SOME ASPECTS OF LARVAL REARING TANK DESIGN

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Abstract

The ability to reliably rear marine finfish larvae is vital to the development of the mariculture industry.

There are many factors affecting the growth and survival of marine larvae in an artificial rearing environment, and in the case of many of these too little is known at present to determine their possible effects. It appears that one such factor is the flow characteristics of the rearing vessel. Very little work has been undertaken in this field, and the present study was aimed at gathering information on the general flow behaviour of several rearing tank systems currently in use, mostly based on the cylindro-conical rearing tank.

Whilst little difference was found between the various designs, in terms of their mixing efficiency (determined using residence time distribution), all designs studied performed well in this respect. Dye studies confirmed these findings.

However, it was concluded that the concept of perfect mixing as a goal in larval rearing tank design was not appropriate, and it was suggested that a system conforming to laminar flow may meet the requirements of larvae better (in terms of their physical environment).

1. INTRODUCTION

1.1 Aquaculture production of marine larvae

1.1.1 Historical perspective

The stimulus for research into hatchery and rearing techniques for marine larvae came about in the last century, in the form of declining wild stocks of commercially important fish species - a result of over-fishing. The development of these methods was aimed, therefore, at restocking, not at aquaculture, which now puts a much greater demand on the present hatcheries than do restocking programmes.

Shelbourne (1964) gives a thorough historical review of the early development of marine fish hatchery practices. Briefly, the first work in this field was undertaken in the U.S.A., following the success of the salmonid stock enhancement programmes in that country, such as that of the shad, *Alosa sapidissima*, during the 1870s. The cod fishery of Cape Ann, Massachusetts, was selected for the first experiments in marine fish stock enhancement. The first artificial fertilization experiments were carried out in 1878, and 1.5 million cod fry were released into local waters after the first attempt. Success was also acheived in these early years with herring (*Clupea harengus*), haddock (*Melanogrammus aeglefinus*) and American pollack (*Pollachius virens*).

This early work stimulated like ventures in Norway, Canada, Newfoundland, England and Scotland before the turn of the century. These concentrated their efforts almost exclusively on flat fish, especially the plaice (*Pleuronectes platessa*), but also lemon sole (*Microstomus kitt*) and flounder (*Platichthys flesus*). The early years of the twentieth century saw the establishment of marine fish hatcheries all over the world (In Australia, for example, a hatchery with an annual production capacity of 150 million fish and shellfish larvae was built at this time). Outstanding among these were those at Concarneau and St. Vaast-la-Houge, both in France, where much pioneering work was done on sole and turbot, respectively. By 1917, the three large hatcheries, which had by now been built on the east coast of the U.S.A., were producing between them 236 million cod (*Gadus callarias*) larvae, 1474 million of pollack, 6 million of haddock, and 1814 million flounder larvae.

Two world wars and the failure to demonstrate sufficient benefit to the fishery from these stock enhancement programmes, led to the gradual closure or conversion of these hatcheries. With today's technology and research base things might have been different, but as it was sufficient success to justify their existance was not forthcoming.

It was not until the refinement of aquacultural practices and the upsurge in interest in marine aquaculture during the 1960s and 1970s, that research into marine hatchery techniques was revived. In Europe, the first successes of the modern era were with plaice (*P. platessa*), but the low market value of this species rendered its artificial culture unviable on a commercial basis. Sole (*Solea solea*) was also successfully reared through the larval stages during this period and proved very hardy up until weaning from live to artificial diets. At this stage, however, extremely high mortalities were consistantly encountered.

The attention of the marine research stations therefore turned elsewhere in the search for a high value species, the large scale production of larvae of which, could form the basis for a commercial mariculture industry. In Norway and the U.K. the choice was limited because of the relatively low prevailing water temperatures. Turbot (*Scopthalmus maximus*), a large flatfish, showed the most promise. Research during the 1970s, in Britain, France and Norway, led to the establishment of a commercially viable industry based on hatchery-produced seed.

Being in warmer climes, the Mediterranean countries, France in particular, although suitable for turbot culture, extended their research efforts to sea bass (*Dicentrarchus labrax*) and sea bream (*Sparus aurata*), two popular and very highly valued marine fish.

Despite the research efforts in Europe, and elsewhere, during the last 20 years, into larval production of marine finfish, it is marine prawns which have given the most success commercially, and for which larval rearing techniques are the most advanced among marine species. Extensive rearing of marine prawns, mainly Penaeids, is a long-established practice in S.E. Asia and very important, both in the local economy and as a source of foreign exchange. Declining abundance of wild larvae and the unreliability of supply, stimulated research into artificial spawning and larval rearing techniques. First success was acheived with the very high value *P. japonicus* by Fujinaga, as early as 1934 (Kungvankij, 1984) - but commercial production did not commence until the early 1960s, in Japan (Aquacop, 1984).

More recently, induced spawning and larval rearing techniques have been developed for *P. monodon*, a more easily and more widely cultured species than *P. japonicus*. The high consumer demand for this species, both in the U.S.A. and in Asia, has brought about a radical redevelopment of traditional aquacultural practices in the Philippines and Indonesia, with the conversion of tidal ponds from extensive milkfish culture and milkfish/prawn polyculture, to intensive and semi-intensive culture of penaeid prawns. The high investment in prawn grow-out operations has led to further heavy investment in hatcheries, both from international aid organisations and private concerns, in an effort to alleviate problems of poor seed supply. Many prawn hatcheries, both large and small, are now established all over the region, some with capital investment running into millions of US dollars.

The technology has also been transferred elsewhere with great success. Ecuador, for example, is the world leader in prawn culture, present annual production being some 72000 tonnes. Although supplies of wild seed are often plentiful, the supply is very variable from year to year, and many farms have the capacity to produce their own larvae if necessary.

1.1.2 Current status

With the recognition of the importance of broodstock husbandry and larval nutrition in recent years, the range of commercially produced marine larvae is much wider than it was at the beginning of the decade. Following on from extensive research in the 1970s, sea bass, sea bream, mullet and turbot are now cultured commercially in Europe from artificially reared larvae, although there are still many problems yet to be solved and hatcheries are often only marginally profitable.

In the Mediterranean, most commercial effort is being directed at the culture of sea bass and sea bream, although turbot is also important, especially in Spain. Of the two former species, particular difficulties in larval rearing, especially during the swim-up and weaning stages, has led farmers to concentrate more on sea bream which is somewhat easier to culture in this respect. A leader in this field, Cephalonian Fisheries Ltd., of Greece, produced 1.4 million juveniles (1.5g individual weight) in 1986 (Anon., 1987). Their projected grow-out production for 1987, of 80 tonnes of bream and 5 tonnes of bass, reflects their preference for larval rearing of bream.

With the successful establishment of turbot culture in the U.K. and Norway, current research in higher latitudes has turned to halibut (*Hippoglossus hipoglossus*), which promises better growth rates in colder waters than turbot. Larval rearing techniques for this species are still in their infancy, the total U.K. output being only four juveniles to date (Dye, 1987). Norway also looks set for success with cod (*Gadus morhua*) culture, the first hatchery-produced juveniles being sold for on-growing late in 1987 (Anon. 1987).

In the Far East, where fish is much more a traditional part of the diet than in Europe, the culture of marine finfish is expanding rapidly as the reliability of seed supply improves, this being attributable to wide scale hatchery production of larvae. The most widely cultured marine finfish in S.E. Asia is the milkfish, *Chanos chanos* (over 300000 tonnes produced annually), and it is hoped that the production of artificial seed on a commercial scale will free the milkfish farming industry from a significant constraint - that of a reliable seed supply. Mullet (*Mugil cephalus*), red sea bream (*Chrysophrys major*), sea bass (*Lates calcarifer*) and grouper (*Epinephalus* spp.) are now also cultured in S.E. Asia from hatchery produced seed.

Penaeid larval culture is practiced over the whole of tropical and much of subtropical Asia, and is likely to continue its recent growth as increasingly heavy demands are made by the rapidly expanding prawn grow-out industry. Another notable centre of marine prawn larval production is Equador, and Mexico seems set to develop a similar industry.

1.1.3 Technical limitations

Although larvae of a number of marine fish and crustacea are produced commercially, there are still many limitations to the technical and financial viability of artificial seed production, which constitute severe constraints to the expansion of the industry.

These problems are well illustrated in the case of sea bass (*Dicentrarchus labrax*) larval culture, and are of both a technical and financial nature. On the technical side, two phenomina seriously reduce larval survival - spinal deformities and non-inflation of the swimbladder. These are thought to relate to nutritional deficiencies, particularly of highly unsaturated fatty acids (HUFAs). The recognition of this fact has enabled hatcheries to significantly increase output. The Greek firm, Cephalonian Fisheries, for example, increased production of healthy juveniles from 15% in 1982 to 45% in 1986, by using HUFA-enriched larval diets. However, this figure still represents a significant waste of resources, in terms of staff time, hatchery space and feed costs, and further improvements are still desirable.

On the financial side, problems concern the high staffing levels involved and their neccesary level of expertise, resulting in high wage costs - 26% of production costs in the case of Cephalonian Fisheries, who employ 13 technicians to produce just 1.4 million juveniles annually (considerably more than would be required to produce an equivalent number of salmon, a similarly priced fish). Much of this labour is required to produce live food for the larvae, artificial diets, although used as a supplement, not yet being of sufficient nutritional quality to replace these completely.

1.1.4 Summary

Larval rearing of marine finfish has a long history, but only recently, with increasing interest in marine aquaculture, has it become a commercially viable proposition. Problems encountered in rearing these larvae beyond the first-feeding stages, prompted a shift in commercial interest to marine prawns, the larvae of which are hardier and much easier to rear. Most developments in larval rearing technology during the past decade have, therefore, been related to prawn culture. These developments, mainly in the fields of broodstock and larval nutrition, and certain aspects of the larval rearing environment (*i.e.*, water quality) have, however, significantly increased the technical viability of marine finfish larval production, thus reviving interest from the commercial sector. At present, a number of marine finfish are cultured exclusively from hatchery reared juveniles, and with the constantly increasing technical base, this number is set to rise dramatically in the near future.

1.2 Rearing tank hydrodynamics and larval survival

Although this relationship has not been studied directly, there is evidence to suggest that larval survival is affected by the flow characteristics of the rearing tank, adversely rather than advantageously. For example, Dye (1987) concluded that poor incubator design (also later used for larval rearing) was in part responsible for the poor hatching success of halibut eggs.

Emadi (1973) recorded yolk-sac malformation in Pacific Salmon when the larvae were subjected to an increase in water velocity within the rearing vessel. This observation was attributed to mechanical injury of the yolk-sac through abrasion against the tank base. This condition was aggravated by high flow rates, but, apart from drawing attention to this fact, no further comments on the results were made.

Possibly, as the water flow was increased, the larvae had increasing difficulty in maintaining station, so increasing the degree of abrasion between the tank base and the larval yolk-sac. Provision of a gravel substrate, in which the larvae could find shelter from the water current and thus reduce the amount of abrasion suffered by the yolk sac against the substrate, may account for the decreased incidence of yolk-sac malformation.

Morgan, Ulanowicz, Rasin, Noe and Gray (1976) studied the effect of shear forces, in an experimental apparatus, on eggs and larvae of striped bass (*Morone saxatilis*) and white perch (*M. americana*). They found that shear forces of 350 dynes/cm² for a period of 4 minutes killed 88% of striped bass eggs so exposed, and 68% of larvae under the same conditions. Egg mortality was attributed to either the separation of the embryo from the yolk, or to the break-up of the yolk droplet.

It was pointed out by the authors that shear stresses can be resolved into rotational and deformational components (see section 2.1). Hickey (1978) tested the resistance to deformation of herring eggs and found them surprisingly tough. Morgan et al (*op. cit.*) calculated that a striped bass egg subjected to a shear force of only 0.2 dynes/cm² would spin at a rate of three revolutions per second. Although the authors make no comments about this, it is possible that the rotational component of the shear force, generated by differential flow velocities within a water mass, is the major operant in natural situations.

Hartman (1977) designed an experimental rearing system for brachyuran crab larvae, which consisted of a vertical, transparent plastic cylinder through which water flowed upwards. Within this cylinder the larvae were reared between two horizontal screens. During initial trials of this system, Hartman discovered that the lower screen support ring was generating a severe eddy current within the rearing chamber. Within a few hours of stocking this rearing unit, all the larvae were "rolled up in a packed ring", resulting in high mortality. Another aspect of the design resulted in a high incidence of damage to the dorsal spine of the larvae. It was noted that all the early mortalities during the rearing cycle had broken spines. Apparently, the healing of this wound (*i.e.* the formation of scar tissue) prevented complete separation of the larva from its old exoskeleton during moulting.

Bourgos (1986) reared larvae in a system recirculated by means of an airlift (in order to keep micro-particulate diets in suspension), and found that the larvae became entrained within the airlift, suffering damage to part of their sensory apparatus (neuromasts, microscopic sensory organs which become incorporated within the lateral line during metamorphosis).

Dye (1987) attempted to rear halibut larvae in rearing units designed for turbot larvae. The attempt was unsuccessful, none of the larvae surviving the "turbulence and abrasion" in the tanks.

Thus the flow pattern of the water in a larval rearing tank can be potentially damaging to marine larvae via a number of different mechanisms.

i) High velocities can result in high energy collisions between the larvae and the tank wall, and between larvae;

ii) Low velocity areas within the tank can create stagnant pools (dead spaces), which have the potential for reduced water quality and limited feed replacements;

iii) Interfaces between masses of water having significantly different velocities (*i.e.*, turbulent zones) can potentially lead to shearing forces, which themselves may cause damage to the larvae.

iv) Finally, the flow regime will influence the suspension of the larva and will affect the presentation rate of feed particles to individual larvae.

These phenomena will be discussed more thoroughly in section 2.1.

