Industrial Seawater Cooling Systems under Threat from the Invasive Green Mussel *Perna viridis*

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ABSTRACT The green mussel *Perna viridis*, native to the Asia-Pacific region, has been introduced to other regions such as the Caribbean, Japan and North and South America. It is a large, commercially important species, widely cultivated and harvested in Southeast Asia, but is also considered an invasive species elsewhere, capable of replacing native species. As a fouling organism in intake systems of coastal power plants, it causes flow blockage and loss of cooling efficiency. