil Engineering (2001)

Fernandes, R.C., R. Semiat & A.E. Duckler "Hydrodynamic model for gas-liquid slug flow in vertical tubes", American Institute of Chemical Engineers Journal 29, (1983)

Giot, M., "Handbook of Multiphase Systems", G. Hetsroni, ed., Hemisphere-McGraw Hill, Washington, DC (1982).

Govan, A.H., G.F. Hewitt, H.J. Richter & A. Scott, "Flooding and churn flow in vertical pipes", International Journal of Multiphase Flow **17**, 27-44 (1991).

Govier, G.W., B.A. Radford & J.S.C. Dunn, "The upwards vertical flow of air-water mixtures", Canadian Journal of Chemical Engineering (1957).

Ishii, M. & N. Zuber, "Drag coefficient and relative velocity in bubbly, droplet or particulate flows", American Institute of Chemical Engineers Journal 25, (1979)

Jayanti, S. & G.F. Hewitt, "Prediction of the slug-to-churn flow transition in vertical two-phase flow", International Journal of Multiphase Flow 18(6), (1992)

Lawniczak, F., P. Francois, O. Scrivener, E.G. Kastrinakis & S.G. Nychas, "The Efficiency of Short Airlift Pumps Operating at Low Submergence Ratios", Canadian Journal of Chemical Engineering 77 (1999)

Markatos, N.C. & A.K. Singhal, "Numerical Analysis of One-Dimensional, Two-Phase Flow in a Vertical Cylindrical Passage", Advanced Engineering Software **4**, 99-106 (1982).

Morrison G.L, T.I. Zeineddine, M. Henriksen & G.B. Tatterson, "Experimental Analysis of the Mechanics of Reverse Circulation in Airlift Pumps", Industrial Engineering Chemical Research 26 (1987

Nenes, A., Assimacopoulos, D., Markatos, N. & Mitsoulis, E., "Simulation of Airlift Pumps for Deep Water Wells", Canadian Journal of Chemical Engineering 74, 448-456 (DATE)

Nicklin, D.J., "The air-lift pump: theory and optimization", Transactions of the Institute of Chemical Engineers 41 (1963)

Nicklin, D.J., M.A. Wilkes & M.A. Davidson, "Two-phase flow in vertical tubes", Transactions of the Institute of Chemical Engineers 40 (1962)

Pickert, F., "The theory of the air-lift pump", Engineering, 34 (1932)

Serdula, C.D. & M. R. Loewen, "Experiments Investigating The Use of Fiber-Optic Probes For Measuring Bubble Size Distributions", Journal of Oceanic Engineering 23, (1998)

Shaw, "Unwatering the Tiro General Mine by Airlift" Transactions of the AIME 421, (1920)

Shelton, S., & S.W. Stewart, "Bubble Pump Design for Single Pressure Absorption Refrigeration Cycles", ASHRAE Transactions 108 (2002)

Taitel, Y., D. Bornea & A.E. Buckler, "Modelling Flow Pattern Transitions for Steady Upward Gas-Liquid Flow in Vertical Tubes", American Institute of Chemical Engineers Journal **26**, 345-354 (1980).