1.3 Larval rearing tank systems and the effect of design on fluid mechanics

During the research phase of the development of marine larval rearing techniques many types of culture vessel were used, ranging from 1 litre glass beakers to 75 litre tanks, or even larger. Only with the commercial development of marine aquaculture have standard types of larval rearing-tank been adopted - and these only by trial and error rather than by any formal recognition of their desirable qualities. Of these the cylindro-conical tank is perhaps the most versatile, being available in plastic and glass fibre, of convenient size and readily adaptable to a number of fundamentally different systems (see below). Even with the widespread use of cylindro-conical tanks, there are other types used for larval rearing. Commercially, flat-bottomed circular or square tanks are often employed, more particularly for marine prawn larvae. Marine finfish larvae, especially halibut (see Blaxter, 1983: Dye, 1987), seem to be much more delicate than prawn larvae and thus require a more exacting rearing system.

Within the confines of the cylindro-conical design, a number of different systems have been used for larval rearing. Before going on to consider specific designs in detail, an effort should be made to classify, in a general sense, the different systems in use. The first level of classification, should differentiate between static and flow-through systems. Each class can be further subdivided.

Static systems are of either the clear-water or the green-water type, although this division is often not very clear and with some systems one may only say that it is tending towards one type or the other. The clear-water system involves frequent water changes in the rearing vessel to maintain water quality (McVey and Fox, 1983). The greenwater system, developed in Japan, makes use of algae cultured within the rearing vessel to maintain water quality (Kungvankij, 1985). Depending on the performance of the algae in this respect, water changes may be more or less frequent, or may be avoided altogether. With the water being static, the design of the rearing vessel is of little relevance (surface area/volume ratio excepted), and these systems, therefore, are of little interest where this project is concerned. The use of special diets and the man power required, on a commercial scale, to undertake frequent water changes, among other reasons, have led to the widespread adoption of throughflow systems as an alternative.

A continuous flow of water through the rearing tank has a number of advantages over static systems, but also creates its own set of problems - now that water is flowing within the system, the design of the system will affect the larval environment. Flow-through systems are of either the gravitational flow or of the upwelling type, and may or may not be part of a recycle system.

Gravitational through-flow systems have a simple downward movement of water, from the inlet at the top to the outlet at the bottom. With the flow being in the same direction as gravity, the settling velocity of solid wastes is enhanced, so speeding their removal from the water column. The same can also be said of food particles, however, and this is one of the major disadvantages with gravitational through-flow tanks - innefficient use of micro-particulate diets. One variation on the theme, is a tank in which the water is continuously recirculated (without passing through any solids removal device) by means of an external airlift, in order to increase the temporal availability of the food to the larvae (Bourgos, 1986). Because of inadequacies in the design of such systems, high flow rates are often generated within the tank, which are too great for young larvae to resist. Larvae may then be drawn onto outlet screens, or entrained within the airlift where they may suffer considerable damage (Bourgos, 1986).

Upwelling systems are used to produce a flow to counter the force of gravity, and so reduce the settling velocity of micro-particulate diets and to buoy up larvae, some of which are known to temporarilly lose buoyancy from time to time (eg. mullet; Houde et al, 1976 : halibut; Dye, 1987). An upwelling current is also thought to produce more gentle hydrodynamic conditions within the rearing tank than gravitational flow.

A common feature of through-flow systems, and this applies to both gravitational and upwelling types, is a single-point inlet and/or outlet. In the case of the inlet the difference between the velocity of water already within the tank and that entering it creates localized turbulence and shear. At the outlet, water velocity increases towards the constriction, again creating localized shear. Various efforts have been made to reduce the effects of inlet and outlet flow on the system.

Hughes et al (1974) designed a multi-point inlet system for a lobster larval-rearing tank. This was an upwelling unit, with a hemispherical bottom and cylindrical sides. The inlet was in the centre of the base and consisted of a short cylindrical block, into the base of which was machined an annular ring, from which grooves radiated outward. A screw-on base plate was provided which sealed the annular ring, but allowed water to exit from the ring via the radial grooves, and so into the tank. The grooves had been machined at an angle so as to induce a circular water flow within the tank. Through the centre of the block ran a verticle standpipe outlet.

Bourgos (1986) used the same concept in a cylindro-conical tank for rearing larval turbot (*Scophthalmus maximus*). Based on the system of Hughes et al (1974), that of Bourgos differed in having the multi-point inlet holes machined at 45° to the verticle through a horizontal baseplate set in the base of the tank. These water channels were aligned in such a way that water entered the tank parallel to the walls of the basal cone and produced a directly upwelling current, with no spiral flow.

Shafland (1976), in his design for an upwelling larval rearing system, attempted to reduce exit water velocities by setting the small (8 litre) cylindro-conical units within an aquarium and incorporating large panels of fine mesh material into the vertical walls of each unit. Water entering at the base of the unit would well up within the rearing tank and exit through the side walls into the aquarium (which was filled with water to the same height as the rearing tanks). Thus it was hoped to produce an even flow within the rearing tank, the bulk of the aquarium damping any directionallity in the flow regime. Water movement through the rearing unit, into the tank and back to the base of the rearing unit, was powered by an airlift pump.

A recently introduced commercial product, of Aqua BioSystems, is an upwelling cylindro-conical larval rearing unit. The inlet is by way of a horizontal pipe which enters through the side wall of the unit. At its end, the pipe turns through 90° so that it opens directly above the centre of the tank base. Thus the incoming flow, directed downwards initially, is deflected upwards and radially from the base of the tank (which is an inverted cone). The outlet consists of a trough which runs around the top of the tank, into which is cut a series of slits which allow the exit flow from the tank to run into the trough, before running to waste via a single pipe. Thus an equal exit flow velocity around the whole circumference of the tank is produced.

Thus many different systems have been used for larval rearing, each with their own merits and demerits. However, despite the interest, from both the commercial and research sectors, in the rearing of marine larvae, little fundamental analytical and design work has yet been undertaken in this field. The present study aims to provide some insight into some of the technical aspects of marine larval rearing tank design.

1.4 Objectives of the present study

The present study aims to quantify, for the first time, the hydraulic characteristics of certain through flow larval rearing tank designs. Particular emphasis will be given to mixing, which has implications for water quality and larval and larval feed suspension and dispersion, and the presence of turbulence, which, by generation of shear forces, may constitute a factor detrimental to larval survival.

In section 1. the rearing of marine larvae has been put into an historical perspective, and its current status and limitations to commercial practice briefly outlined. The reported effects of water movement on larval survival, and the different types of larval rearing tanks used presently, and in the past, have been reviewed.

Section 2. introduces the concepts involved in the consideration of flow patterns within larval rearing tanks, and previous flow pattern studies throughout the field of aquaculture are reviewed. The experimental techniques used in the present study are explained, and the methodology detailed.

In section 3. the results obtained during the present study are presented, and discussed in the light of previous knowledge, in section 4., with comments on the methodology employed in this and past work, and the relevance of these results to larval rearing tank design.

Finally, Section 5. summarises the conclusions which may be drawn from this work, about larval rearing tank design and the importance of flow patterns, and future research needs are identified.

2. Hydrodynamics of throughflow rearing tanks

2.1 Theory

Many of the physical parameters in a larval rearing tank, such as temperature, dissolved oxygen, light intensity etc., can be closely controlled by the culturist. However, there are some compromises which have to be made. If continuous water replacement is used to control the levels of metabolites and dissolved oxygen within the rearing vessel, then, as an unavoidable consequence, there will be a mass flow of water through the tank. A second complicating factor is the use of airlifts to recirculate the water within the tank in order to resuspend micro-particulate diets, so as to increase their temporal availability to the larvae (Bourgos, 1986) - again, a consequence being the mass flow of water within the tank.

In systems characterised by throughflow, frictional forces, acting locally upon the water flowing through the tank, will result in the development of differential flow velocities within the water body, such that relatively discrete water masses exist (inlet and exit streams to and from the tank are also sources of differential flow velocities). Between such water masses, and between these and stationary objects, such as pipes, the tank walls, etc., a boundary layer will exist which, in terms of flow velocity, is transitory between the two phases. Consequently, these regions are high in energy and any objects within them are subject to a shear force, the magnitude of which is a product of the difference between the flow velocities of the adjacent phases. Shear forces can be resolved into two components; deformational and rotational (Morgan et al, 1976). It is the latter which is most likely the cause of stress to marine fish larvae (see section 1.2), although this is not proven.

Shear forces and turbulence are very much interrelated, turbulence being an extreme example of differential flow velocities within the water body, and shear forces being a result of these differential flow velocities. Thus it follows that turbulence is an indicator of the presence of shear forces within the larval rearing tank, and may be used as such in the absence of any practical means of measuring shear force.

Another aspect of larval rearing tank hydrodynamics (its flow characteristics in a throughflow system), concerns the efficiency of a tank as a mixing vessel - the ideal of which is known as a complete mixed flow reactor (CMFR) for a through flow system. In a poorly mixed system, the water quality in the tank is likely to vary spatially, because some areas of the tank will be isolated to a certain degree from the main flow of water within the tank. This phenomenon is refered to as short-circuiting, and is associated with the presence of so-called 'dead spaces' within the tank. These are zones which receive a smaller proportion of the incoming water than other areas, and so dissolved or suspended substances in the water have a longer residence time in these dead spaces than in other regions of the tank. The larger the proportion of dead space in the tank the more poorly is the tank mixed.

A poorly mixed tank will have a number of inadequacies as far as larval rearing is concerned. First, waste metabolites may build up in the dead volume, and larvae moving into these areas may suffer a higher rate of mortality. Furthermore, disturbances to the tank may release water with a higher level of waste metabolites (and perhaps associated pathogens) into the mixed volume of the tank, in which case larval survival may be detrimentally affected. The same argument may be applied to dissolved oxygen levels (although they would be lower in the dead spaces and higher in the well mixed portion of the tank).

Second, the dead spaces are subject to lower current velocities, as they receive less water than other zones of the tank. Thus it is likely that sedimentation of suspended solids, such as micro-particulate diets, will occur at a higher rate than in the better mixed areas of the tank. Being an ideal substrate for bacteria, the presence of a layer of organically rich sediment (where a dead space is adjacent to the tank wall) may cause severe deterioration of the water quality of these regions. Some marine larvae are known to intermittantly lose buoyancy in the first week after hatching (Nash, Kuo and McConnel 1974; Dye, 1987), at which time they may also settle out of the water column if the water velocity to which they are subjected is significantly reduced. In such a situation high mortalities would almost certainly result, as a consequence of the presence of dead spaces.

Finally, the existence of dead spaces implies the presence of differential flow velocities within the rearing tank, the dead spaces having a reduced water supply as a result of poor mixing and short-circuiting. As explained in section 1.2, a difference in water velocity between two water masses generates shear forces which, as has been shown by Morgan et al (1976), are detrimental to larval survival.

2.2 Flow distribution studies in aquaculture

Studies of flow patterns and tank hydrodynamics have been confined until now (with one exception; Hughes, Shleser and Tchobanoglous, 1974) to on-growing tanks. Two techniques have been used, usually separately but sometimes in a complimentary fashion - residence time distribution (RTD) analysis, and flow visualization using dye. The latter involves the introduction of a solution of dye to the inlet stream of the tank, and following its path as it moves to the outlet. Residence time distribution involves the introduction of a tracer into the inlet stream of the tank. Its concentration in the exit stream is recorded over a period of time, and the data so obtained is used to analyse the flushing characteristics of the tank, from which can be inferred its mixing efficiency. This technique is examined in more detail in section 2.4.

Although the possible applications of this technique in aquacultural engineering are many, it has been very little used to date. The earliest use of RTD anlysis to evaluate the hydraulic behaviour of fish rearing systems was by Burrows and Chenoweth in 1955, in comparing the hydraulic characteristics of three types of salmonid on-growing pond, namely the Foster-Lucas, circular, and raceway types. Using dye as the tracer in full scale ponds and one tenth scale models, the authors identified considerable short-circuiting in the Foster-Lucas and circular ponds, and concluded that ponds characterised by circular flow could not be freed of short-circuiting and mixing (this is a surprising finding in view of the widespread use of circular tanks, although their advantageous self-cleaning properties probably outweighs this factor in commercial use). These ponds were found to be inferior to the raceway system in respect of both short-circuiting and the higher volume of dead space within the pond. However, the self-cleaning properties of the raceway were found to be considerably lacking. Flow visualization studies using dyes confirmed the presence of dead space in the Foster-Lucas and circular ponds, and severe eddies, causing mixing, in the Foster-Lucas pond.

It is almost twenty years later that RTD analysis next appears in the aquacultural literature, this time in an analysis of the hydraulic characteristics of a rearing tank for lobster larvae (Hughes et al, 1974). Here, a dye (rhodamine B) was used as a tracer, and the results revealed the good mixing characteristics of this design. The authors used the extent of mixing within the tank to infer the degree of contact between lobster larvae and food particles. The degree of mixing was found to increase with flow rate.

Weatherley (1982) demonstrated the application of RTD analysis as a tool in recycle system design, using it, in a slightly modified form, to predict the distribution of ammonia in an experimental system, following different operator-induced stimuli. These mimicked the effect of artificially seeding a new biological filter, and suddenly increasing the stock biomass of a system.

Burley and Klapsis (1985), following on from their review of flow distribution studies in on-growing tanks (Klapsis and Burley, 1985), used RTD analysis in their efforts to improve the hydraulic performance of a 1m tank operating under a circular flow regime. RTD analysis was used to indicate the existence of dead spaces, so implying incomplete mixing, by comparing observed values to theoretically derived values of mean residence time. The design and operational parameters of the tank were adjusted until optimal hydraulic performance had been acheived.

