PERGAMON

Water Research 37 (2003) 329–338

WATER RESEARCH

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How effective is intermittent chlorination to control adult mussel fouling in cooling water systems?

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Received 30 October 2001; received in revised form 5 June 2002; accepted 12 June 2002

Abstract

Mussel control in cooling water systems is generally achieved by means of chlorination. Chlorine is applied continuously or intermittently, depending on cost and discharge criteria. In this paper, we examined whether mussels will be able to survive intermittent chlorination because of their ability to close their valves during periods of chlorination. Experiments were carried out using three common species of mussels: a freshwater mussel, *Dreissena polymorpha*, a brackish water mussel, *Mytilopsis leucophaeata* and a marine mussel, *Mytilus edulis*. The mussels were subjected to continuous or intermittent (4 h chlorination followed by 4 h no chlorination) chlorination at concentrations varying from 1 to 3 mg l^{-1} and their responses (lethal and sublethal) were compared to those of control mussels. In addition, shell valve activity of mussels was monitored using a Mussel-monitor®. Data clearly indicate that mussels shut their valves as soon as chlorine is detected in the environment and open only after chlorine dosing is stopped. However, under continuous chlorination mussels are constrained to keep the shell valves shut continuously. The mussels subjected to continuous chlorination at 1 mg l^{-1} showed 100% mortality after 588 h (*D. polymorpha*), 966 h (*Mytilus edulis*) and 1104 h (*Mytilopsis leucophaeata*), while those subjected to intermittent chlorination at 1 mg l^{-1} showed very little or no mortality during the same periods. Filtration rate, foot activity index and shell valve movement of *D. polymorpha*, *Mytilopsis leucophaeata* and *Mytilus edulis* decreased more than 90% at 1 mg l^{-1} chlorine residual when compared to control. However, mussels subjected to intermittent chlorination showed a similar reduction (about 90%) in filtration rate, foot activity index and shell valve movement during chlorination and 3% during breaks in chlorination. The data indicate that intermittent chlorination between 1 and 3 mg l^{-1} applied at 4 h on and 4 h off cycle is unlikely to control biofouling if mussels are the dominant fouling organisms.

Keywords: Biofouling; Adult mussels; *Dreissena*; *Mytilopsis*; *Mytilus*; Chlorination; Mortality; Mussel-monitor®

1. Introduction

Mussels are known to be the most problematic fouling organisms in power plant cooling systems [1,2]. Uncontrolled growth of mussels in the pre-condenser regions of the cooling water systems can disrupt normal operation of a power plant, irrespective of its geographical location [3]. Therefore, plant operators take great care to ensure that mussel populations are kept under check using appropriate control measures [1]. In general, heat treatment or chemical dosing are resorted to, depending on plant design and a number of other factors [4]. Heat treatment is done by recirculating a part or the whole of the discharge through the intake pipes, so as to raise the

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0043-1354/02/$ - see front matter
PII: S0043-1354(02)00270-1

temperature of the water to the required lethal levels. Since this involves a penalty in terms of lost production [5], heat treatment is used only occasionally depending on breeding season of important fouling organisms in a given location. The most commonly used chemical antifoulant in cooling water systems is chlorine [1]. Chlorination is practiced either in continuous or intermittent modes. The most important criteria deciding the chlorine dosing frequency are cost and environmental discharge specifications [6]. Jenner et al. [1] have reviewed the chlorination regimes being practiced in a number of European and North American power stations. Some of them use intermittent chlorination (Ontario Hydro plants, Canada; DOW chemicals plant, Maasvlakte, Velsen and Hemweg power stations, The Netherlands; Flamanville, Martigues-Ponteau and Dunkerque power stations, France) to control bivalve mussels such as *Dreissena polymorpha*, *Mytilopsis leucophaeata* and *Mytilus edulis*.

Chlorine acts on the target organism at organ, cellular and subcellular levels, and kills the organism, depending on the dose and contact time [6–8]. Interestingly, in the case of mussels, the organisms are capable of protecting themselves, to some extent, from the deleterious effects of chlorine by shutting their shells. They have the ability to sustain themselves on anaerobic metabolism for a considerable length of time, often for several days [4]. If this is so, how could one expect to kill mussels by following an intermittent chlorination regime, where chlorine is injected for a few hours (1–4 h), to be followed by a gap of few hours before the next dosing? Are mussels simply closing their valves during chlorination and opening them as soon as chlorination is stopped? In that case, the utility may be wasting money by dosing chlorine into the cooling water, without the added chlorine actually achieving anything that is intended of it. The objective of this paper is to test the hypothesis that chlorination is ineffective in achieving adult mussel control if the dosing is intermittent. To test this hypothesis three species of mussels were used in dynamic laboratory bioassays at various concentrations of residual chlorine. The Mussel-monitor® was also used to monitor the shell valve movements of test mussels during bouts of chlorination and no chlorination.

