Freshwater Biology (1998) **39,** 49–59

A portable flow chamber for *in situ* determination of benthic metabolism

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SUMMARY

1. Many stream ecologists are interested in determining the metabolic rates of benthic organisms, particularly those of production and respiration. It is often necessary to make these measurements on fresh material in the field at remote sites. Recirculating chambers are commonly used for this purpose.
2. A broad variety of recirculating chambers are described in the literature, but each design has inherent limitations. The most common are inability to control flow in the chamber and match it with external flow rates, and a lack of the power required to do this for extended periods. Alteration of spectral irradiance, temperature rise and elevated internal chamber pressures are additional limitations that have received little attention.
3. We have designed and constructed a flow chamber that eliminates some of these problems. The chamber utilizes a DC motor-driven propeller as an efficient recirculator (axial impeller), minimizing power requirements and it is constructed of UVB transparent acrylic to allow a full spectral complement of solar irradiance in the interior. Modular components allow the chamber to be taken apart quickly for cleaning and replacement of parts, making it more functional than some previous designs.
4. The axial impeller chamber was compared to a similar sized conventional chamber that had a small diameter return line and a high capacity centrifugal pump. The axial impeller chamber had less of a temperature rise during field incubations, lower power consumption and less internal pressure in the return line when producing equivalent water velocities.
5. The reported axial impeller design had relatively homogeneous velocity across the working section relative to other chambers and was capable of water velocities in excess of 1 m s^{-1}.

Introduction

Recirculating chambers are commonly used for estimation of metabolic activity of benthic organisms. These chambers are helpful because they allow for isolation of the organisms from the surrounding environment and assessment of exchange of materials between the benthos and the water column. Such chambers may be used for toxicology work, assessment of nutrient uptake, behavioural studies and, most often, assessment of photosynthesis and respiration of benthic algae and macrophytes. The ideal chamber would accurately represent natural conditions in the environment.

McIntire & Phinney (1965) introduced the use of respirometer chambers that allowed community metabolism to be measured from changes in dissolved O_2. In the past few decades, recirculating chambers have been the most frequently used tools to estimate lotic productivity (e.g. Sumner & Fisher, 1979; Bott *et al.*, 1985). Chamber techniques may introduce uncertainty related to working with restricted substratum area, inability to include all types of substratum (such as hyporheic sediments), nutrient limitation, alteration of flow regime, change in light field, temperature rise and bubble formation when supersaturation of O_2 or CO_2 occurs (Bott *et al.*, 1997). In most studies, the extent to which these problems affect the reliability of metabolism estimates in chambers is unknown.

Some of the problems with chambers have been addressed as follows: Uehlinger & Brock (1991) devised flow-through chambers with metered inputs of new water to circumvent problems with nutrient limitation. Pennak & Lavelle (1979) minimized disruption of substratum by pushing a chamber into the streambed, thereby isolating an area for metabolism measurements.

Of the problems affecting metabolism measurements in chambers, perhaps the most difficult to deal with is accurate representation of hydrodynamics. Current has a wide variety of influences on algae (Stevenson, 1996), for example turbulent forces may be important to biofilm productivity (Stevenson & Glover, 1993). Metabolic rates also respond to current velocity (Statzner, Gore & Resh, 1988) measured at macro-(Whitford & Schumacher, 1964; Stevenson & Glover, 1993) and microscales (Dodds, 1991a). Microelectrode measurements have revealed that steep gradients of O_2 can occur within benthic communities (e.g. Revsbech, Jørgensen & Brix, 1981; Revsbech & Jørgensen, 1983), and that small-scale hydrodynamic transport can alter these gradients (Carlton & Wetzel, 1987; Dodds, 1989, 1991b). A recirculating chamber that is not able to recreate water velocities typical of streams may not allow accurate estimation of *in situ* metabolic rates.

Light attenuation by chambers may alter estimates of photosynthetic rates and reduce the harmful effects of UV irradiance. Any material with which chambers are constructed alters the light field to some degree, and this may alter measured rates of metabolism. For example, photosynthesis irradiance curves for biofilms can exhibit photoinhibition (Meulmans, 1988; Dodds, 1991a), but often do not (e.g. Turner, Schindler, & Graham, 1983; Hill & Boston, 1991; Hill, 1996). If light attenuation is increased by chambers, photosynthesis will be overestimated under inhibitory conditions, and underestimated when light is not saturating photosynthesis. Additionally, the level of UV may have effects on benthic metabolic rates, and all the closed chambers of which we are aware screen UVA and UVB. Ultraviolet irradiance harms algae and other benthic organisms (e.g. Calkins & Thordardottir, 1980; Bühlmaan, Bossard & Uehlinger, 1987; Bothwell *et al.*, 1993).