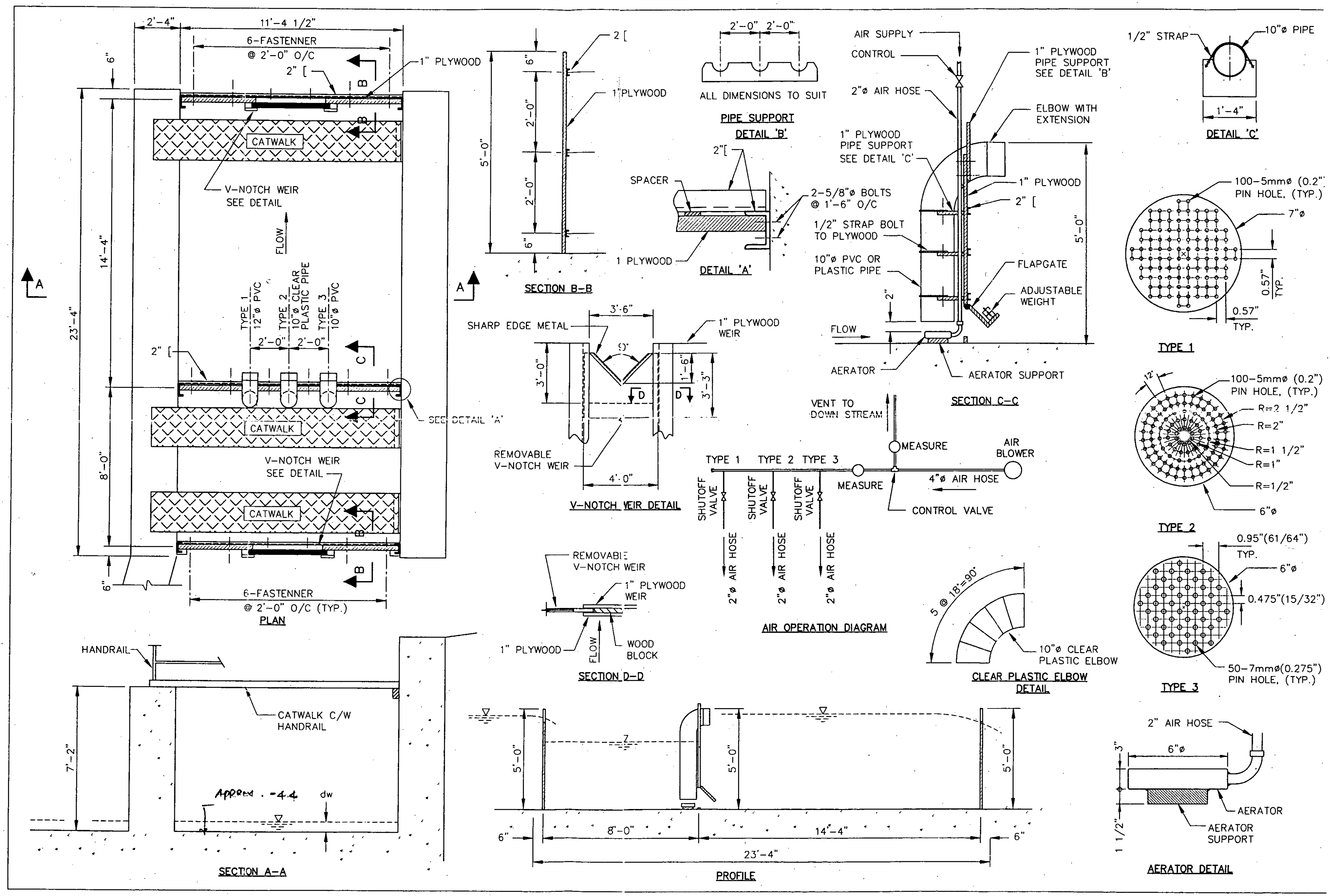
Turer, D., B.J. Maynard & J.J. Sansalone, "Heavy metal contamination in soils of urban highways: Comparison between runoff and soil concentrations", Journal of Water, Air and Soil Pollution, **132**(3) (2001).

Wallis, G.B., "One-Dimensional Two-Phase Flow", McGraw-Hill, New York (1969).

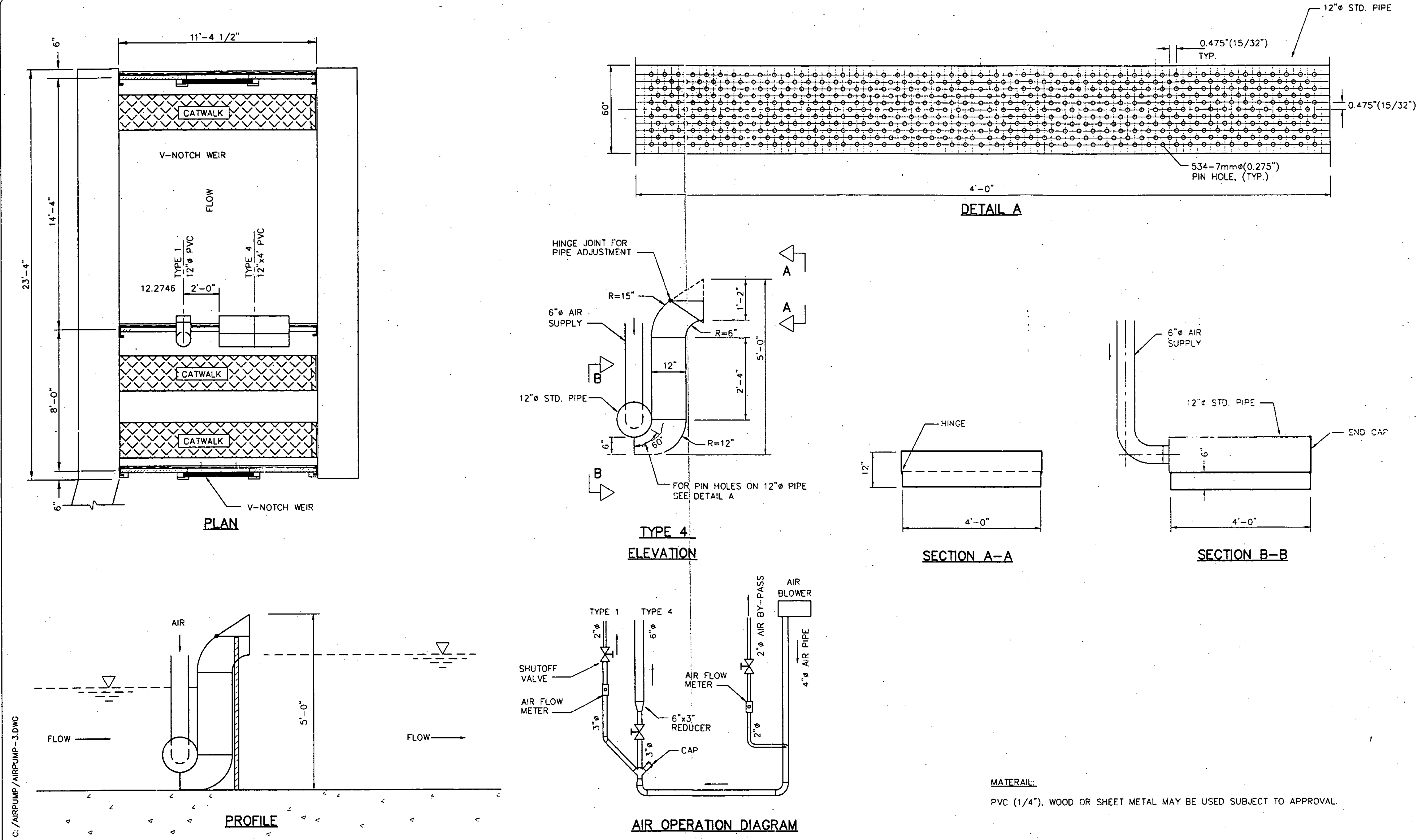
Ward, D. "Experimental Study of Air Lift Pumps" Bulletin of the University of Wisconsin Engineering Services 3, 4 (1924)