Finally, Watten and Beck (1987) used RTD analysis to prove the effectiveness of a new channel catfish (*Ictalurus punctatus*) rearing tank design. In this, they attempted to combine the desirable water circulation characteristics of circular rearing tanks, with the ease of management afforded by raceways. A raceway is designed to conform to a plug flow regime, and as such is not well mixed. Thus a gradient of decreasing dissolved oxygen and increasing metabolite levels exists between its inlet and outlet. Watten and Beck (*op. cit.*) modified an existing raceway to incorporate a multiple inlet and a multiple outlet system running along opposite lengths of the tank, their configuration generating a circular water flow across the tank (centred on a horizontal axis). Using RTD analysis, the flow characteristics of this system were compared to those of a theoretically ideal system and a conventional circular tank, and almost perfect agreement found between all three. Incidentally, the presence of fish (at a stock density of $29kg/m^3$) had no discernable effect on mixing efficiency, in all tanks studied.

Other hydrodynamic studies of rearing tanks have been undertaken, but often using flow visualization techniques to discern the flow pattern, rather than a proceedure yielding numeric data. Burrows and Chenoweth (1970) described the flow characteristics of a rectangular circulating rearing pond, basically a D-ended raceway with a central, longitudinal division and square rather than semi-circular ends, and employing fixed metal vanes to direct the water flow round the corners. Turbulence and eddies within the system were described, and some water velocities measured, but no mention was made of the techniques involved.

Larmoyeux, Piper and Chenoweth (1973) described the flow characteristics of circular salmonid tanks, featuring central outlets and induced spiral water flow. They identified a turbulent zone, of considerable extent, associated with the walls and base of the tanks, which surrounded an annular viscous zone of greater velocity. Closely associated with the tank base was a boundary layer. Whereas the flow in the turbulent and viscous zones was essentially tangential, that of the boundary layer had a radial component, which imparted self-cleaning properties to such tanks. Again, no mention was made of the methods employed in this study.

2.3 <u>Hydrodynamics of larval rearing tanks</u>

Whilst hydrodynamic studies of on-growing ponds are few in number, those of larval rearing tanks, in which the flow characteristics may be more crucial, are virtually non-existent, and to date, no rigorous hydrodynamic studies have been performed on larval rearing tanks. In fact, there seems to be very little awareness of the effect of system design and construction on their flow characteristics. Hence, the evidence that poor design might adversely affect larval survival is scant (see section 1.2), although some authors have inferred that this is the case (e.g. Dye, 1987), and Hughes *et al* (1974), stated that the hydraulic characteristics of the rearing tank were one of the most important factors controlling larval lobster survival.

Commercial experience with marine and freshwater prawns indicates that even vigorous aeration has little obvious effect on larval survival. Marine finfish, however, appear to be far more delicate than crustacea during the larval stages, and there is some evidence that shear forces, resulting from turbulence associated with high current velocities and strong aeration, may be detrimental to larval survival (Morgan et el, 1976)). Bourgos (1986) concluded that, "...turbulence and larval recirculation [through an airlift pump] had negligible effects on larval survival". However, his study concentrated upon rearing trials using an airlift-driven recirculating system designed to keep micro-particulate diets in suspension. Turbulence, in his study, was merely inferred from the relative magnitude of the mass flow of water through the tank, and not actually measured or observed. However, using the same system (but with a different species, halibut), Dye

(1987) suggested that the turbulence within the system, and the consequent abrasion suffered by the larvae, caused total mortality within a few days.

Thus, there is a need for a thorough evaluation of the flow characteristics of the larval-rearing systems (tank design, inlet/outlet configuration, flow pattern, and mixing efficiency) currently in use, in order to quantify their flow characteristics - and using this data as a basis, to formulate improvements to existing designs. In the following sections of this chapter the experiments carried out towards this end are described and discussed.

2.4 Mixing studies - the use of residence time distribution analysis

In the field of industrial process engineering a technique was sought whereby the efficiency of reactor vessels could be determined. In the case of batch reactors, into which various reagents were introduced and mechanically agitated until a homogeneous mixture was achieved, this was simple. However, in the case of throughflow reactors, in which the reagents were required to mix as they travelled through the system, assessing efficiency was much more complicated, and much more crucial, as the flow characteristics of the reactor vessel directly affected the degree of mixing of the reagents and thus the efficiency of the reaction.

Residence time distribution (RTD) analysis is now widely used for this purpose (see Danckwerts, 1953; Cholette and Cloutier, 1959; Levenspiel, 1979), and is also finding applications in other disciplines. The technique involves the introduction of a non-reactive tracer into the affluent stream of the reactor vessel, and the measurment of its concentration in the effluent stream. By comparison of the exit-age distribution of the tracer in the effluent stream (in the form of a graph of tracer concentration versus time) with a theoretical response curve, that for a complete mixed flow reactor (CMFR), one can determine the reactor's efficiency as a mixing vessel under a continuous flow regime.

A mean observed residence time of less than the theoretically derived residence time (a simple function of vessel volume and fluid flow rate) is indicative of stagnant regions within the reactor vessel, and of short-circuiting (i.e. where a proportion of the reagent reaches the outlet more quickly than the remainder, and so is not as completely mixed with the contents of the vessel). An observed mean residence time larger than the theoretical residence time is indicative of fluid recirculation within the vessel. Each individual vessel is characterised by its linear dimensions and the flow pattern of fluid through the vessel. The relationship between these variables results, for each different combination, in a characteristic flow path, or series of flow paths, along which elements of the inlet stream will travel as they move toward the outlet (Levenspiel, 1979). In the case of fluid recirculation in the vessel, the residence time of any particular element of fluid is extended if it recirculates and travels a flow path more than once before exiting from the vessel.

This technique was used in the present study to evaluate the mixing performance of seven types of larval rearing tank (the distinction of types being based upon both tank shape and flow path). These seven were;

i) A cylindro-conical tank of 69 litres capacity, with a perpendicular downward flow pattern.

ii) As above, but with the geometry of the inlet changed so as to induce a helical downflow.

iii) A cylindro-conical tank as before, but of 81 litres capacity and altered to accomodate a perpendicular upwelling flow.

iv) A scale model of system iii), of 2.45 litres capacity, with perpendicular upwelling flow via a multi-point inlet and a vertical stand pipe outlet.

v) As for iv), but with the inlet slots angled so as to induce helical upwelling flow.

vi) A cylindrical flat-bottomed tank of 1 litre capacity, with a radial inlet at the surface and a central outlet in the base of the tank.

vii) A conical tank of 1.3 litres capacity, the slope of the sidewall being 7° from the verticle, adapted to a perpendicular upwelling flow regime.

Figure 1 shows the basic form of the tanks used in these systems.

2.5 Residence time distribution - experimental method

Nomenclature

C	Tracer concentration in effluent above normal supply level (expressed as conductivity in mmho)
C_i	Tracer concentration in effluent at time i (expressed as conductivity in mmho)
C_{min}	Tracer concentration in effluent following step down (expressed as conductivity in mmho)
C_o	Tracer concentration in affluent above normal supply level (expressed as conductivity in mmho)
ΔC_{max}	Maximum change in tracer concentration (expressed as conductivity in mmho)
Q	Volumetric flow rate (l min^{-1})
t	Time (min)
$\bar{t}$	V/Q, theoretical mean retention time (min)
$\bar{t}_c$	Calculated mean retention time (min)
V	Volume of liquid in tank (l)
θ	$t/\bar{t}_c$, normalized time, dimensionless

The experimental procedure used in this study for the determination of residence time distribution, involved the flushing of a salt water filled rearing system with fresh water. This constituted a step-down in tracer concentration (see Watten and Beck, 1987, and section 2.4). The technical considerations involved in the system design were:

i) Before the step-down in tracer concentration took place, the salt water had to be flowing through the system, so that flow patterns characteristic of the system when in operation, were established (*i.e.*, the inertia of the static system must be overcome) before the trial commenced.

ii) The flow rate of water through the system had to be the same before and after the step-down in tracer concentration.

In order to satisfy these conditions a system was designed which comprised a larval rearing tank, which could be adapted to various designs or exchanged for a different tank altogether (see figure 2). This was supplied by two constant head tanks (each part of a recirculating system), one containing tap water, the other the same to which had been added a small quantity of sodium chloride, as a tracer. These emptied into the rearing tank via a common pipe, controlled by a diaphragm valve. Other valves in the system allowed either salt water or fresh water to be run into the tank via this pipe, from one or other of the header tanks, as appropriate. Each unit was identical in respect of pipe length and static head, so each delivered the same flow of water from the pipe mouth for a given setting of the diaphragm valve.

Into the outlet from the rearing tank, which was directed to waste once the experiment had started, was plumbed a transducer (Phillips, type 9550/60), to monitor the change in conductivity attributable to changing tracer concentration during each trial. The change in conductivity sensed by the transducer was converted by a Portland Electronics (model P310) conditioning unit to a DC voltage output, which was proportional to conductivity over a range of 0-50mV. This output was translated into a graphic form by a Smiths Servoscribe RE 511.20 chart recorder. A permanent record of the change in conductivity of the exit stream from the tank over time, was thus obtained. From Trial 12 onwards, recordings were made direct from the conditioning unit (over a range of 0-1mmho) at appropriate time intervals, usually five minutes.

Other records kept for each trial were as follows:

i) Tank volume and flow rate - The latter was measured with a stop watch and measuring cylinder, three readings being taken and the mean value calculated. Measurements were taken before and after the trial to check for continuity.

ii) Water temperature - Conductivity varies with temperature, increasing 3% for every 1°C rise. Thus it was important that there were not large variations in temperature between the salt and fresh water systems and the tap water, which was used for topping up the fresh water system as the trial proceeded. If required, the temperature of the tap water was equalised with that in the recirculating systems.

iii) Duration of the trial - This was noted so that the time axis of the chart recording could be calibrated.

iv) Conductivity - At the start and finish of each trial the conductivity of the exit stream was read from the conditioning unit, in mmho. These figures were used to calibrate the conductivity axis of the chart recording.

v) Design parameters - For each trial, particulars of the inlet and outlet systems were noted, as was the flow type of the tank, i.e. upwelling flow or gravity flow, and within these classifications whether this flow was helical or perpendicular.

Analysis of the data produced values for the mean residence time of tracer for each trial, using the following equation;

$$\bar{t}_c = \frac{\int_0^\infty (C_{min} - C_i)dt}{\Delta C_{max}}$$

The area under the curve on the chart recording (in units of time and conductivity) was found, using squared paper, and used to approximate

$$\int_0^\infty (C_{min} - C_i)dt$$

ΔC_{max} represents the change in conductivity between the start and finish of the trial.

Thus the mean residence time of the tracer in the rearing tank was calculated for each trial (see Levenspiel, 1979, for a full account of the theory of RTD analysis).

In order to avoid unecessary, and time consuming experimental work, a predictable relationship beween flow rate and mean residence time was sought. This would enable conclusions to be drawn regarding the flow behaviour of the different tanks tested from trials conducted for only one flow rate, rather than a wide range, thus saving considerable time and work.

Systems i) to iii), section 2.4, were tested at a variety of flow rates. Regression analysis of mean residence time against flow rate, performed on logarithmic transformations of the data, revealed a highly significant relationship ($\rho=0.01$) for each of the three systems. Plots of this data are shown in figure 3.

Having established this relationship, the remaining systems were tested at one flow rate, three replicates being performed.

Dye tests were performed on model tanks, made from 15cm Ø perspex tubing and glass funnels. Flow rates were scaled down in accordance with Froude's Law (see Burrows and Chenoweth, 1955), *i.e.*, to the square root of the scale ratio. Dye was injected into the inlet pipe, some distance from the outlet so as not to disturb the flow, and a photographic record was made of the movement of the dye through the tank.