Simultaneously solving all of the problems with chambers (flow, temperature rise, light alteration, internal pressure, power consumption, portability) is not possible. Any chamber design results in some compromise to optimize overall usefulness. Furthermore, finding suppliers of the materials necessary to build chambers can be difficult. We describe the construction of a chamber with particular attention to the methods and reasoning behind our construction technique in the hope that some of our mistakes will be avoided by others. The new chamber we describe minimizes problems of altered flow pattern, temperature rise, power consumption and alteration of light field.

Materials and Methods

Approach

Our general design came from one proposed by Vogel & LaBarbera (1978) for a laboratory flow chamber. For a discussion of flow tanks, see Vogel & LaBarbera (1978) and appendix I in Vogel (1981). The feature of their design that differs from previous field-portable models generally used by stream biologists is the use of a large-diameter water-return pipe with a propeller to drive the water. Most of the portable chambers we have seen or used employ a small diameter centrifugal pump on a return line, which results in a significant power loss (Vogel, 1981). The high power consumption not only causes problems related to transporting power to remote sites, but also results in considerable heating of the water. The two negative aspects of using a large, slow-moving propeller in the return line (axial impeller) are that connecting the motor requires a leak-free connection of the drive shaft of the propeller to the outside of the chamber, and increased chamber volume makes determination of slow metabolic rates difficult.

Our model differs from previous propeller-driven models in that the return line is on one side of the chamber rather than below it. This requires a watertight seal on the chamber axle, but allows the chamber to be submerged in shallow streams so temperature can be maintained at close to ambient temperatures and ambient light can be used.

Another general limitation in chamber construction is the problem of obtaining uniform laminar flow in the chamber working section. Vogel & LaBarbera (1978) suggested a working section about 10 times as long as wide; however, this is impractical for field-portable chambers because this length to width ratio, and a reasonably sized working section, increases the weight too much. Also, such long chambers contain a large volume of water relative to the amount of biologically active material, making it difficult to determine low metabolic rates. After an earlier unsatisfactory version using the axial impeller design described below with a 2:1 length to width ratio (inability to obtain uniform flow characteristics), we opted for a 4:1 length to width ratio.

A final important feature of our design lies in the ability to easily disassemble the chambers. Based on our considerable field experience with a variety of chamber designs, we feel that the ability to quickly open chambers for cleaning and the interchangability of parts both are facilitated by modular construction.

Design and construction

Our basic design is presented in Fig. 1. Table 1 lists non-standard parts, suppliers and rationale for using specific parts. When possible, stainless steel, non-toxic plastic, silicon sealant approved for aquariums or aluminum was used. This minimizes corrosion and possible toxic effects on organisms.

The main body of the chamber is constructed from UV-transparent acrylic. This product offers superior spectral quality for *in situ* incubations. A problem with using this type of acrylic is that it is not available in thick enough stock to allow for construction of leak-free chambers without additional reinforcement where the lid and the bottom connect to the chamber. We used a thin layer of double wall around the top and bottom of the chamber to construct leak-free systems.