Wurts, A.W., S.G. McNeill & D.G. Overhults, "Performance and design characteristics of airlift pumps for field applications", World Aquaculture 25(4) (1994)

Zenz, F.A., "Explore the Potential of Air-Lift Pumps and Multiphase Systems", Chemical Engineering Progress, 89(8), August (1993)



PLAN
2'-4"
11'-4 1/2"
6-FASTENNER @ 2'-0" O/C
2" [
1" PLYWOOD
CATWALK
V-NOTCH WEIR SEE DETAIL
FLOW
TYPE 1 12"ø PVC
TYPE 2 10"ø CLEAR PLASTIC PIPE
TYPE 3 10"ø PVC
2'-0" 2'-0"
SEE DETAIL 'A'
6-FASTENNER @ 2'-0" O/C (TYP.)
23'-4"
14'-4"
8'-0"
6"
SECTION B-B
2 [
1" PLYWOOD
5'-0"
2'-0"
PIPE SUPPORT DETAIL 'B'
ALL DIMENSIONS TO SUIT
DETAIL 'A'
SPACER
2" [
2-5/8"ø BOLTS @ 1'-6" O/C
1 PLYWOOD
V-NOTCH WEIR DETAIL
SHARP EDGE METAL
1" PLYWOOD WEIR
REMOVABLE V-NOTCH WEIR
3'-6"
3'-0"
1'-6"
3'-3"
4'-0"
90°
SECTION C-C
AIR SUPPLY
CONTROL
2"ø AIR HOSE
1" PLYWOOD PIPE SUPPORT SEE DETAIL 'B'
ELBOW WITH EXTENSION
1" PLYWOOD PIPE SUPPORT SEE DETAIL 'C'
1/2" STRAP BOLT TO PLYWOOD
10"ø PVC OR PLASTIC PIPE
FLAPGATE
ADJUSTABLE WEIGHT
FLOW
AERATOR
AERATOR SUPPORT
AIR OPERATION DIAGRAM
VENT TO DOWN STREAM
MEASURE
AIR BLOWER
TYPE 1 TYPE 2 TYPE 3
SHUTOFF VALVE
2"ø AIR HOSE
4"ø AIR HOSE
CONTROL VALVE
DETAIL 'C'
1/2" STRAP
10"ø PIPE
1'-4"
TYPE 1
100-5mmø (0.2") PIN HOLE, (TYP.)
7"ø
0.57" TYP.
TYPE 2
100-5mmø (0.2") PIN HOLE, (TYP.)
R=2 1/2"
R=2"
R=1 1/2"
R=1"
R=1/2"
6"ø
12°
TYPE 3
0.95"(61/64") TYP.
6"ø
0.475"(15/32")
50-7mmø(0.275") PIN HOLE, (TYP.)
SECTION D-D
REMOVABLE V-NOTCH WEIR
1" PLYWOOD WEIR
1" PLYWOOD
WOOD BLOCK
FLOW
CLEAR PLASTIC ELBOW DETAIL
5 @ 18°=90°
10"ø CLEAR PLASTIC ELBOW
SECTION A-A
HANDRAIL
CATWALK C/W HANDRAIL
7'-2"
Approx. -4.4
dw
PROFILE
5'-0"
8'-0"
14'-4"
23'-4"
6"
AERATOR DETAIL
2" AIR HOSE
6"ø
3"
1 1/2"
AERATOR
AERATOR SUPPORT



MATERAIL:

PVC (1/4"), WOOD OR SHEET METAL MAY BE USED SUBJECT TO APPROVAL.

City of Richmond
6911 No. 3 ROAD RICHMOND B.C. V6Y 2C1

AIR PUMP PROJECT
TYPE 4 LAYOUT

DESIGN:	A.L.	DWG. No.	A-03
DRAWN:	C.Y.		
CHECKED:		SCALE: N.T.S.	DATE:
ENGINEER:		SEC. No:	