2. Materials and methods

2.1. Experimental animals

The response of mussels to different chlorine concentrations was studied in the laboratory between October 1997 and May 1998, using animals collected from the Noordzeekanaal at IJmuiden (*Mytilus edulis*) and at Velsen (*Mytilopsis leucophaeata*) and from a lake near the River Waal (*Dreissena polymorpha*), The Netherlands. Mussels attached on stones were collected from the littoral and sub-littoral zone and transferred to the laboratory. Water collected from the field site was used to acclimate mussels to the laboratory conditions. Prior to the experiments, mussels were acclimated at 20°C for a minimum of 2 weeks in a temperature-controlled room.

2.2. Bioassay preparation

Mussels were tested for three different chlorine concentrations (1–3 mg l^{-1}). A total residual chlorine level of 1 mg l^{-1} is normally used in Europe for mussel control [1]. Water collected from the field was used for the experiment, after a day's storage. Factors which may influence the response of mussels, such as salinity, pH, temperature, dissolved oxygen, suspended particulate matter (SPM), chlorophyll-*a* and flow rate were kept constant in each of the experimental treatments (Table 1). In preliminary experiments, similar mortality responses to chlorine were observed between fed and

Table 1
Summary of parameters measured during chlorine toxicity experiments of *Dreissena polymorpha*, *Mytilopsis leucophaeata* and *Mytilus edulis*

Parameters	*Dreissena polymorpha*		*Mytilopsis leucophaeata*		*Mytilus edulis*	
	Range	Mean ± SD	Range	Mean ± SD	Range	Mean ± SD
Temperature (°C)	19.6–20.4	20.1 ± 0.2	19.5–20.4	20.1 ± 0.3	19.7–20.4	20.0 ± 0.2
Salinity (‰)	0.1–0.7	0.3 ± 0.1	4.8–5.5	5.2 ± 0.1	20.9–23.2	22.7 ± 0.5
pH	7.2–8.0	7.7 ± 0.2	7.4–8.1	7.8 ± 0.2	7.8–8.2	8.0 ± 0.1
Dissolved oxygen (mg l^{-1})	6.3–7.9	6.9 ± 0.9	5.6–7.0	6.3 ± 0.8	5.5–6.7	6.1 ± 0.7
SPM (mg l^{-1})	29.1–38.5	33.6 ± 2.1	39.4–49.7	46.5 ± 3.6	35.8–42.3	39.8 ± 4.0
Chlorophyll-*a* (μg l^{-1})	32.9–45.2	38.4 ± 3.4	26.4–38.2	33.9 ± 4.9	18.9–28.0	23.5 ± 3.4
Mussel size (mm)	19.6–21.3	20.1 ± 0.7	19.2–21.6	20.4 ± 1.0	19.6–22.9	21.2 ± 1.6
Water flow (ml min^{-1})	98–102	100.1 ± 2.0	97–102	99.9 ± 2.7	98–103	100.1 ± 2.4

starved mussels. Therefore, the experimental mussels were not fed during the course of the experiment. The experiments were conducted in continuous once-through flow systems. Water was stored in a 100 l aquarium tank and chlorine solution prepared from sodium hypochlorite was stored in a volumetric flask. An appropriate mix of the two were used to maintain the desired chlorine concentration in 20 l experimental tanks having an outlet at the 17 l mark, using a peristaltic pump. Mixing of the water with sodium hypochlorite was facilitated by the use of mixing pumps. A continuous flow at a rate of $100\,ml\,min^{-1}$ was maintained throughout the test. The experiments were conducted in a temperature-controlled room (20°C) under 12:12 h dark: light conditions.

2.3. Bioassays

After 2 weeks of acclimation, mussels were allowed to colonize naturally to polystyrene artificial substrates ($10 \times 10\,cm^2$) of their own [9]. The artificial substrates with 20 mussels of a known size group were introduced into the experimental tanks containing a known chlorine concentration. The chlorine levels were measured periodically at different locations in the experimental tank to ensure a uniform distribution of chlorine residuals. Total residual chlorine (sum of free chlorine and combined chlorine) was measured as total residual oxidants by the iodometric method [10,11]. The criterion for mortality of mussels was valve gaping with no response of exposed mantle tissues to external stimuli. The number of dead animals in each experiment was recorded along with their shell lengths and total weights for each observation time. In the intermittent chlorination experiments, a 4 h chlorination was followed by a 4 h break cycle was maintained.

Four replicates of each chlorine treatment concentration and of controls were used for all toxicity studies. Altogether, 1920 mussels were used for the mortality experiments (20 mussels in each experiment × 2 continuous and intermittent × 4 chorine doses including control × 3 species × 4 replicates = 1920 mussels).

2.4. Filtration rate

Filtration rate of mussels was studied at $1\,mg\,l^{-1}$ residual chlorine. Total period of experimental duration was 20 h in continuous chlorination, while in the intermittent mode it was 4 h chlorination followed by a 4 h break for 20 h. Filtration rate was measured following the method described by Coughlan [12], which is based on the clearance of neutral red by mussels from ambient water [13]. A concentrated solution of neutral red was added to Millipore (0.45 μm) filtered water (collected from the field site) to obtain a final concentration of $1\,mg\,l^{-1}$ of the dye. The test mussels were introduced into a 3 l beaker containing the dye alone (control) and five other sets ($n = 6$ for each beaker) with a known chlorine concentration and dye. Ten milliltres aliquots of water were drawn at 30 min intervals for 20 h and the concentration of dye in each aliquot was determined by measuring the optical density at 530 nm in a spectrophotometer. Concentrations were read off a calibration curve prepared earlier. Altogether, 504 mussels were used for filtration rate studies (6 mussels per experiment × 2 continuous and intermittent × 3 species × 2 chlorine doses including control × 5 replicates = 360 mussels). Rate of filtration was calculated using the following equation of Coughlan [12]:

$$m = M/nt \log C_0/C_t,$$

where m is the rate of filtration ($ml\,mussel^{-1}\,h^{-1}$), M the volume of the test solution, n the number of mussels used in the experiment, t the duration of the experiment (h), C_0 the initial concentration of the dye, C_t the concentration of the dye at time t.

2.5. Foot activity index

Ten mussels were placed in 3 l of water and left undisturbed for 12 h. Every 10 min, a note was made of the number of mussels with the foot extended outside the shell [13]. No attempt was made to follow the foot activity of individual mussels. For each experiment, all foot activity readings were analyzed and percentage foot activity was calculated (foot activity index). The same experiment was repeated three times for each mussel species at $1\,mg\,l^{-1}$ residual chlorine (10 mussels per experiment × 2 continuous and intermittent × 3 species × 2 chlorine doses including control × 3 replicates = 360 mussels).

2.6. Shell valve movement

Shell valve movements of *D. polymorpha*, *Mytilopsis leucophaeata* and *Mytilus edulis* were studied at $1\,mg\,l^{-1}$ chlorine residuals in the laboratory using a Mussel-monitor® [14]. Six to seven mussels (shell length ± SD; 21.3 ± 1.2 mm) were individually glued by means of dentists glue (Unifast, GC Dental Industrial Corp., Tokyo) to PVC plates on the mussel monitor following procedures outlined by Jenner et al. [15]. Measurement of shell valve movement of individual mussels was recorded automatically every minute through AD-conversion (analog devices) in a PC. The relative position of the shell valves (between totally closed and fully open) was readily displayed graphically on the screen for direct observation [15]. For each experiment, all shell valve open readings were analyzed and an average of 6–7 mussels was calculated for every minute. Total period of experimental duration was 48 h [16]. All test animals were allowed an acclimation period of 12 h

before the start of the experiments (pre-exposure). In the next 12 h, shell movement data were collected in a non-chlorinated environment (control). In continuous chlorination experiments, the animals were exposed to 24 h of chlorination, while in the intermittent chlorination experiments, a 4 h exposure was followed a 4 h break cycle for 24 h. The total experimental duration in each case was 24 h, inclusive of the breaks (refer to [16] for details).

2.7. Statistical analysis

A four-way ANOVA was used to analyze data for the combined effects of chlorine concentration on the survival time of the continuous and intermittently exposed mussels [17]. The variables of interest were mode of chlorine application (continuous and intermittent), residual chlorine concentration and relative chlorine tolerance of different mussel species. The fourth factor was used to test for possible block effects caused by use of different experimental tanks. Before analysis, survival time was log transformed for homogeneity. Differences between median values of survival time for each group were tested by Tukey's pair-wise multiple comparison test. The data obtained on mortality of *D. polymorpha*, *Mytilopsis leucophaeata* and *Mytilus edulis* at different chlorine doses were subjected to probit analysis, yielding the statistic LT_{50} [18]. The differences in filtration rate, foot activity index and shell valve openings between control and experimental ($1\,mg\,l^{-1}$ residual chlorine) mussels were compared by student-*t* tests after Bonferroni corrections [17]. All analyses were performed using a Statistical Analysis Systems package [19].

3. Results

3.1. Mortality

No mortality occurred in the control tanks. The three mussel species (*D. polymorpha*, *Mytilopsis leucophaeata* and *Mytilus edulis*) showed 100% mortality at significantly different exposure times when subjected to continuous chlorination (mussel species effect: $F_{(2,238)}=219.63$, $P<0.001$, Fig. 1). At $1\,mg\,l^{-1}$ residual chlorine, *D. polymorpha*, *Mytilus edulis* and *Mytilopsis leucophaeata* took 588, 966 and 1104 h, respectively, to achieve 100% mortality. The time taken for 100% mortality of mussels decreased with increasing chlorine concentration. The exposure time required to 100% mortality was analyzed by ANOVA for all three concentrations of chlorine ($1–3\,mg\,l^{-1}$) and was found to be highly significant (chlorine dose effect: $F_{(2,714)}=687.04$, $P<0.0001$). The mortality rate at different chlorine residuals showed that $1\,mg\,l^{-1}$ exposure was significantly less toxic than other chlorine concentrations (Fig. 1). The effect of mode of chlorine application (continuous and intermittent) on mortality of mussels was significant (chlorine application effect: $F_{(1,239)}=903.71$, $P<0.001$). Mussels subjected to continuous chlorination at $2\,mg\,l^{-1}$ showed 100% mortality between 444 h (*D. polymorpha*) and 798 h (*Mytilopsis leucophaeata*), while those subjected to intermittent chlorination showed only 5% mortality during the same period (Fig. 1). No significant differences were found between replicate experiments (replicates: $F_{(3,1916)}=0.79$, $P>0.05$).

The time to 50% mortality (LT_{50}) of mussels was investigated by probit and regression analysis (Fig. 2), and also shows a significant chlorine dose effect ($F_{(2,238)}=366.71$, $P<0.001$) and species effect ($F_{(2,238)}=147.52$, $P<0.001$) on LT_{50} of *D. polymorpha*, *Mytilopsis leucophaeata* and *Mytilus edulis*. At $1\,mg\,l^{-1}$ chlorine concentration, *Mytilopsis leucophaeata* took 904 h to reach 50% mortality, whereas *Mytilus edulis* and *D. polymorpha* took 772 and 451 h, respectively (Fig. 2).

3.2. Filtration rate and foot activity index

The maximum filtration rate and foot activity index of *D. polymorpha*, *Mytilopsis leucophaeata* and *Mytilus edulis* were observed in control experiments (Table 2). Mussels subjected to continuous chlorination at $1\,mg\,l^{-1}$ showed a reduction of 87 (*Mytilopsis leucophaeata*) to 92% (*D. polymorpha*) in filtration rate and 88 (*Mytilopsis leucophaeata*) to 94% (*D. polymorpha*) in foot activity index when compared to control experiments (*t*-tests, $P<0.001$). Mussels subjected to intermittent chlorination showed a similar pattern of reduction in filtration rate and foot activity index during chlorination (*t*-tests, $P<0.001$) but no significant reduction during stoppage of chlorination compared to control experiments (*t*-tests, $P>0.05$, Table 2). For example, *Mytilus edulis* subjected to intermittent chlorination showed a reduction of 92% during chlorination ($t=34.269$, $df=18$, $P<0.001$) and 3% during breaks in chlorination ($t=0.945$, $df=18$, $P>0.05$, Table 2).

3.3. Shell valve movement

The percentage shell opening frequency was higher in control experiments (Fig. 3). The percentage shell openings of *D. polymorpha*, *Mytilopsis leucophaeata* and *Mytilus edulis* were not significantly different in control experiments (ANOVA, $df=19$, $F=1.065$, $P>0.05$). However, shell-opening frequencies of mussels subjected to continuous chlorination ($1\,mg\,l^{-1}$) showed a reduction of 90 (*Mytilopsis leucophaeata*) to 97% (*D. polymorpha*) when compared to control experiments. For example, *Mytilus edulis* subjected to continuous