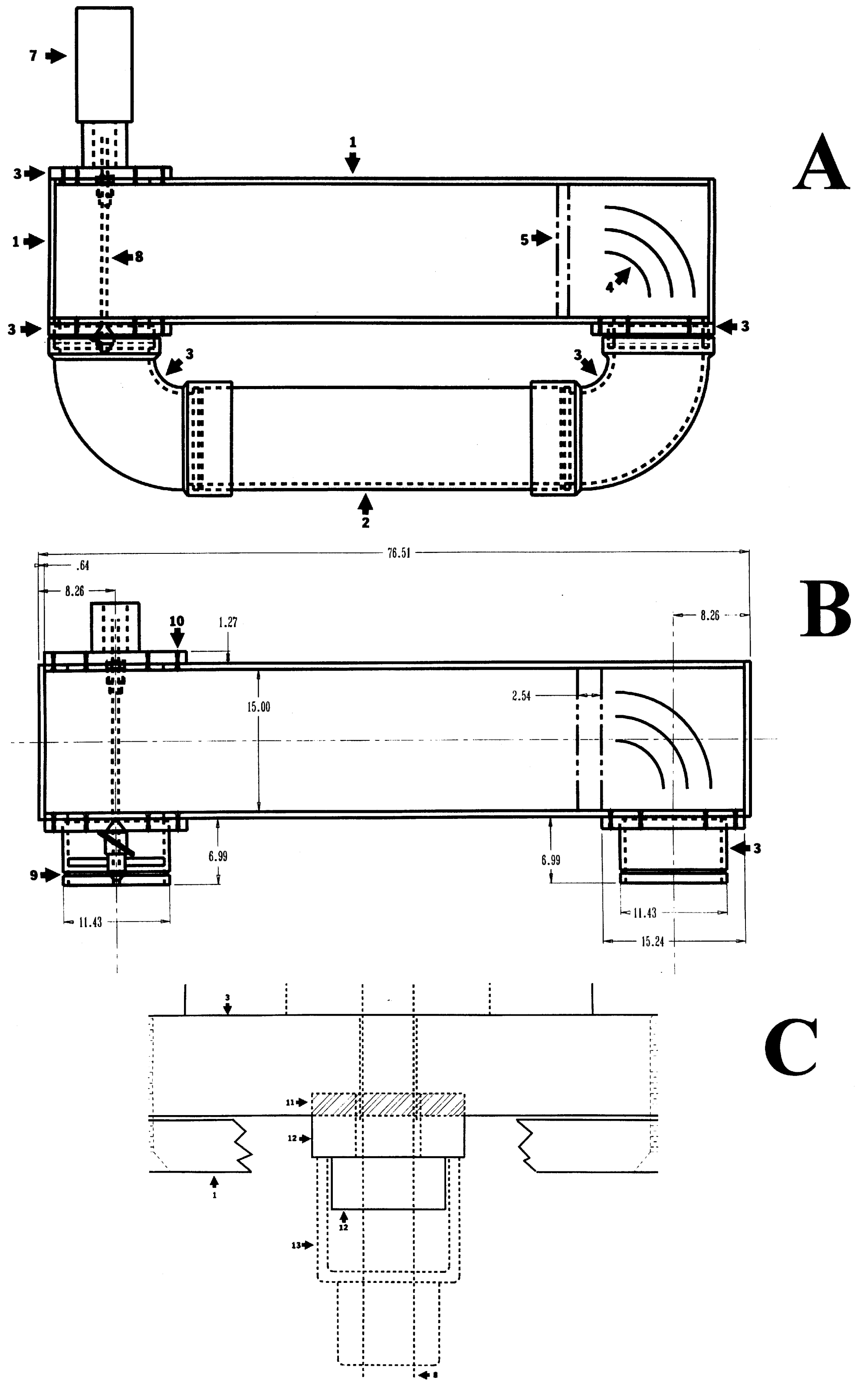
The return lines were attached onto the chamber walls with PVC flanges which were mounted as close to the ends as possible to minimize dead space. The return lines could be detached from the body of the chamber at the angle pipes. To accomplish this, grooves were milled on the outside of the PVC pipes leading into the angle pipes, and o-rings and silicon grease provided the seals. When the return lines are installed in this manner, they do not leak and did not fall off with normal use (i.e. motor running at top speed for 1 month or lifting the chamber when it is full of water). The main return pipe was clear to allow visibility of air bubbles that may be trapped inside and to minimize light attenuation adjacent to the working section.

The shaft hole through the wall was sealed with a Teflon-impregnated plastic washer attached to the shaft against a stainless steel washer fixed in the PVC flange that serves as the motor mounting. The plastic washer was held snugly against the stainless washer by a rubber sleeve attached to the propeller shaft. The propeller shaft was attached to the motor shaft with a flexible-toothed neoprene coupling. This allowed for rapid removal of the motor and tolerance for a moderate degree of misalignment between the motor shaft and the axial impeller shaft. The motor and incoming power lines were coated with rubber to make them waterproof.

Water exited from the return line with the highest velocity on the outside of the radius of the turning water, and with some rotational momentum from the propeller. We installed a series of stainless steel flow directors at the upstream end of the chamber to control these problems. These curved plates were adjustable, and could be used to equalize the flow across the working section of the chamber.

We also included a single collimator at the upstream end of the chamber to minimize turbulence. The material we used is easier to work with than large numbers of soda straws (e.g. Vogel & LaBarbera, 1978). It is also clear and minimizes light absorption.

Water velocity profiles within the chamber were characterized with a thermistor flow probe (LaBarbera & Vogel, 1976). Although the axial impeller chamber is capable of much higher velocities, the probe maximum is approximately 0.70 ms^{-1}. These measurements were taken every centimetre by depth, every 4 cm by width and every 6 cm by length. A running average of 5 s was used for water velocity measurements, and six instantaneous (0.25 s response time) measurements were used for the coefficient of variance (turbulence). The probe tip was about 1 mm diameter, and so encompassed the lower size range possible for turbulence given Reynolds numbers. Similar measurements were made for comparative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purposes on two additional chambers. The first was a square chamber (Dodds *et al.*, 1996) with two narrow diameter input and output lines on either end of the chamber. The second was an oval 'racetrack' chamber with input and output lines off one end that move a portion of the water around the oval (Dodds, 1989).