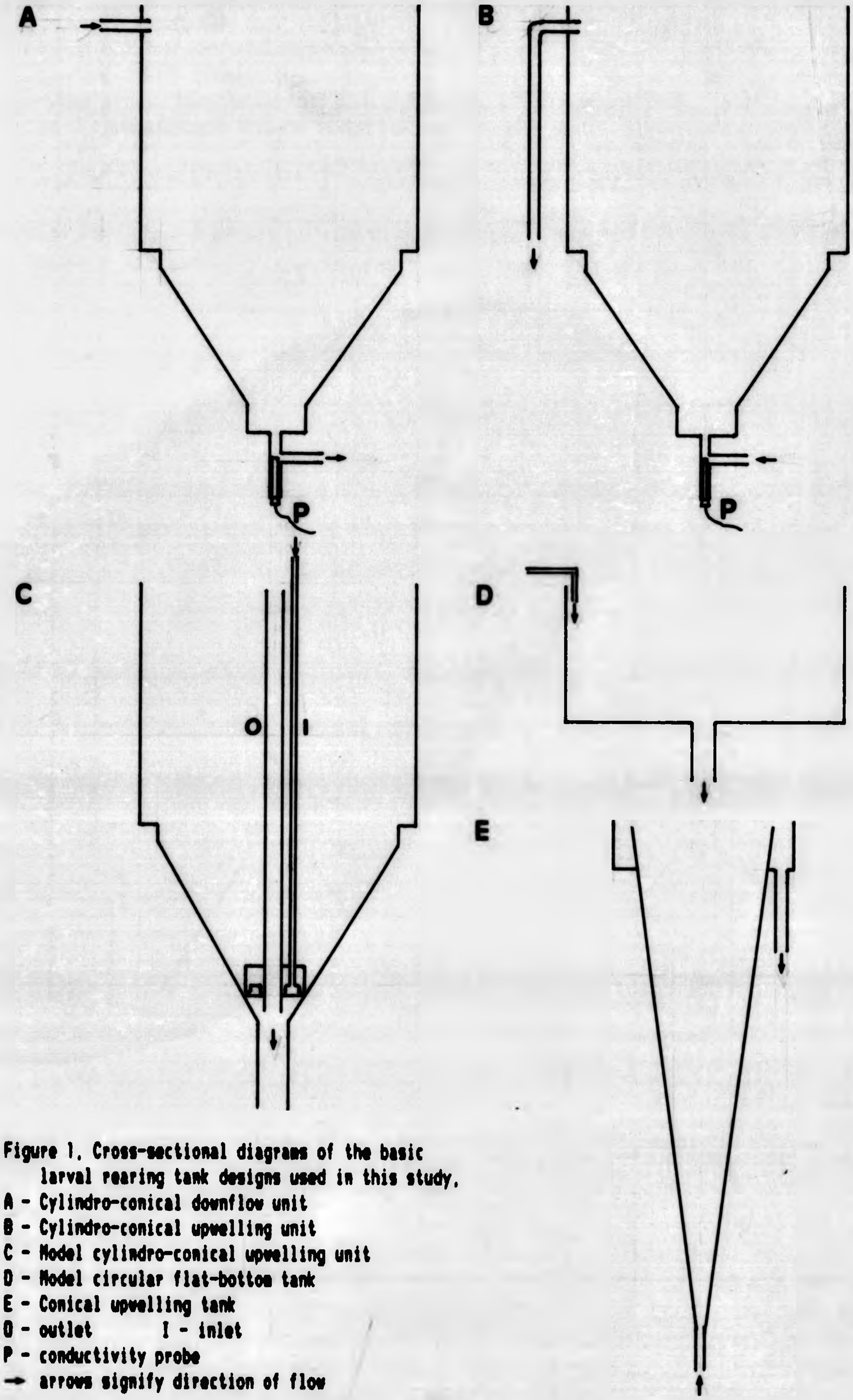
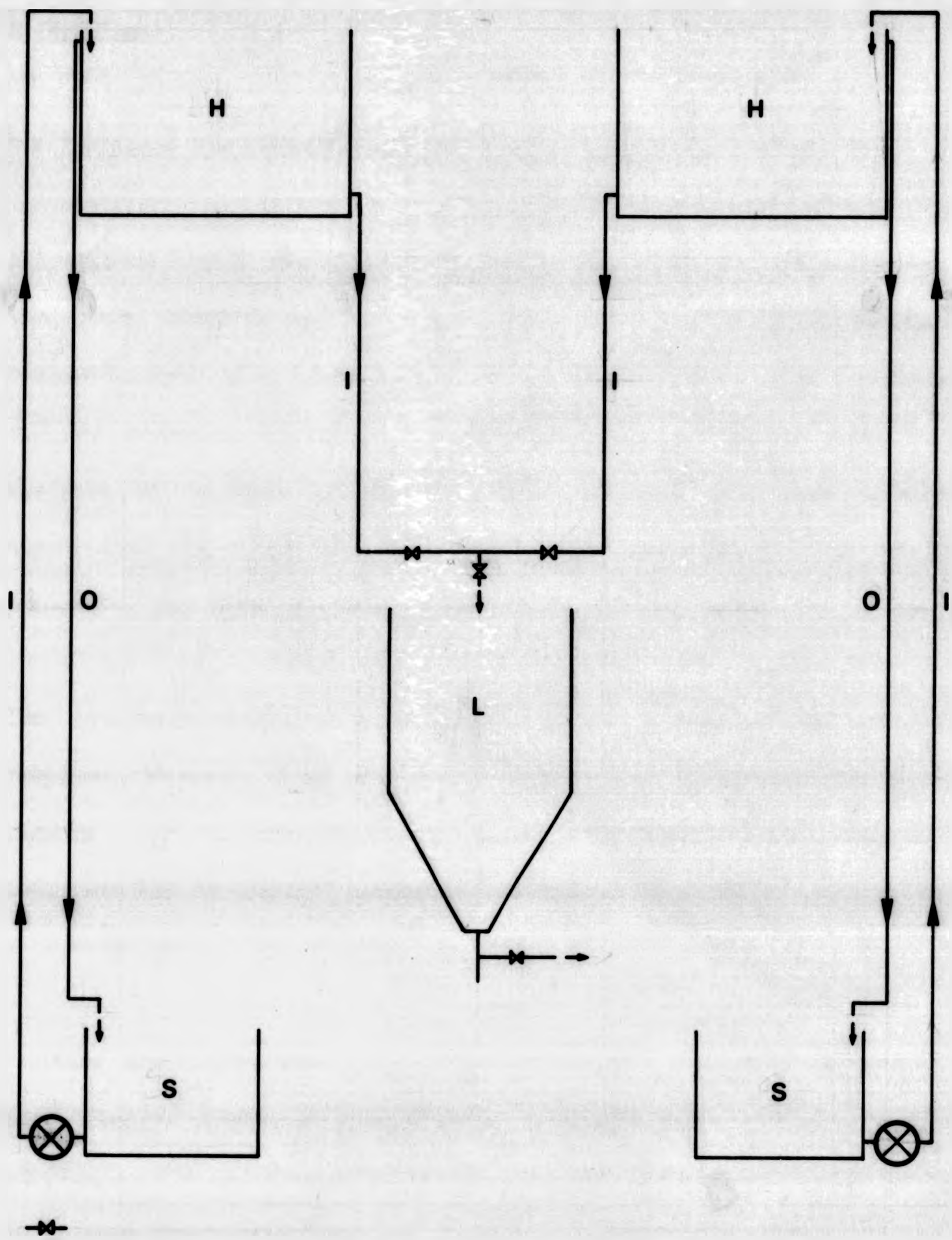


Figure 1. Cross-sectional diagrams of the basic larval rearing tank designs used in this study.

A - Cylindro-conical downflow unit
B - Cylindro-conical upwelling unit
C - Model cylindro-conical upwelling unit
D - Model circular flat-bottom tank
E - Conical upwelling tank
O - outlet   I - inlet
P - conductivity probe
→ arrows signify direction of flow



- valve
S - sump
H - header tank
- pump
L - larval rearing tank
I - inlet
O - overflow
- direction of flow

Figure 2. Diagramatic representation of the experimental system used in residence time distribution analysis.

3. Results

3.1 Residence time distribution analysis - results

All systems tested showed a close similarity in their flow behaviour to the theoretical ideal of perfect mixing, when compared using the statistic mean residence time (see Table 1). Generally, the observed mean residence time, $\bar{t}_c$, was somewhat greater than the theoretical residence time, $\bar{t}$, but an analysis of variance of the $\bar{t}_c/\bar{t}$ ratio against tank type identified no significant difference (ρ=0.05) between tank type and deviation of the mean residence time from the theoretical mean residence time.

The cylindro-conical perpendicular downflow tank showed a different response, however, from the other tank types tested, as examination of figures 4-10 reveals. Here are plotted normalised tracer concentration, C/C_o, and the theoretical response, $e^{-(\theta)}$, versus normalized time, $\bar{t}_c/\bar{t}$, for a representative trial of each tank type.

Plotting $\log_{10} C/C_o$ and $\log_{10} e^{-(\theta)}$ versus $\bar{t}_c/\bar{t}$, shows these differences more clearly. These are also shown in figures 4-10.

No obvious short-circuiting was observed in any of the trials.

3.2 Dye tests

The cylindrical flat-bottomed tank was characterised by a high degree of turbulence. The inlet stream travelled down through the water column to be deflected by the bottom of the tank in all directions. Thus the tank was well mixed in a few seconds (see figure 11).

In both the cylindro-conical upwelling units, laminar flow was observed at very low flow rates (see figure 12). As the water moved towards the outlet the laminar flow broke down to turbulent flow. Figure 13 shows the flow pattern of this unit at a more representative flow rate.

The cylindro-conical upwelling helical unit showed only very slight helical flow, being inconsistant in its occurance and bearly detectable.

The dye tests revealed that turbulence existed in all tank types tested, at most flow rates (e.g. figure 13).

Figure 3. Plots showing the relationship between flow rate and $\bar{t}_c$, for three different larval rearing systems based on the cylindro-conical tank.
A - perpendicular downflow unit:- y=4.22-0.966x
B - helical downflow unit:- y=4.22-0.955x
C - perpendicular upwelling unit:- y=4.3-.881x

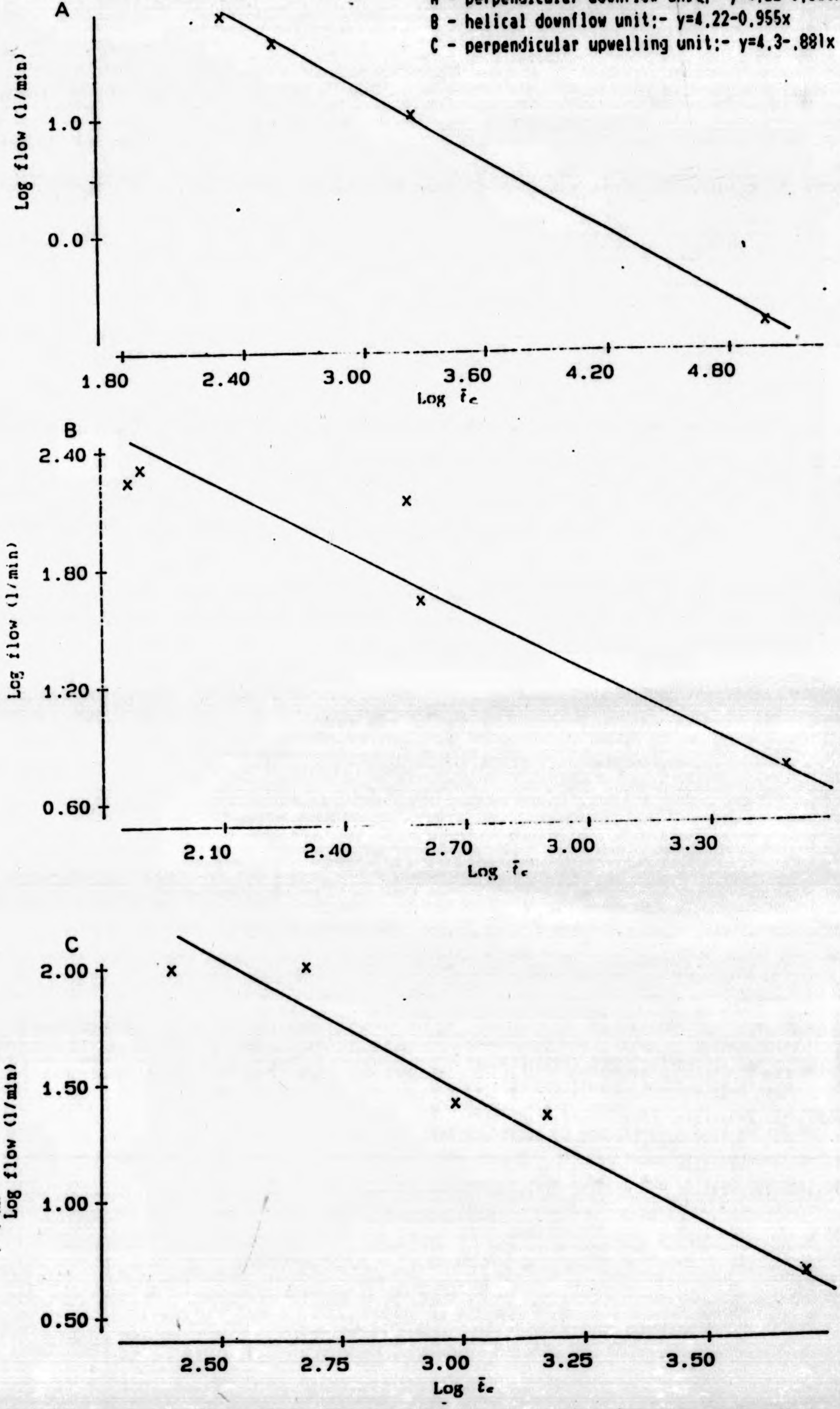


TABLE 1 - Results of residence time distribution analysis for seven different tank systems. Values presented are the mean value for each parameter, as indicated.