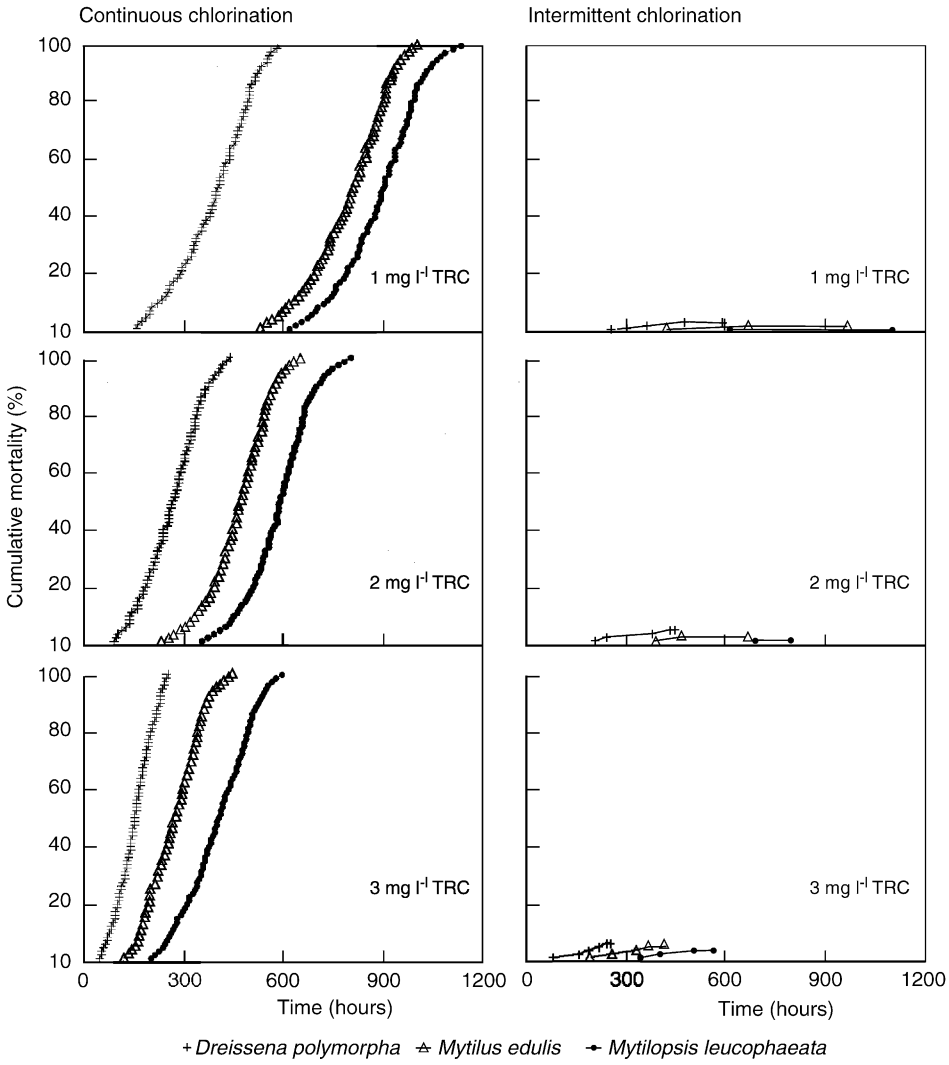

Fig. 1. Cumulative mortality (%) of *Dreissena polymorpha*, *Mytilopsis leucophaeata* and *Mytilus edulis* subjected to continuous and intermittent chlorination at different concentrations (TRC = total residual chlorine). Eighty mussels were used at each chlorine dose for each species. Mortality of mussels was monitored at 6 h intervals. The criterion for mortality of mussels was valve gaping with no response of exposed mantle tissues to external stimuli.

chlorination (1 mg l^{-1}) was reduced to 7% from 92% in control experiment ($t = 32.089$, df = 12, $P < 0.001$, Table 2). Mussels subjected to intermittent chlorination showed a significant decrease in shell opening (93–98%) during chlorination (Fig. 3). However, no significant differences were observed in percentage shell opening between control (91–93%) and during breaks (87–88%) in chlorination (Table 2). The results clearly indicate that mussels subjected to intermittent chlorination shut their shell valves during chlorination and open only after chlorine dosing is stopped. However, under continuous chlorination mussels were constrained to keep the shell valves shut (Fig. 3).

4. Discussion

Mussels generally dominate power stations cooling water circuits because of their ability to colonize hard surfaces under high water velocity conditions using byssus threads [2,3]. Their growth rate also increases at high flow rates [20]. In general, tolerance of mussels to control measures is high as compared to other groups of fouling organisms [1,4]. While chlorine serves as an excellent biocide for controlling biofouling in cooling water systems, its use is restricted due to environmental considerations. Efficacy of chlorine as an antifoulant depends on various parameters, most importantly

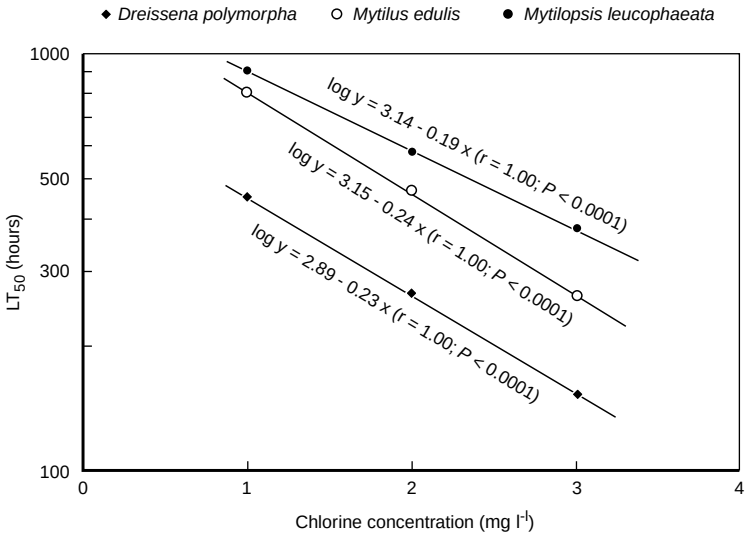

Fig. 2. Time required for 50% mortality (LT_{50}) of *Dreissena polymorpha*, *Mytilopsis leucophaeata* and *Mytilus edulis* subjected to continuous chlorination at different concentrations (after probit and regression analysis).

Table 2
Filtration rate (ml mussel^{-1} h^{-1}), foot activity index (%) and shell valve movement (% shell valve open) of *Dreissena polymorpha*, *Mytilopsis leucophaeata* and *Mytilus edulis* at 1 mg l^{-1} residual chlorine

	Continuous chlorination experiment		Intermittent chlorination experiment		
	Control	Chlorination	Control	Chlorination	Break in chlorination
Filtration rate					
Dreissena polymorpha	76.6±5.2	6.2±2.8*	75.5±6.1	5.9±3.2*	71.0±6.1[a]
Mytilopsis leucophaeata	46.2±5.1	5.9±3.0*	47.1±5.9	6.2±2.7*	44.3±5.5[a]
Mytilus edulis	87.5±6.4	7.8±3.1*	85.3±5.8	6.8±3.5*	82.3±6.0[a]
Foot activity index					
Dreissena polymorpha	62.3±4.7	3.9±2.7*	60.9±5.2	3.6±2.5*	57.9±6.2[a]
Mytilopsis leucophaeata	78.2±5.4	9.5±3.8*	76.6±6.7	8.7±4.0*	79.1±5.6[a]
Mytilus edulis	68.6±5.1	6.7±2.5*	69.8±5.8	7.1±3.3*	67.5±6.4[a]
Shell valve movement					
Dreissena polymorpha	90.1±5.1	3.0±2.1*	90.6±5.8	2.5±2.0*	83.8±6.5[a]
Mytilopsis leucophaeata	90.4±7.3	9.4±6.4*	91.7±6.6	6.1±4.9*	86.7±5.3[a]
Mytilus edulis	92.0±5.6	7.1±4.2*	92.7±5.1	5.7±4.6*	87.4±6.2[a]

*Significant at $P<0.001$.
[a] Not significant.
Data are expressed as mean±SD *(n=6–30)*. Differences between control and experimental mussels (continuous and intermittent chlorination) were compared by student *t*-tests after Bonferroni corrections.

residual levels of chlorine and contact time [6,8]. A survey of existing literature shows that at residual levels commonly employed (1 mg l^{-1}) in power station cooling circuits, mortality takes several days. For example, Lewis [21] reported that at 1 mg l^{-1} continuous chlorination, *Mytilus edulis* takes 480 h for 100% mortality. In tropical marine mussels, Rajagopal [4] reported that *Perna viridis* takes 816 h for 100% mortality at 1 mg l^{-1} residual chlorine applied continuously. Van Benschoten et al. [22] recorded 95% mortality of *D. polymorpha* after 552 h exposure to 1 mg l^{-1} residual chlorine. In the present study, *Mytilopsis leucophaeata* takes 1104 h to achieve 100% mortality at 1 mg l^{-1} residual chlorine (Fig. 1). The exposure time required for 100% mortality

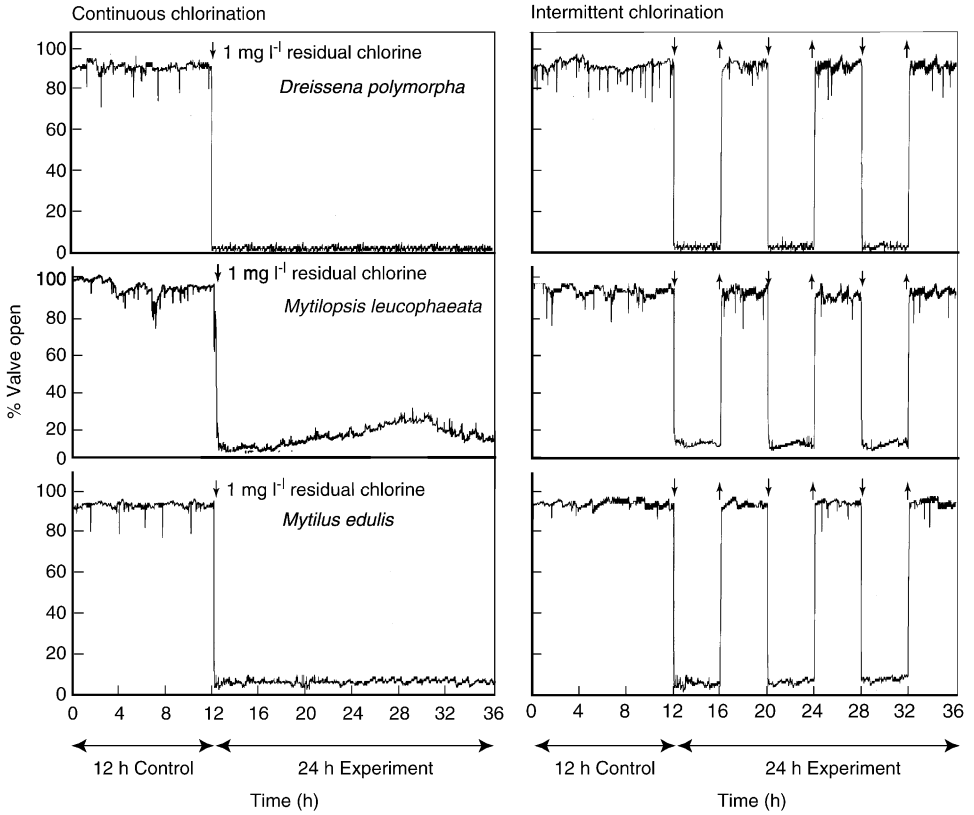

Fig. 3. Average ($n = 6-7$) patterns of shell valve movements of *Dreissena polymorpha*, *Mytilopsis leucophaeata* and *Mytilus edulis* subjected to continuous and intermittent chlorination (4 h on and 4 h off cycle) at 1 mg l^{-1} chlorine concentration. The status of the shell valves was logged every 1 min. ↓ denotes addition of chlorine and ↑ denotes stoppage of chlorine.

of *Mytilopsis leucophaeata* at different chlorine concentrations were much higher than that required for *D. polymorpha* (588 h) and *Mytilus edulis* (966 h).

In spite of the efficacy of continuous chlorination, utilities still use intermittent chlorination to get rid of adult mussel populations, largely due to cost factors and the need to reduce discharge levels. Various types of chlorination (semi-continuous and discontinuous) are in use [1,3]. A review of literature indicated that majority of industries which follow intermittent chlorination use about 1–4 h chlorination followed by 1–8 h break cycle, depending on the water temperature and breeding season of mussels [1,3,20]. For example, at Maasvlakte power station (Rotterdam, The Netherlands), a intermittent chlorine regime of 4 h on and 4 h off (0.2–0.3 mg l^{-1} residual chlorine) is used to control mussel fouling [1]. In the present study, a 4 h chlorination followed by 4 h break cycle was selected in order to assess the effects of intermittent chlorination on mussels. While adult mussels of all three species tested can be killed in 588 h (*D. polymorpha*) to 1104 h (*Mytilopsis leucophaeata*), similar doses applied intermittently failed to achieve any significant mortality (Fig. 1). Although concentrations as high as 3 mg l^{-1} were used in the experiment, mussels were able to protect themselves against chlorine by closing their shell valves, surviving for long periods. The data, therefore, indicate the inherent limitation of intermittent chlorination (4 h on and 4 h off cycle) in situations where mussels are involved. It may be possible that organisms other than mussels, which do not have the capacity to seal off their body parts against toxic environment, will succumb to intermittent chlorination [23,24]. Literature data on the efficacy of intermittent chlorine treatment program to control mussel fouling are conflicting. At the Martigues–Ponteau plant on the French Mediterranean coast, hypochlorite injection for 1 h every 8 h at 2.5–3.0 mg l^{-1} was successful against mussels, *Mytilus galloprovincialis* [1]. Turner et al. [25] and Anderson and Richards [26] observed that intermittent chlorination was not effective in preventing settlement and growth of *Mytilus edulis* in power station cooling circuits. Similar data were also presented by James [27] for the Carmarthen Bay power station (*Mytilus edulis*, England), by Khalanski and

Bordet [28] for the Dunkerque power station (*Mytilus edulis*, France), by Jenner [29] for the Maasvlakte power station (*Mytilus edulis*, The Netherlands), by Rajagopal et al. [30] for the Velsen and Hemweg power stations (*Mytilopsis leucophaeata*, The Netherlands) and by Rajagopal [4] for the Madras Atomic Power Station (*Perna viridis*, *P. perna*, *Brachidontes striatulus*, *B. variabilis* and *Modiolus philippinarum*, India). It is reported that in food-rich environment, intermittent chlorination lasting for a few hours per day or a few days per month even at higher concentrations (3–5 mg l^{-1}) does not kill mussels because the mussels close their shell valves during chlorine treatment and start feeding a few minutes after chlorination is stopped [4,21]. On the contrary, similar treatment in food-poor waters (e.g. Martigues–Ponteau plant) may effectively control mussel growth by trophic limitation [1]. Therefore, knowledge about the trophic status of the site would be helpful in predicting whether intermittent chlorination would be effective against bivalve mussels. Due to the somewhat conflicting literature on mussel control, it would be worthwhile to investigate whether intermittent chlorination will be able to control mussel fouling under actual operating conditions. It must be borne in mind that while shell valve opening under chlorination permits the mussel to feed, it also entails a risk that the soft tissues are exposed to the toxic environment [16]. Since shell valve opening during chlorination would be the major factor deciding the survival of mussel specimens, it was thought appropriate to use a Mussel-monitor® to supplement mortality data. Filtration rate and foot activity index are also related to valve opening by the mussels. Therefore, they too are excellent indicators of the propensity of the mussel to open its valves.

Mussel-monitor® data show that the valve activity of *D. polymorpha*, *Mytilopsis leucophaeata* and *Mytilus edulis* decreased more than 90% when compared to control at 1 mg l^{-1} chlorine concentrations (Table 2). While control mussels subjected to intermittent chlorination showed a shell opening of 90–93%, test mussels subjected to 1 mg l^{-1} showed shell valve opening varying from 3% to 6% (Table 2). However, break in chlorination after 4 h, invariably resulted in resumption of valve activity comparable to the control readings, indicating complete recovery. On the other hand, shell valve openings of continuously chlorinated mussels remained low as compared to control experiments throughout the experimental period. The same patterns were also observed in filtration rate and foot activity index (Table 2).

The responses of mussels to intermittent chlorination are quite different from that of continuous chlorination. It is well known that chlorination adversely affects the pumping rate, feeding, shell opening and byssus production in mussels and therefore, growth rate is reduced [13,31]. However, in intermittent chlorinated waters, recuperation of mussels is possible because during the breaks in chlorination they can actively feed and produce byssus threads [1,20,32]. Lewis [21] reported that in *Mytilus edulis*, 20 days of starvation during chlorination could be compensated by 1 day of feeding under good conditions. High flow conditions that exist in power plant cooling circuits invariably ensure increased food availability and removal of metabolic wastes [2,33]. Therefore, mussels can easily compensate any resource drain caused by short-term chlorination [1,20]. However, in continuously chlorinated waters, mussels are forced to shut their valves and exist on stored food reserves and anaerobic respiration, until energy resources are depleted or metabolic wastes reach a toxic level [4,21]. Obviously regular breaks in chlorination would allow mussels to recuperate their energy losses. Intermittent chlorination regimes prac-

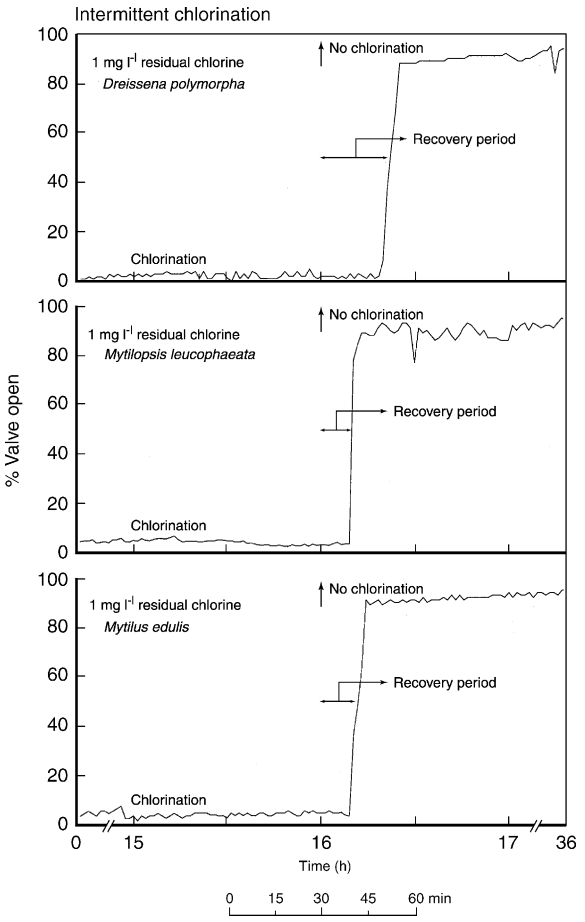

Fig. 4. Mussel-monitor® data (magnified between 15 and 17 h in Fig. 3) showing recovery period (between cessation of chlorination and resumption of feeding) in *Dreissena polymorpha*, *Mytilopsis leucophaeata* and *Mytilus edulis* during intermittent chlorination. ↑ denotes stoppage of chlorine.

ticed in some power stations need to be reexamined in the light of experimental results presented in this paper.

A recent development in chlorination strategy, known as Pulse-chlorination® attempts to dose chlorine intermittently [1], but giving little time for mussels to recover. This technology makes use of the time lag between stoppage of chlorination and full resumption of mussel feeding (Fig. 4). Chlorination is resumed a little before the mussels start feeding after a bout of chlorination, with the end result they experience the total period as continuous chlorination, even though it is, in fact, intermittent chlorination. But if this break in chlorination is continued well beyond the recovery period, the mussels can make use of the period for feeding. More importantly the length of recovery period is different for different mussels, the duration ranging from 7 min for *Mytilopsis leucophaeata* to 15 min for *Dreissena polymorpha* (Fig. 4). Therefore, this procedure has to be employed judiciously depending on the species one is dealing with. When used in this way, Pulse-chlorination® can result in considerable economic gain for the utility due to reduced chlorine inventory [1].

5. Conclusions

The study conclusively proves inadequacy of intermittent chlorination to control fouling mussels. The data show that in *Dreissena polymorpha*, *Mytilopsis leucophaeata* and *Mytilus edulis*, 100% mortality can be achieved from 588 to 1104 h, at a continuous chlorine concentration of 1 mg l^{-1}. However, application of the same concentration in the intermittent mode (4 h on and 4 h off cycle) results in little (5%) or no mortality during the same period.

Filtration rate, foot activity index and shell valve movement data show that, irrespective of chlorine concentration employed, breaks in chlorination allow mussels to open their shells and resume feeding. However, the recovery period (between cessation of chlorination and resumption of feeding) differs from species to species (ranging from 7 to 15 min). This would imply that intermittent chlorination, even at relatively higher chlorine residuals, might not affect mussel survival significantly in food-rich environments. Therefore, use of intermittent chlorination with the objective to attain mussel mortality in reasonable times would be ineffective, because mussels can rapidly compensate for trophic limitation by feeding during breaks in chlorination that would typically last for 4 h.

Acknowledgements

We would like to thank C. van de Rijt for help with statistical analysis, M.G. Versteeg and H. Polman for assistance with mussel collection and maintenance in laboratory, and Dr. V.P. Venugopalan for useful discussions. Department of Aquatic Ecology, University of Nijmegen, The Netherlands and KEMA Power Generation and Sustainables, Arnhem, The Netherlands funded this research. This is publication number 304 of the Centre of Wetland Ecology.

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