A final design issue was how to power the axial

Table 1 List of chamber parts requiring special order. The suppliers on this list are not necessarily the only sources for the products, and we do not endorse any specific company

Part	Number-Size	Supplier	Comments
UV transparent acrylic	SUVT 0.22	Polycast Technology Corporation, Stamford CT	See text for spectral acrylic properties; bond with standard bonding solvents
Spring-loaded link lock	SL3–10 Versa Latch, stainless	Austin Hardware, Raytown, MO	Stainless to avoid corrosion; must manufacture own hooks
Lid seal, Foamaya nontoxic silicon foam sheeting	86235K24, 118′	McMaster-Carr, Chicago, IL	Neoprene can be toxic
Aluminum propeller	3502K142, 4′ × 4′	McMaster-Carr, Chicago, IL	Use plastic to connect to drive shaft to avoid electrochemical corrosion
Silicone sealant	clear	local hardware store	Use aquarium-safe type to avoid toxic effects; seals for gaskets, to hold on top and bottom seals, to plug screw holes
Motor, 0.5 amp, 2900 r.p.m. motor, 24 V DC	DCM 9053	C and H Sales, Pasadena, CA	
PVC 'Ells'	4′	AgriDrain	Shallow turn radius on these lowers turbulence; flared end connector facilitates connection
Acrylic return pipe	clear, 4 1/2′ diameter and 1/4′ wall	Cope Plastics, Inc., Godfrey, IL	Clear pipe allows for visibility of trapped air bubbles
Flow straightener, polycarbonate, Twin Wall sheet	clear, 0.220′	Cope Plastics, Inc., Godfrey, IL	
Shaft couplings, neoprene flexible	6428K41 6428K51	McMaster-Law, Chicago, IL	Allows motor shaft to couplewith propeller shaft, previous alignment not necessary
12 V DC power supply	80–217	Hosfelt Electronics Inc., Stubenville, OH	Pulses 12 V; more efficient than power converter

Fig. 1 (A,B) Schematic diagrams of construction details for entire chamber basic chamber with dimensions in cm and (C) close-up of the seal of the propeller shaft through the wall. Flow is counterclockwise. Labels are: 1, SUVT acrylic; 2, acrylic tube; 3, PVC pieces; 4, adjustable stainless steel baffles; 5, Lexan colimiter; 6, aluminum propeller; 7, motor; 8, stainless propeller shaft; 9, grooves for o-rings; 10, nylon screws to attach PVC flanges; 11, stainless washer attached to PVC flange; 12, Delrin AF (Teflon-impregnated) attached to propeller shaft; 13, rubber septum (acts as spring held in place with a nylon wire holder on shaft).

Table 2 Characteristics of chambers used to compare temperature rise

Characteristic	Units	Chamber CP	Chamber AI
Circulation		Centrifugal Pump	Axial-Impeller Pump
Dimensions of sample compartment	cm	10 × 20 × 56	10 × 20 × 56
Working section cross sectional area	cm^2	200	200
Return piping cross sectional area	cm^2	2.8	45.6
Inlet/outlet ports cross sectional area	cm^2	1.8	5.3
Capacity	L	11.4	18.9
Volts		110 AC	24 DC
Amperage		3.2	0.4
Watts		352	9.6

impeller. In general, batteries are used, but a major problem is that they lose voltage over time. A power regulator maintains constant power, but may have poor efficiency. We used a timed-pulse power regulator with higher efficiency than that of a simple voltage regulator. In our system, it drew less than 1 amp with water velocities well above 70 cm s^{-1} in the working section.

Comparison of heat rise and power consumption with a conventional chamber

Metabolism test chambers circulated with an axial impeller pump would be expected to generate less internal heat than would a comparable chamber circulated with a centrifugal pump. To test this, water temperature in our axial impeller chamber and in a centrifugal pump chamber was monitored with thermistors. The acrylic chambers had similar sized sample compartments, but differed with respect to circulation mode and diameter of inlet and outlet ports, as well as return piping (Table 2). The centrifugal pump chamber was circulated with a 50 W, 110 V AC, oil-filled submersible centrifugal pump (Little Giant Model 4E-34N). The axial impeller chamber used a 36.8 W brushless DC motor drive (Aliquot Model K2301) with stainless steel, two-blade propeller (7.0 cm diameter, 10.7 cm pitch; Prather Model B-270).

Both chambers had cobble added and were submersed at 10 cm water depth in the Colorado River at Lees Ferry, Arizona. One axial impeller chamber was used in the experiment and the power was controlled to operate at 955 r.p.m., which resulted in a current velocity of 0.15 m s^{-1}. This velocity was similar to that in the centrifugal pump chamber running at maximum speed. During the period when metabolism of material in the chambers was being measured, chambers were run, sealed, for periods of 2–6 h and then purged with river water that had been pumped to a header tank for the purpose of deoxygenation. Temperature in the header tank tended to be 3–4 °C warmer than ambient river water. Throughout the experiment, the centrifugal chamber was covered with greenhouse shading that attenuated approximately 50% of incident solar radiation. The axial impeller chamber was covered with similar shading fabric beginning at 11.30 h on 6 April 1996.

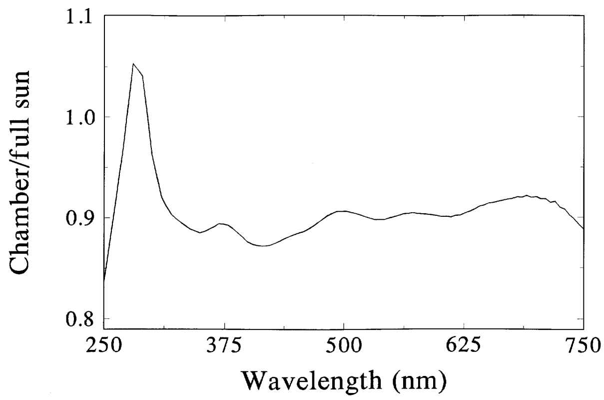

Fig. 2 Spectral transmittance of the axial impeller chamber in full sun in 30 cm of water. Measurements were made inside the chamber, in the same location with the chamber removed and once again inside the chamber. The ratio is the mean of the two measures inside the chamber/the measurement without the chamber.

Results

Spectral quality

The spectral quality in the completed chamber (Fig. 2) was very close to the incoming solar spectrum. For this measurement, an Optronics 752 scanning spectrometer with a submersible right angle cosine corrected sensor

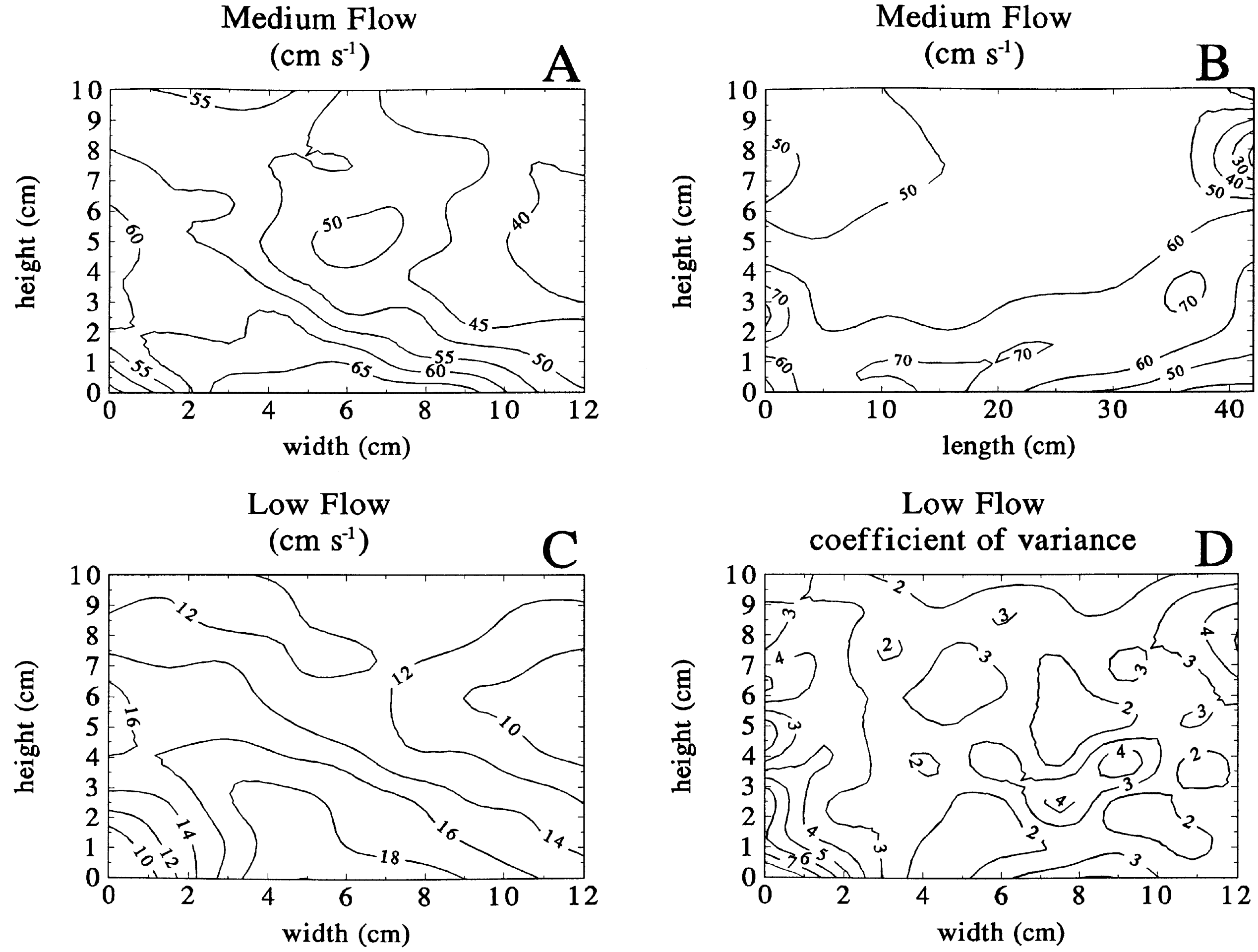

Fig. 3 (A) Water velocity profiles at medium velocity across the axial impeller chamber, (B) along the length of the chamber, (C) across the chamber at low velocity and (D) turbulence across the chamber at low velocity. Measurement A was made at 10 cm on measurement B. In A and C, the outside edge of the chamber is on the left. In B, upstream is to the right, and 0 cm is at the edge of the effluent line, near the propeller.

was used. Data were obtained in a 30-cm-deep pool of water at midday under clear conditions. The figure shows the ratio of energy measured every 5 nm in the chamber to the energy in the pool with no chamber. The low solar signal below 300 mm results in an apparent deviation from the optimal value of one. From 300 to 750 mm the spectral response is relatively flat with about 90% transmission. This is acceptable because little solar energy is present below 300 nm.

Velocity, internal pressure, and turbulence

The maximum velocity of the axial impeller chambers described here when run on a 12 V battery was 1.6 m s^{-1}, measured by a small propeller meter. We have worked with more than 10 different recirculating chambers designed for field work, and none of these were able to reach water velocities of this magnitude. Across the working area of the axial impeller chambers, water velocity was highest on the outside wall, lowest on the inside wall, and constant across the central 8–10 cm of the chamber (Fig. 3A,C); maximum velocity was at the bottom of the working section. When velocity was characterized by length, 20 cm of working area starting 5 cm from the downstream end, had relatively consistent flow characteristics (Fig. 3B). The coefficient of variance (turbulence) was less than 4%, except near the outside wall (Fig. 3D).

The velocity in the axial impeller chamber is more homogeneous than in two other designs of centrifugal-pump driven chambers. In a square chamber

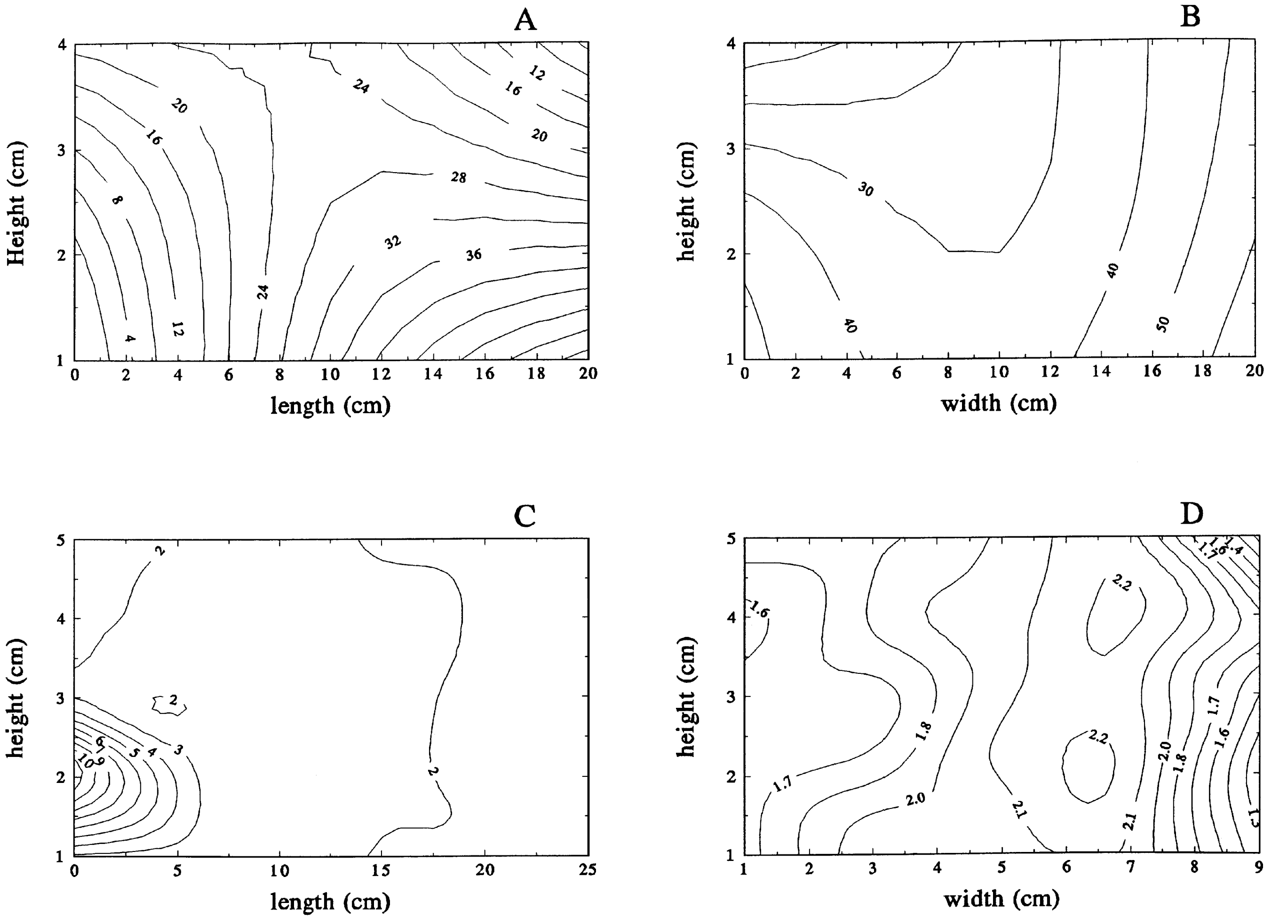

Fig. 4 Water velocity profiles from two centrifugal pump chambers taken along the length (A) and width (B) of a square chamber, and the length (C) and width (D) of an oval chamber.

(Fig. 4A,B), water velocity varied almost 10 fold along the length of the chamber, and two fold across its width. In an oval racetrack chamber (Fig. 4C,D), velocity was fairly uniform across the length, but high velocities occurred at the upstream end where the pump discharge was located. There was only about 50% variation in water velocity across this chamber at a point 20 cm downstream from the inlet. The velocity values across the oval chamber compared favourably to the axial impeller chamber, but we could not attain more than 0.5 m s^{-1} mean water velocity from the oval chamber.

Power requirements and temperature rise

Centrifugal pumps also require more power to drive than axial impeller pumps. When we compared two similar sized chambers, the centrifugal chamber needed 36 times more power than the axial impeller chambers to achieve similar velocities (Table 2). In remote situations, where battery power is limited, low power consumption is a distinct advantage.

There was clearly a greater temperature rise in the centrifugal pump chambers compared to the axial impeller chamber (Fig. 5). Temperature conditions measured in three replicate centrifugal pump chambers yielded similar results; for purposes of clarity, data from only one chamber are reported here. In the dark, the axial impeller chamber stayed within 1 °C of the water column temperature, and the centrifugal pump chamber 4–5 °C above the ambient temperature. After the centrifugal pump chamber was purged with ambient water at midnight on 6 April, internal chamber temperature rose over a 3-h period until the equilibrium temperature of 14 °C was reached. During the morning of 6 April, temperature in the shaded centrifugal chamber increased from 8.9 to 15.1 °C, while the unshaded axial impeller chamber (which

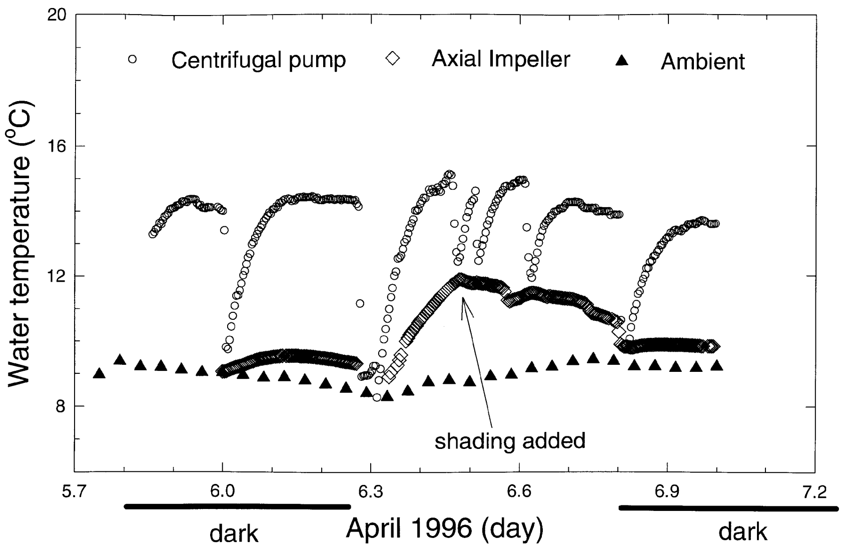

Fig. 5 Comparison of heat rise in a centrifugal pump chamber, axial impeller chamber and ambient river temperatures. The sharp temperature drops are where the chamber water was replaced. Midnight of 6 April is 6.0 on the *x*-axis.

was exposed to 50% greater solar radiation) warmed from 8.9 to 11.8 °C. After shading was added to the axial impeller chamber, it cooled to only 1.7 °C above ambient temperature, while the centrifugal pump chamber warmed to 5–6 °C higher than ambient.

Discussion

Acrylic or Plexiglas materials used in previous chambers typically have sharp cutoff of UV in the region of 350 nm. Until recently, the only material available for chamber construction able to pass UV was quartz. Such chambers would be prohibitively expensive and not well suited to field conditions; the UV transparent plastic is an obvious improvement where UV transmission is important.

The chambers we have used previously (e.g. Fig. 4) have all exhibited inconsistent water velocity patterns across the working area and large areas of turbulent back flow, particularly near intake and outlet ports. These flow patterns were observed using dye releases. Similarly, the 2:1 length:width version of the chamber presented here had inconsistent flow patterns in the working section. The final version of the axial impeller chamber described in this paper, apparently solves the problems of inconsistent water velocity patterns.

We suggest that the ratio of influent and effluent port cross sectional area to chamber compartment cross sectional area provides a useful metric for characterizing the geometry of aquatic metabolism test chambers and associated problems of heat rise and inconsistent water velocity fields. We define the dimensionless term, chamber influent area ratio as:

$$\text{chamber influent ratio} = \frac{c}{i} \qquad (1)$$

where c is the sample compartment cross sectional area and i is the total area of influent ports. A similar metric can be defined for chamber effluent ratio, and influent and effluent ratios are often equal in recirculating chambers. The c/i ratios were 79 and 5 in the centrifugal and the axial impeller chambers, respectively (Table 2). This approximately 15-fold increase in entrance and exit cross sectional surface area relative to the centrifugal chamber, results in substantially reduced turbulence within the sample compartment of the axial impeller chamber (Fig. 3) and elevated current velocities could be achieved more practically.

Our results illustrate that river metabolism test chambers with axial impeller circulation and relatively large diameter return piping can be expected to run several degrees cooler than chambers circulated with a centrifugal pump. Other investigators using stream metabolism chambers typically have not reported a rise in temperature. Such a temperature rise can alter the rates of all metabolic processes.

Several factors are responsible for the greater heat generated in a centrifugal pump chamber. (i) Heat generated by the electric motor dissipates through a jacket of either oil, water or epoxy. A portion of this heat is transferred to the chamber. The low cost and ready availability of DC marine bilge pumps has resulted in their frequent use. They are cooled with a water jacket through which the pumped fluid is passed, leading to appreciable heating of chamber contents due to the motor driving the pump. (ii) The degree of heating by centrifugal pumps is also influenced by the type of seal used to support the rotating shaft in the pump. The axial impeller design minimizes this problem. (iii) The higher the velocity of water through pump parts and associated piping, the greater the friction and associated generation of heat. Chambers circulated with centrifugal pumps tend to run hotter than those with axial impeller pumps, in part because the latter have relatively greater cross-sectional area in the return piping. For example, for the two chambers with similar-sized sample compartments described in Table 2, the axial impeller chamber has a larger cross sectional area of return piping by a factor of 16.

In summary, we describe construction of a portable flow chamber and attempt to optimize it for *in situ* stream research. We have used these chambers successfully in the field and laboratory for production measurements and other benthic metabolism (Dodds & Brock, unpublished) and behaviour (Edler & Dodds, 1996) measurements. We provide the first detailed characterization of flow properties, temperature rise and spectral quality that we are aware of for such chambers. We propose that such documentation be made available for chambers constructed in the future and those currently in use. This will allow researchers to compare results obtained from systems with different design characteristics. We hope that the data and techniques provided here will lead to even better technologies in the future.

Acknowledgements

The authors thank Dave Hill and Richard Zotti for excellent machine work and numerous design suggestions. Steve Kelly and Mark Ross provided electronic advice. Dolly Gudder provided technical assistance. This research was supported by project DEB-9411380 from the National Science Foundation. This is contribution no. 96-457-J from the Kansas Agricultural Experiment Station.

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(Manuscript accepted 24 July 1997)