Tank type	$\bar{x}$ $\bar{t}_c$	$\bar{x}$ $\bar{t}$	$\bar{x}$ $\bar{t}_c/\bar{t}$	$\bar{x}$ $\%V_d$(1)
perpendicular downflow	35.06	35.60	1.03	4.42
helical downflow	13.44	13.49	0.98	1.03
perpendicular upwelling	21.89	20.55	1.10	1.39
perpendicular upwelling (M)	12.12	10.36	1.17	-
helical upwelling (M)	13.20	10.21	1.29	-
cylindrical flat-bottom (M)	5.21	4.84	1.08	-
conical upwelling	6.63	6.20	1.08	-

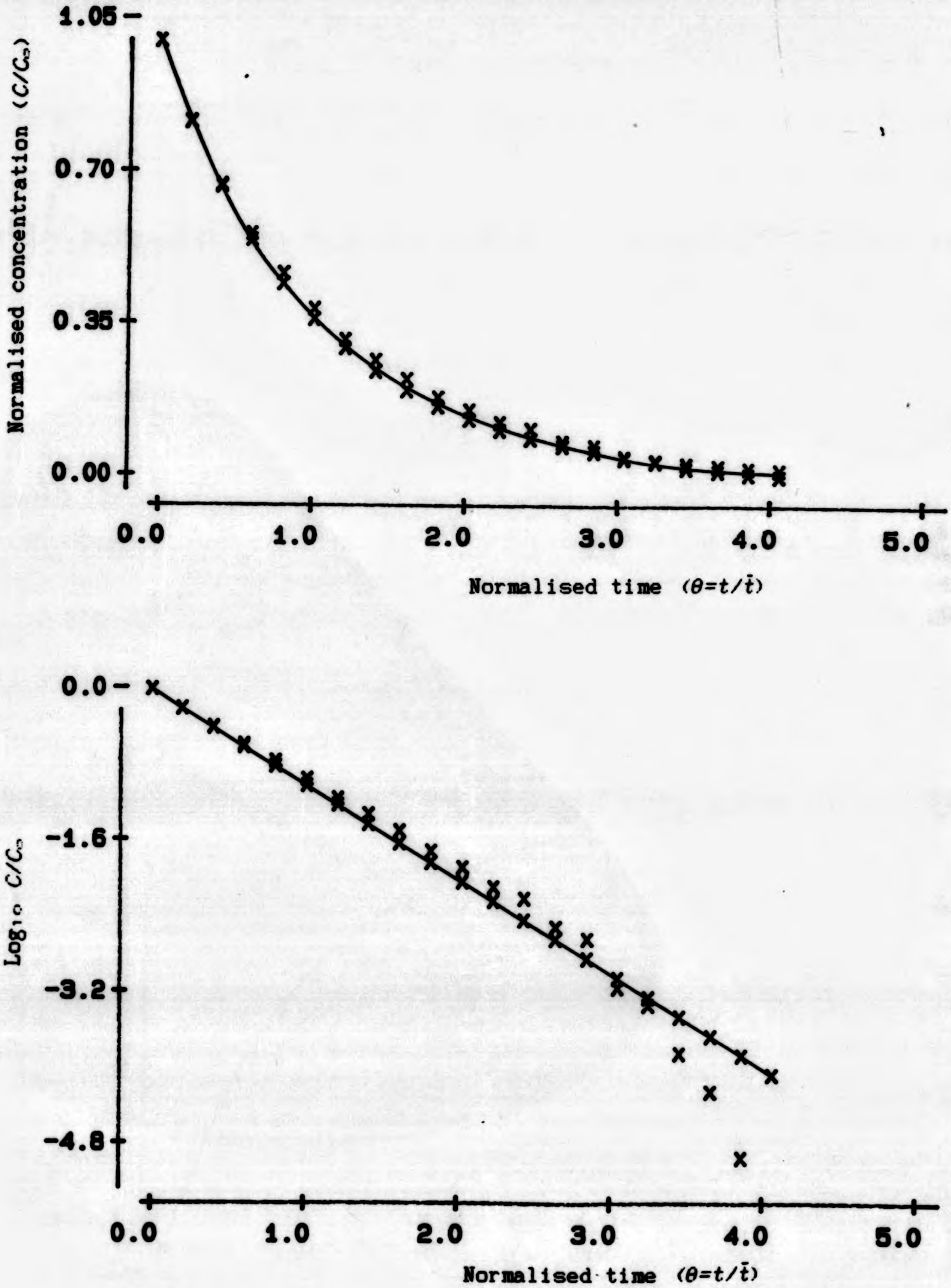


Figure 4. Cylindro-conical perpendicular downflow tank. Joined data points represent the theoretical curve, $C/C_0 = e^{-\theta}$. Unjoined data points represent observed values.

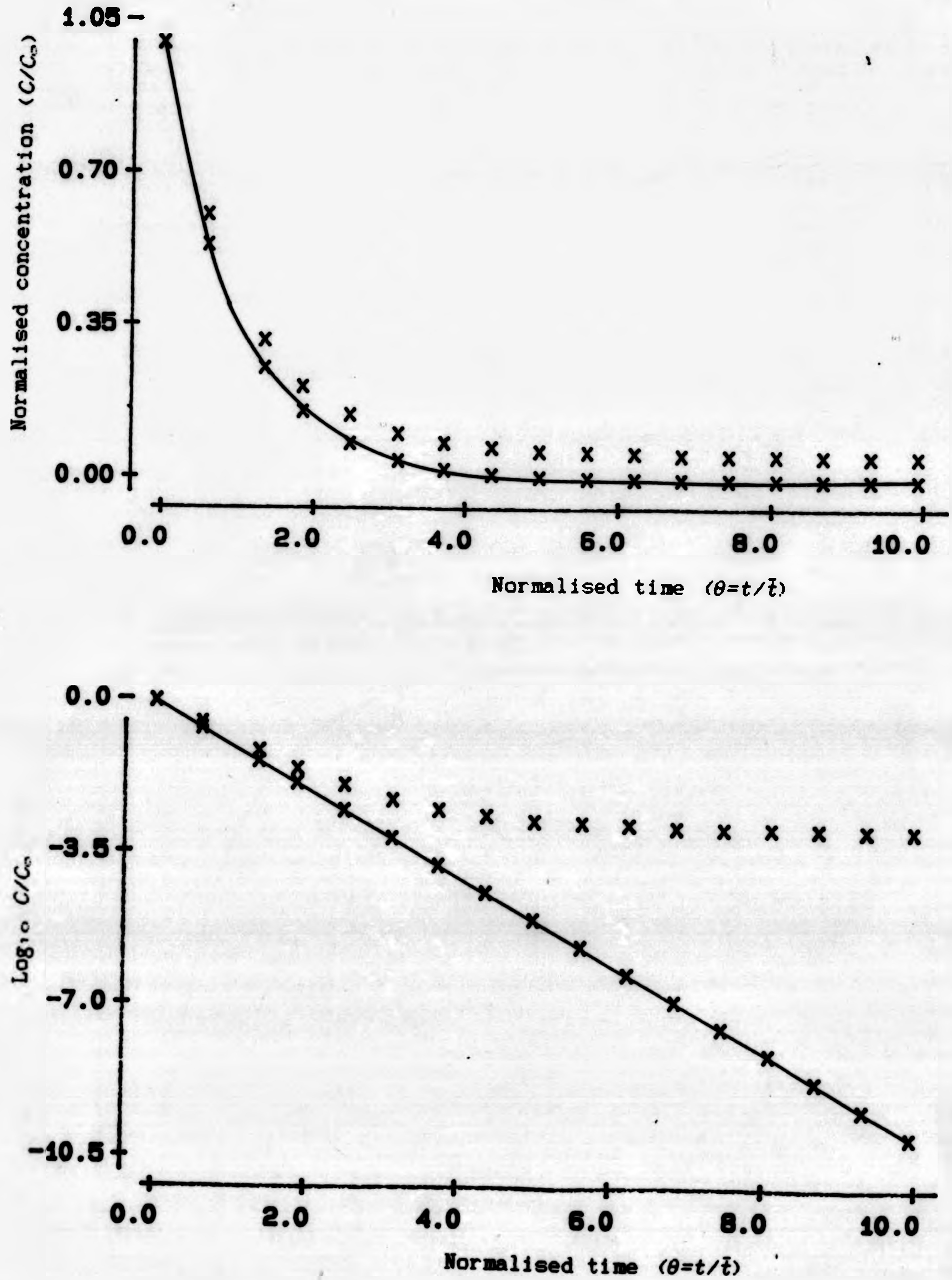


Figure 5. Cylindro-conical helical downflow tank. Joined data points represent the theoretical curve, $C/C_\infty = e^{-\theta}$. Unjoined data points represent observed values.

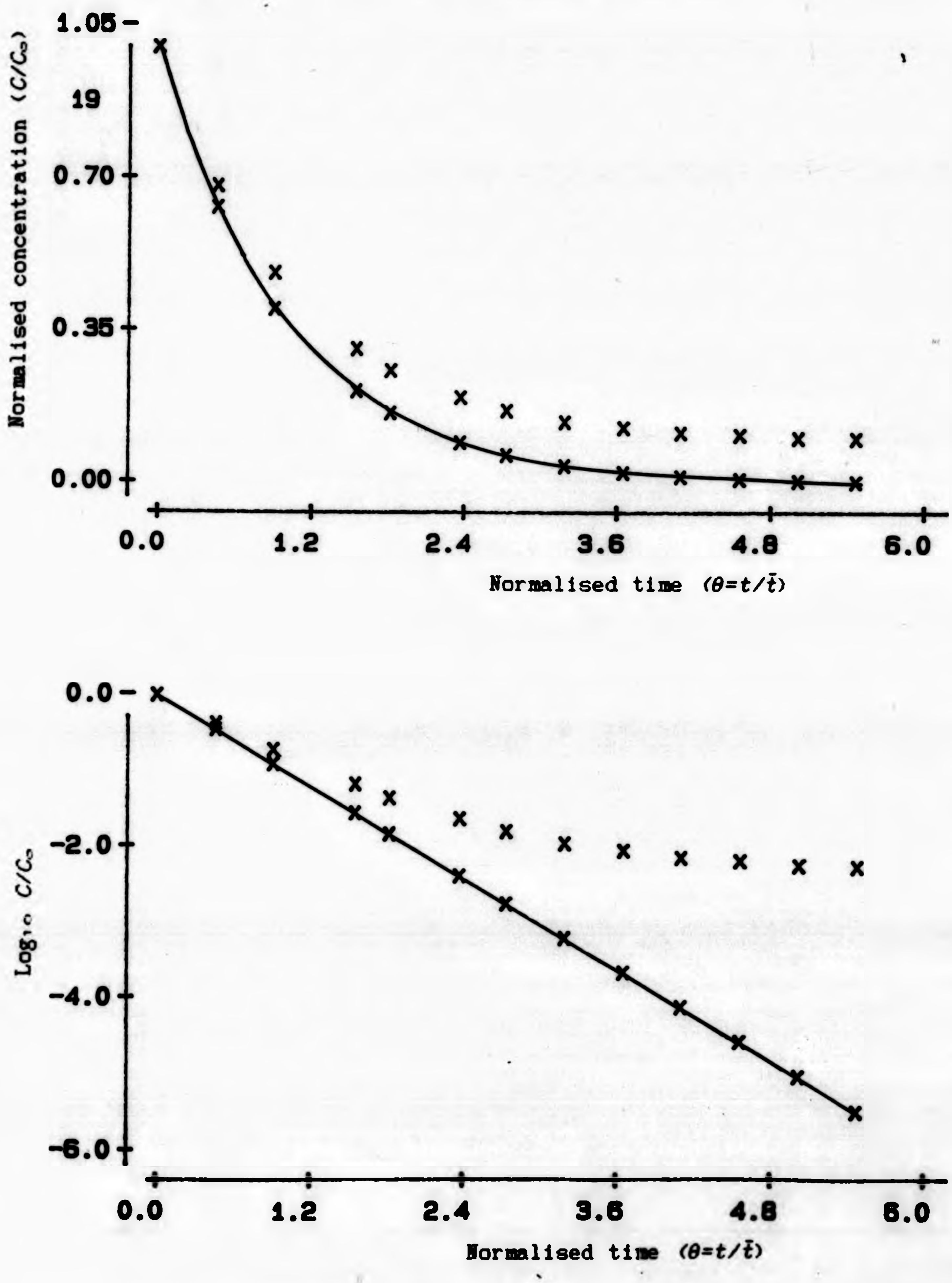


Figure 6. Cylindro-conical perpendicular upwelling tank. Joined data points represent the theoretical curve, $C/C_\infty = e^{-\theta}$. Unjoined data points represent observed values.

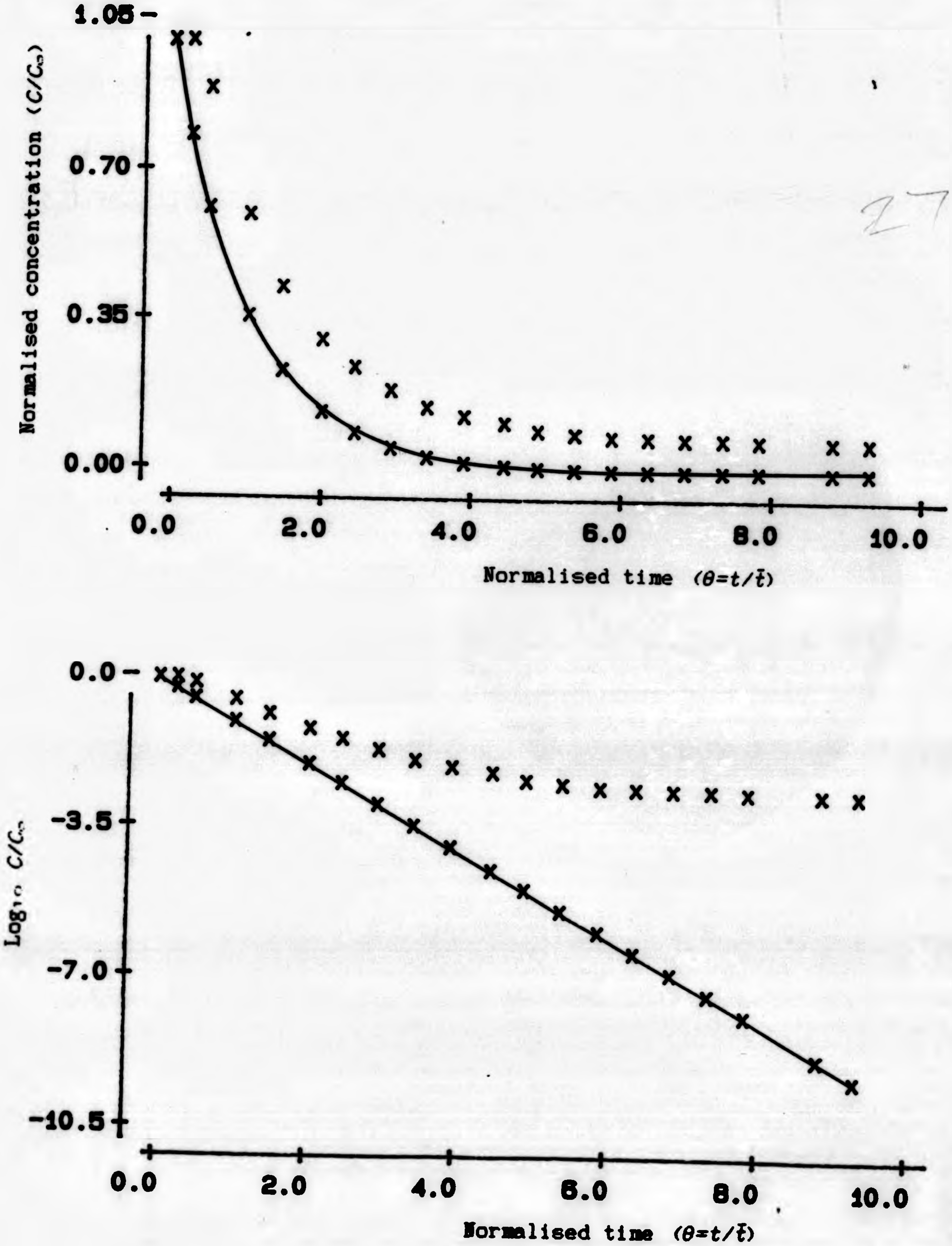


Figure 7. Cylindro-conical perpendicular upwelling tank (model). Joined data points represent the theoretical curve, $C/C_0 = e^{-\theta}$. Unjoined data points represent observed values.

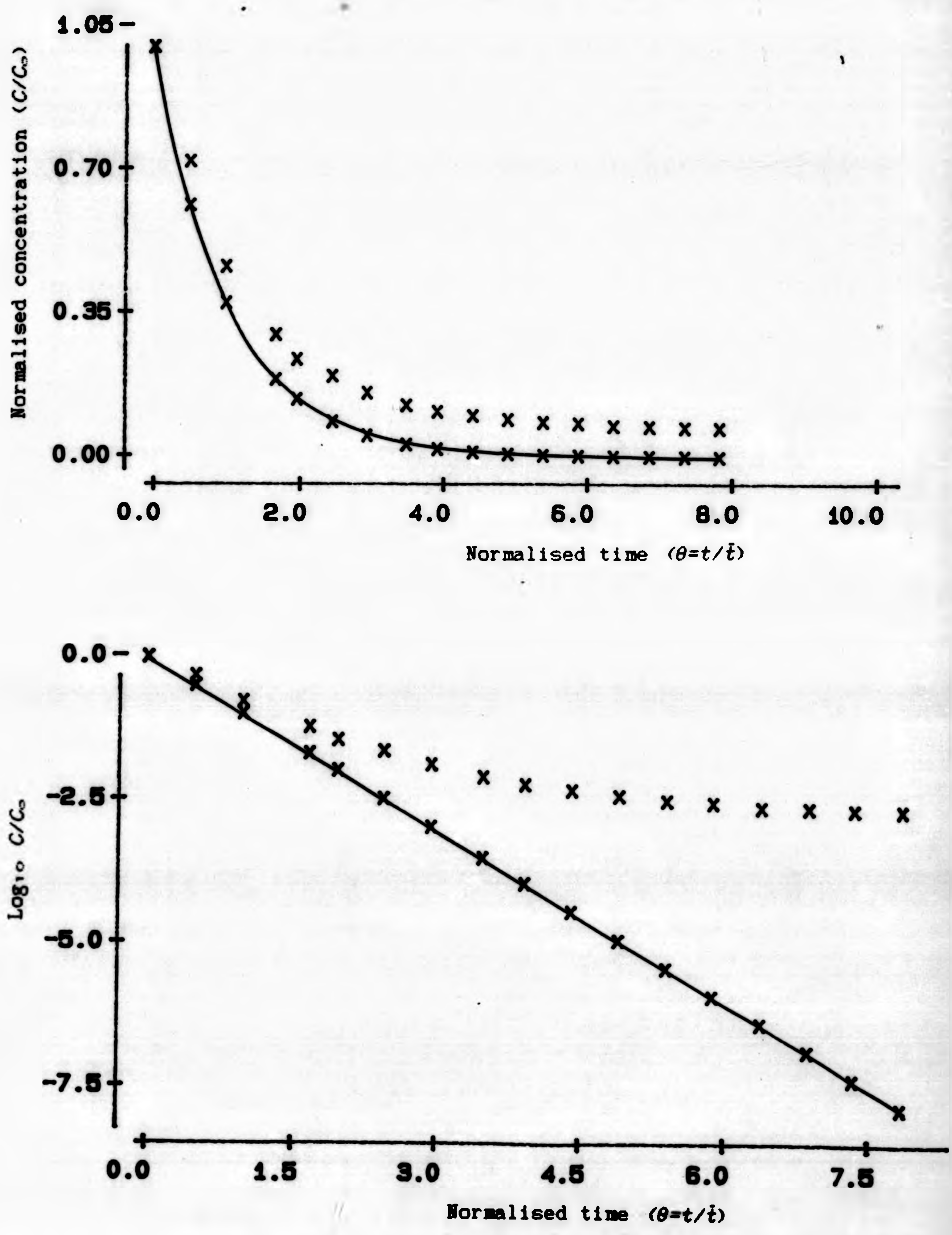


Figure 8. Cylindro-conical helical upwelling tank (model). Joined data points represent the theoretical curve, $C/C_\infty = e^{-\theta}$. Unjoined data points represent observed values.

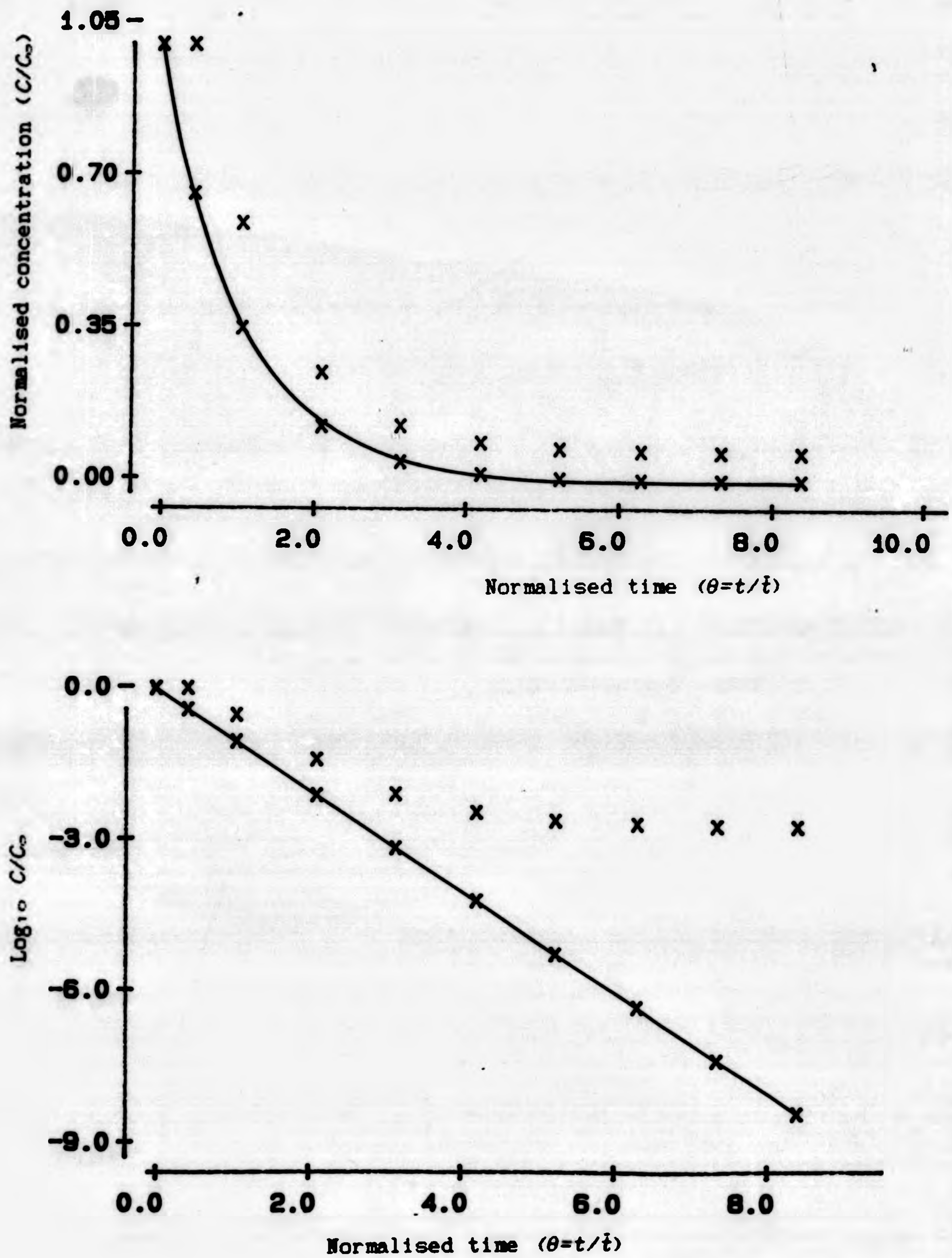


Figure 9. Cylindrical flat-bottom tank (model). Joined data points represent the theoretical curve, $C/C_o = e^{-\theta}$. Unjoined data points represent observed values.

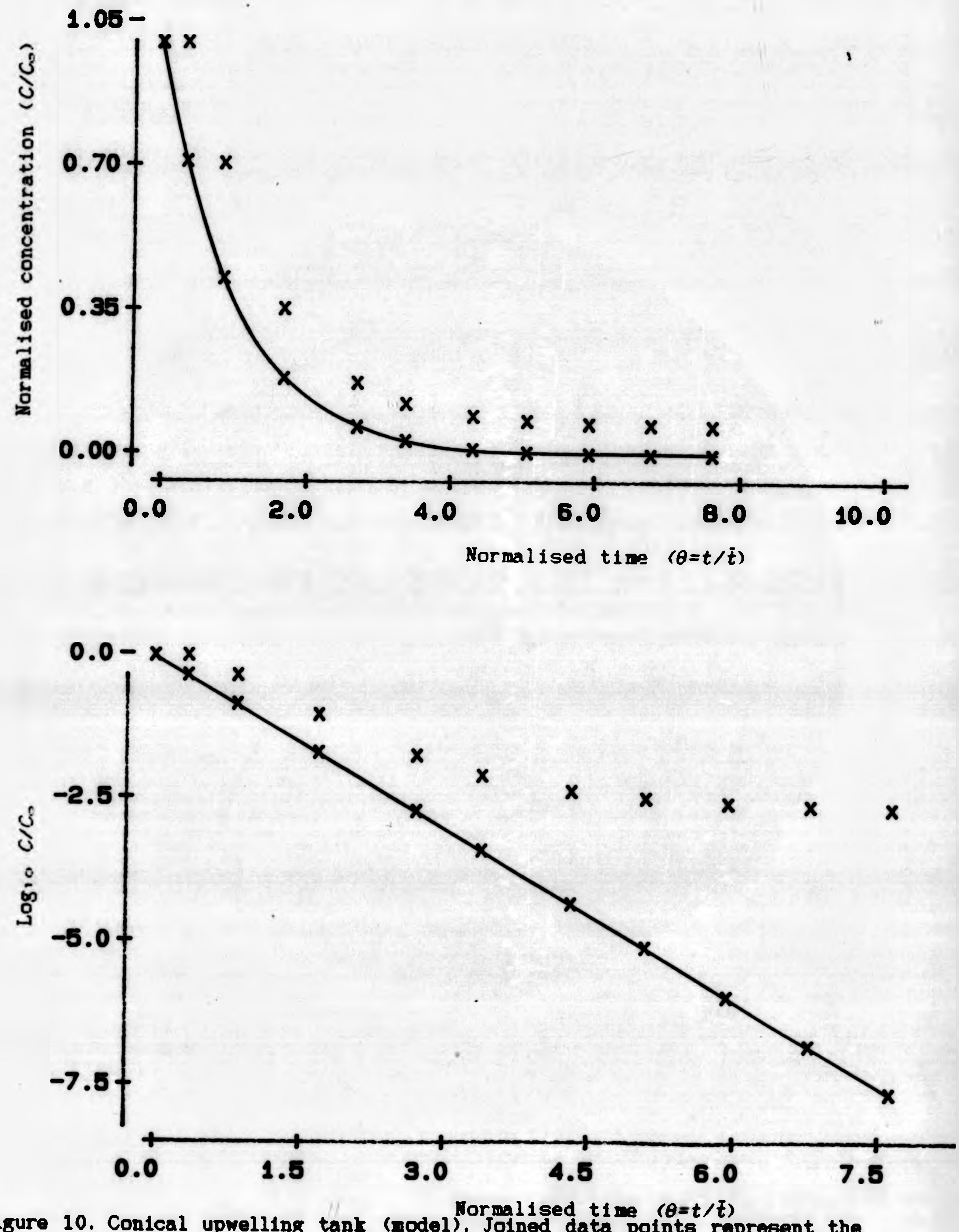


Figure 10. Conical upwelling tank (model). Joined data points represent the theoretical curve, $C/C_0 = e^{-\theta}$. Unjoined data points represent observed values.

PHOTOS WILL BE ADDED LATER

Figure 11. Time series photographic record of dye entering a model cylindrical flat-bottom tank. 'A' shows the situation a moment after the dye first enters the tank. 'B','C' and 'D' follow at 2 second intervals (flow rate about 0.21 min^{-1}).

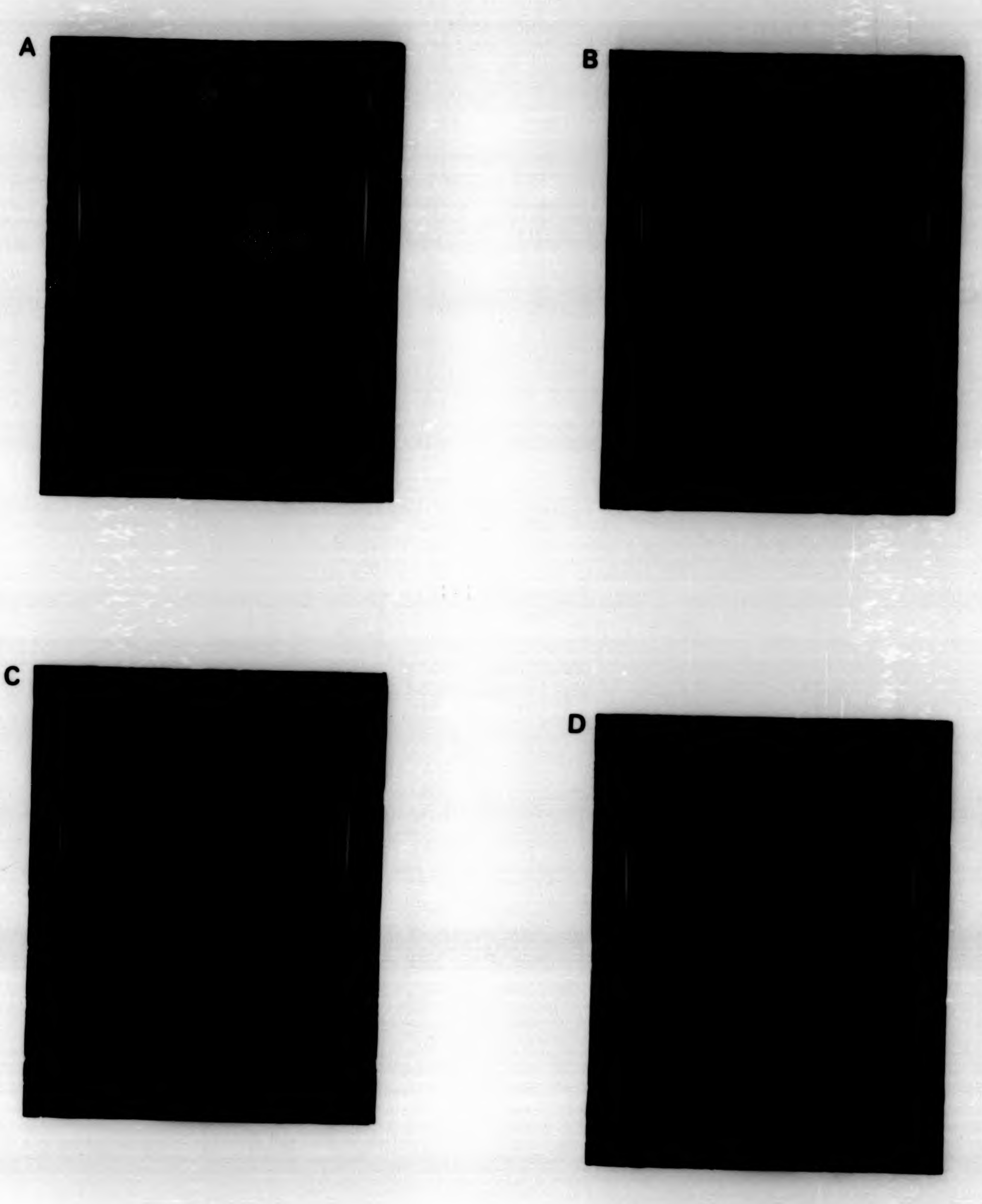


Figure 12. Time series photographic record of dye flowing through a cylindro-conical upwelling flow tank (model), at a slow flow rate (about 0.11 min^{-1}) showing laminar flow.

Figure 13. Time series photographic record of dye entering a model cylindro-conical upwelling flow tank. 'A' shows the situation 5 seconds after the dye first entered the tank. 'B' is after 10 seconds, 'C' after 20 seconds, 'D' after 35 seconds, 'E' after 45 seconds, and 'F' after 55 seconds. Flow rate was about 0.21 min^{-1}.

A

B

C

D

E

F

4. Discussion

4.1 Residence time distribution analysis - data interpretation

In the consideration of the flow characteristics of throughflow larval rearing tanks, there are two conceptually different flow regimes to which the tank may conform. These are;

i) Perfect mixing. This is the theoretically ideal situation and in its purest form cannot be attained in reality, although it is a useful conceptual tool. The model assumes that any elements of water entering the tank are instantaneously and evenly dispersed throughout the tank. In real situations, especially at high flow rates, this model may be approximated, so is, in fact, of some practical use.

ii) Bulk flow. In contrast to the perfect mixing model, only localized mixing occurs, so it is possible for there to be concentration gradients within a tank conforming to the bulk flow regime.

Since, in a bulk flow regime, the contents of the tank are not equally mixed, there is the potential for gradients to become established in the water mass. These may be of concentration, temperature, water velocity *etc.*, and are superimposed upon the bulk flow. Thus various flow patterns may characterise bulk flow regimes. The more important of these are introduced below.

i) Laminar and turbulent flow. At very low velocities a mass of water flows in a laminar pattern; that is, elements of water, aligned in the direction of flow, slide smoothly past one another. As the flow rate is increased, transverse swirls and eddies develop, and the laminar pattern of flow breaks down as it becomes more and more unstable. This instability causes mixing between the elements, and is known as turbulence.

ii) Short-circuiting. When a fraction of the inlet feed travels directly to the outlet, without mixing appreciably with the remainder of the tank, it is said to short-circuit, or bypass, the system. This element of the general flow pattern is often associated with the presence of dead spaces within the tank. These are zones which receive less water than the remainder of the tank, and constitute relatively discrete regions which have a longer flushing time than the remainder of the system (although still being a part of the whole).

Residence time distribution analysis can be used to elucidate, in a quantifiable form, the flow regime of a larval rearing tank, being a relatively simple method which yields a considerable amount of information.

Levenspiel (1962) describes four types of input stimuli used in residence time distribution analysis - a pulse input, a step input, a cyclic input and a randomly variable input. Each gives rise to a characteristic type of curve (see figure 14). The first two input stimuli are the most commonly used, being more simple to analyse, and the only ones used in aquaculture to date. A step input stimulus was used by both Hughes *et al* (1974) and Watten

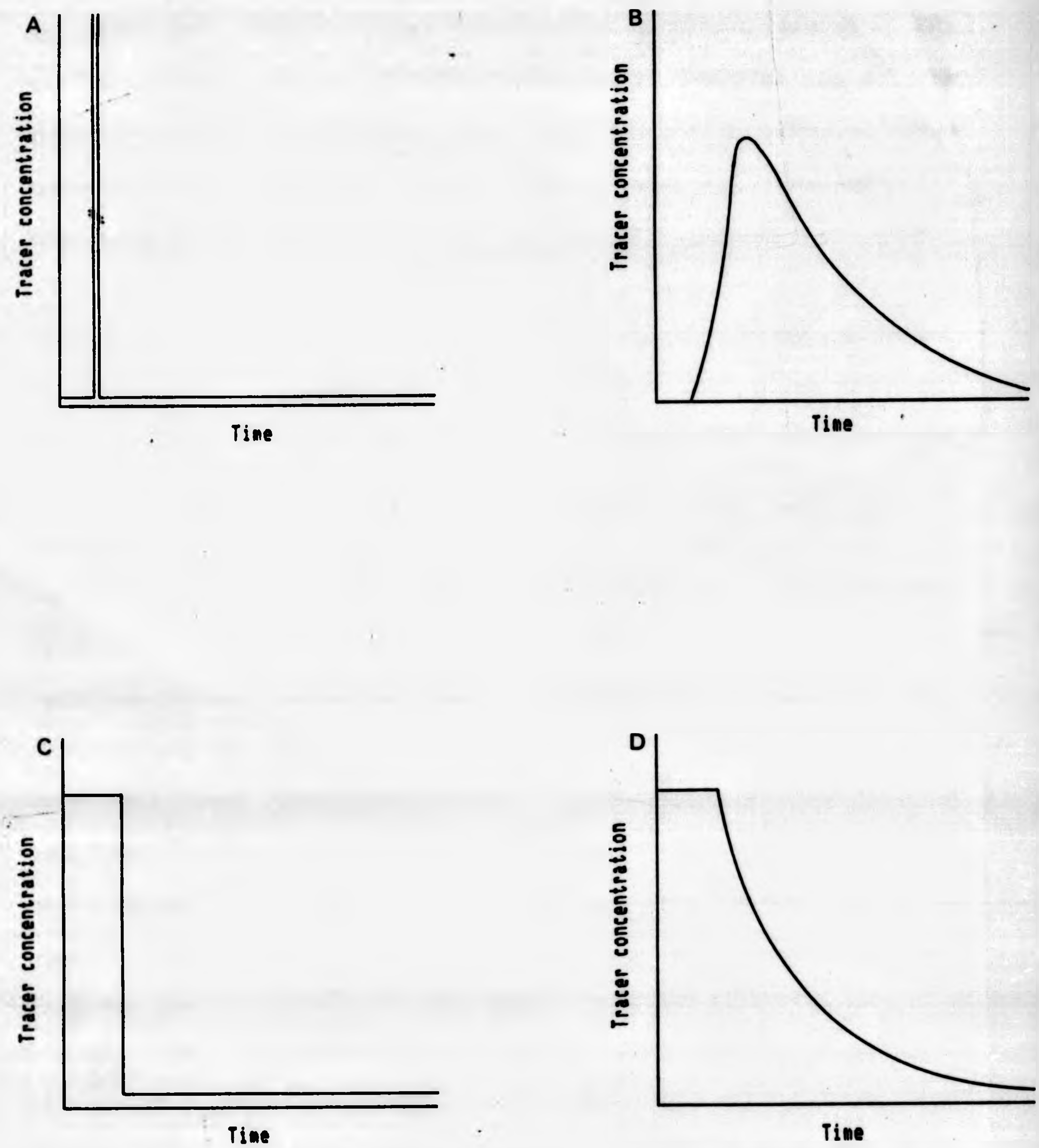


Figure 14. Diagramatic representation of the response (B) to a pulse input of tracer (A) into a system (measured at the outlet), and response (D) to a step down in tracer concentration (C). After Levenspiel (1979).

and Beck (1987), whilst Burrows and Chenoweth (1955), Weatherley (1982) and Burley and Klapsis (1985) used a pulse input stimulus. Although the same information may be derived from data obtained by either of these techniques, it is felt that results from the step input are easier to understand visually, and therefore constitute a better form of presentation.

Data on the exit age distribution of a tracer, although simple to collect, can yield a disproportionate amount of information. In the case of a step down in tracer being the stimulus, as in the present study, the area under the tracer concentration versus time curve can be used to calculate the mean residence time of the tracer in the vessel. A comparison of this with the theoretical mean residence time, $\bar{t}$ (where $\bar{t}=V/Q$), in the form of a ratio ($\bar{t}_c/\bar{t}$), can indicate the presence of dead space and short-circuiting, if less than one, and experimental error or recirculation, if greater than one.

Dead space reduces the effective volume of the tank, as this water is relatively stagnant. Thus, assuming the remainder of the tank to be well mixed and conforming to the theoretical model of this, the deviation of the observed mean residence time from the theoretical can be used to calculate the proportion of dead space in the tank.

The presence of dead space implies short-circuiting, the extent of which can be found from comparison of the plots of tracer concentration versus time. If a point on the time axis is selected, say half-way, then a comparison can be made of the area under the relative curves up to this point. If short-circuiting is present, the area under the observed curve will be less than that for the theoretical (having accounted for the effect of dead volume), a higher proportion of the exit water being flushing medium which has not fully mixed with the contents of the tank.

Recirculation occurs in the following situation. Each element of water entering the tank follows a certain path to the outlet, the mean length of all the paths in a tank being characteristic of that tank. Each element thus takes a certain length of time to reach the outlet, where its presence is recorded, from first entering the tank. If, however, its path is diverted from that characteristic path, by recirculation of elements within the mass of water in the tank, then its path length, and so its residence time in the vessel will be increased. The result of this is a time lag in response of the system to the input stimulus. The mean residence time of elements within the vessel will therefore be increased, by an amount proportional to the time lag. If the system otherwise performs as a well mixed vessel then the observed mean residence time will exceed the theoretical.

There is some dispute in the literature over this point. Burrows and Chenoweth (1955) and Burley and Klapsis (1985), state that a $\bar{t}_c/\bar{t}$ ratio of greater than one is indicative of recirculation, but explain neither how this interpretation is derived, nor do they elaborate further on the concept of recirculation. Watten and Beck (1987), on the other hand, claim that, "A $\bar{t}_c$ greater than $\bar{t}$ is not in accord with the Law of Conservation of Matter and as such is used as an indicator of error in analytical procedure." By this they refer to the fact that the integral of the concentration/time curve (in normalized units) represents a measure of the total input of tracer. An observed mean residence time of greater than the theoretical implies that more tracer has left the vessel than was put in -

an impossibility. However, as explained above, a time lag between the inputing of tracer into the system, and its being recorded in the outlet can appear to extend the holding time of the vessel, and thus the mean residence time. If, for analytical purposes, the start of the experiment was taken to be the first appearance of tracer in the outlet, so eliminating the time lag, then a $\bar{t}_c/\bar{t}$ of greater than one could indeed be used as an indicator of error in the experimental proceedure.

4.2 Interpretation of the results of the present study

In the present study the flow behaviour of the tanks tested was found to be surprisingly uniform in response to tracer stimulus. Figures 4-10 show representative normalized time versus normalized concentration curves, both observed and theoretical, for each of the tank types studied. It is evident that the observed mean residence time, $\bar{t}_c$, is greater than the theoretical mean residence time, $\bar{t}$, in all cases except the cylindro-conical downflow unit. In the latter case the observed and theoretical curves are very similar.

Comparison of the mean values of $\bar{t}_c/\bar{t}$ *(using ANOVA)* revealed no statistical difference, however, the calculated mean residence time being very close to unity (See Table 1). Burley and Klapsis (1985), studying the flow characteristics of salmonid on-growing tanks of a variety of tank dimensions and water flow rates, observed $\bar{t}_c/\bar{t}$ ratios ranging from 0.75 - 1.13. In the present study the $\bar{t}_c/\bar{t}$ value in all but three of the tank types tested was within 5% of the theoretical figure, and for only one tank type, the cylindro-conical perpendicular upwelling model, did the $\bar{t}_c/\bar{t}$ value differ from unity by more than 10%. Thus it is within the realms of possibility that the difference between the observed and theoretical values, being relatively small, were due to experimental error, and that, in fact all tanks closely approximated the flow characteristics of an ideal mixing vessel. Possible sources of error will be discussed below.

The high mean residence time of the upwelling perpendicular flow unit, is thought to be attributable to limitations in the experimental design. The feed to the model was via an extension of pipe. Thus, the pipe length between the valves which controlled the switch from salt to fresh water, and the pipe outlet into the tank was increased. This brought about two factors which may be responsible for the long residence time. First, mixing may have occurred in the length of pipe immediately after changeover which may have dampened the input signal. Second, from the start of the experiment water took some time the reach the tank along the pipework. Thus the effect of the step down in tracer concentration was delayed. Recording the conductivity of the effluent as a function of time, then integrating this to calculate the mean residence time, resulted in an over estimate of $\bar{t}_c$ because of this extra time element at the start of the experiment (*i.e.*, the measured area under the curve was larger than for the true situation, by an amount equal to the time taken for the water to travel the length of the pipework, multiplied by the concentration of the effluent at that time). Burrows and Chenoweth (1955) note similar problems in their use of models. This was accounted for in later trials with the models during the present study, by recording the time of first appearance of the tracer in the effluent and using this as time zero (although this would represent a slight under estimate of $\bar{t}_c$, as the path length of the tank and possible recirculation were therefore not accounted for).

The $\bar{t}_c/\bar{t}$ ratio for the helical upwelling model is lower, and reflects these improvements. However, it is likely that a characteristic of the system has been obscured - that of recirculation. In contrast to the theoretical ideal, in which water entering a mixing vessel is instantly dispersed throughout the vessel and the influence of a tracer on the composition of the tank is therefore recorded in the exit stream immediately, in a real situation elements of the inlet stream take a certain length of time to reach the outlet, and there is therefore a delay between tracer entering the tank and its presence being recorded in the outlet. Burrows and Chenoweth (1955) used the relative length of this delay as an indication of short-circuiting within the vessel. If recirculation is occuring in the tank, then elements of water may be diverted from their progress toward the outlet, such that they travel the path through the tank more than once. Hence the first elements of tracer-seeded water will take longer to reach the outlet than if recirculation was not present. Thus the concentration/time curve will have an extra time element at the beginning of the trial, during which the influence of the tracer is not recorded in the exit stream. Therefore, the integral of the concentration/time curve will exceed the theoretical value (assuming the whole volume of the tank to be well mixed), *i.e.*, the $\bar{t}_c/\bar{t}$ ratio will be greater than unity.

In the case of the helical upwelling model (and the perpendicular upwelling model) dye studies revealed the presence of recirculation in the system. The inlet water would rise about half way to the surface, then reverse its direction by flowing towards the centre of the tank then flowing down beside the central outlet (see figure 13). It was quite some time before any dye reached the outlet. The fact that this was not detected in the RTD analysis is attributable to the modified analytical techique described above, in which the first record of tracer in the outlet was taken as the start of the trial. Thus the time lag between first entry and exit of the tracer was ignored.

The cylindrical flat-bottomed tank was expected to give results indicative of short-circuiting and dead space. This was not the case, however, the $\bar{t}_c/\bar{t}$ ratio for this design being little different from that of any of the other designs. Examination of the flow pattern using a pulse of dye in the inlet revealed the reason. The inlet to the tank was from a verticle pipe such that the inlet stream entered the tank verticly. It would travel to the base of the tank, from which it was deflected across the base to the other side of the tank, and thence to the surface and back to the inlet. Thus in a few seconds at the flow rates used (equivalent to a flushing rate of 12 per hour) the tank was very well mixed (see figure 11). However, this mixing was the product of high velocities and turbulence. Burley and Klapsis (1985) used high velocity inlet jets to enhance mixing of an on-growing tank. In the circular flat-bottomed tank tested in this study the velocity of the inlet stream was about 7cm s^{-1}, in a tank only 6cm high and 15cm in diameter. However, that of the full-scale cylindro-conical tank, at half the flushing rate, is about 9cm s^{-1}, so it is unlikely that the result obtained is entirely attributable to errors resulting from the use of a model.

Considering the C/C_o v. $t/\bar{t}$ plots for representative trials of each tank design (Figures 4-10) these reveal that there is only a slight difference between the observed and theoretical curves. By plotting the same data on semi-log paper, with C/C_o on the log axis, these differences are amplified and are therefore much clearer. In the case of the cylindro-conical perpendicular downflow unit, this is particularly useful as it reveals a distinct downturn in the tail of the graph, below that of the theoretical curve, which could not readily be seen in the conventional plot. Cholette and Cloutier (1959) describe six characteristic age distributions of tracer in the exit stream of a mixing vessel, each of which can be described by relatively simple models.

Model 1 depicts perfect mixing, in which the contents of the inlet stream are instantly and evenly dispersed throughout the vessel upon entry. Thus the composition of the exit stream is always equal to that of the tank contents.

Model 2 depicts partial mixing and short-circuiting. That is, a portion of the inlet stream travels directly to the outlet, without mixing completely with the remainder of the contents of the tank, which are perfectly mixed.

Model 3 introduces a further concept, that of piston flow (synonymous with plug and slug flow). Under a piston flow regime, a tracer introduced into the feed, such as a dye, would remain within the volume of feed into which it was introduced as it advanced through the vessel as a discrete water mass - a plug. This model describes a situation in which a fraction of the contents of the mixing vessel are perfectly mixed, whilst the remainder of the vessel is operating under a plug flow regime.

Models 4, 5 and 6 refer to the more complex situation in which the flow pattern of the vessel is characterised by partial mixing, piston flow and short-circuiting.

In Model 4 the vessel consists of two regions, one perfectly mixed and the other relatively stagnant. Part of the feed directly displaces a fraction of the stagnant zone, by plug flow, into the perfectly mixed zone, whilst some of the feed short-circuits both zones and travels directly to the outlet.

In Model 5 the piston flow element of the flow pattern does not involve the zone of perfect mixing. Part of the feed directly displaces a fraction of the stagnant zone, by plug flow, around the zone of perfect mixing and so directly to the outlet.

Model 6 describes the situation in which the fraction of the stagnant zone which is displaced, by plug flow, into the zone of perfect mixing, is displaced by a fraction from the zone of perfect mixing, rather than directly from the feed.

Comparison of the curve for a cylindro-conical helical downflow tank, for example (figure 6), with these models, suggests that the flow pattern in this case is conforming to a Model 4 or Model 6 type, more probably the latter. Dye studies undertaken on the cylindro-conical perpendicular upwelling units revealed that water entered the tank with relatively little turbulence, so mixing very little. As the water flowed upwards this, sometimes laminar, flow pattern broke down into a mildly turbulent one and fractions of this zone recirculated to a certain extent. Water leaving the tank, above this turbulent zone, was relatively well mixed (see figure 13).

Returning to the cylindro-conical perpendicular downflow system mentioned above, this rearing tank would appear to conform to the flow pattern approximated by Model 3, *i.e.*, partial mixing and plug flow, this taking place either before or after mixing.

The reason for this may be as follows. The inlet stream has a certain velocity as it enters the tank. This creates a turbulent zone in the vicinity of the inlet, which helps mixing. As the water moves down towards the outlet the energy of the inlet stream is dispersed such that the flow pattern becomes much more uniform (turbulence constitutes a random flow pattern, in both time and space) so approaching plug flow. As the flow rate increases so too does the inlet velocity (assuming the pipe diameter remains constant), and so the turbulent mixing zone extends further down into the tank before the flow regime stabilises. This being the case, $\bar{t}_c$ would approach $\bar{t}$ as the flow rate increased.

4.3 The application of mixing studies to larval rearing tank design

The whole relevance of mixing and recirculation in the context of larval rearing tank design needs to be thoroughly re-examined in the light of the present study. There are two desirable properties for the flow characteristics of a larval rearing tank. First the velocity profile of the tank should be even, so as to eliminate shear forces, and second, the complete volume of the tank should be well flushed (not necessarily well mixed), in order to prevent accumulation of dissolved metabolites in any one area, and to ensure even dispersion of feed and larvae throughout the complete volume of the tank (Hughes *et al*, 1974; Bourgos, 1986).

In considering the design of the ideal larval rearing tank, from the point of view of its flow characteristics which is the most desirable situation:-

i) a completely mixed vessel, which seems to be the criterion for on-growing tanks (see Burley and Klapsis, 1985, and Klapsis and Burley, 1985)

ii) bulk flow in which localized, turbulence-induced mixing takes place, which is the situation found in raceways, and is usually referred to as plug flow,

iii) or laminar bulk flow, in which there is negligible mixing?

An upwelling or down flow system, as opposed to a crossflow system, can be considered as a section of pipe, open at both ends and with a mass flow of water through it (Equivalent terms used in the literature include bulk, plug, slug or piston flow. It is suggested that only the term bulk flow be used, as the others mentioned better describe case ii), above). Superimposed on this mass of water are various states of flow. In laminar flow, which is only present at low flow rates, water flows through the system as a series of separate elements, or lamina, which are annular in cross section. The frictional effect of the pipe walls slows the flow of that nearest the wall, the wall effects becoming progressively less towards the centre of the pipe, where the water velocity is greatest. The difference in velocity between the lamina generates shear forces between them.

As the flow rate is increased, transverse swirls and eddies develop, and the laminar pattern of flow breaks down as the system becomes more and more unstable. This instability causes mixing between the elements, and is known as turbulence. It represents a higher state of energy than the laminar flow regime, and thus the forces generated within it, principally shear forces, are of greater magnitude.

In studies of the flow characteristics of on-growing tanks, the concept of complete mixing has been used (Burrows and Chenoweth, 1955; Burley and Klapsis, 1985; Watten and Beck, 1987) as it precludes the presence of dead space and gradients or patchyness of dissolved substances within the tank volume. However, this is just a specific example of a well flushed tank, which also has no dead space, although, depending on the flow state superimposed upon the bulk flow through the system, there may be concentration gradients within the tank volume. Burley and Klapsis (*op. cit.*) make the distinction between dispersive flow (perfect mixing) and plug flow (laminar or turbulent flow characterised by a poor degree of mixing). The high degree of mixing in a well mixed tank, represents a high energy, turbulent system, and as such does not approach the ideal of a larval rearing tank. In a conventional larval rearing tank, such as the cylindro-conical type, the flow pathway between the inlet and outlet is sufficiently short, and the stocking density of larvae sufficiently low, that the establishment of concentration gradients under a bulk flow regime, be it laminar or localized turbulence, is not likely to be a limiting factor to the use of these flow regimes. Thus the concept of complete mixing is not appropriate to the design of larval rearing tanks.

However, RTD analysis can still be used in the identification of dead space, and refinement of the flushing characteristics of the design, as shown by Burley and Klapsis (1985). One parameter derived from this type of analysis, is the vessel dispersion number, $D/\mu L$. The dispersion number is a measure of the ratio of dispersive or random flows to bulk flow (Burley and Klapsis, 1985). It is a product of bulk flow, a characteristic dimension of the system, and a constant, the coefficient of dispersion, also characteristic of the system. Being defined as random flows in time and space the degree of turbulence can be estimated by the dispersion number. Whereas in an on-growing system the ideal is a high dispersion number, that for a larval rearing tank would be a low dispersion number, *i.e.*, a lower energy system. Laminar flow would best fit this ideal in a throughflow system.

Experimentally, there may be problems in aquiring truly representative data for such a system, because mixing will occur toward the outlet and in the vicinity of the instrument used to measure, or to sample, the composition of the exit stream.

4.4 Summary

In summary it would appear that RTD analysis is not sensitive enough for refinement of larval tank design at this level of devlopment. That is, most of the designs tested were of the cylindro-conical design, a tried and tested larval rearing tank which would be expected to have good flow characteristics, and therefore, there may have been little to distinguish between them. However, some fundamentally different flow patterns were examined, *i.e.*, downflow, both perpendicular and helical, and upwelling flow, which are very different in respect of the larval environment. RTD analysis does not appear to represent a technique which can be used to evaluate their flow characteristics in a form which can be related to the rearing environment of marine finfish larvae.

In addition, RTD analysis is primarily a technique for investigating the mixing characteristics of vessels. As explained, the concept of mixing is not appropiate to larval rearing tank design, and the use of RTD analysis in this field is therefore limited.

5. Conclusions

i) The successful rearing of marine larvae is likely to be increasingly important in the worldwide development of aquaculture, as demand of wild seed exceeds supply, and as previously unexploited species are developed for aquaculture.

ii) Marine larval rearing techniques, although widely practiced, lack refinement, being still in the developmental stages for some commercially produced species (*e.g.* sea bass)..

iii) The present study has identified a serious lack of awareness, among both the scientific and farming community, of the influence of the flow characteristics of rearing vessels in larval survival, and the importance of this factor in the development of effective rearing tank designs.

iv) A suitable technique for the assessment of the flow behaviour of tank designs, in the larval rearing context, has yet to be found. Residence time distribution analysis, used in the present study, has proven unsuitable in this respect.

v) The cylindro-conical larval rearing tank, tested with various flow patterns, performs well as a mixing vessel.

vi) The hydraulic concepts applied to on-growing rearing tank design, that of mixing in particular, are not applicable to the study of larval rearing tank design, because of the different environmental requirements of marine larvae from adult fish.

vii) Future research needs centre on determining the limits of tolerance of larvae to physical environmental parameters likely to be of importance in a rearing tank. Flow patterns are the least understood of these, yet probably the most important. It is vital to follow up work, such as is presented in this study, with larval rearing trials.

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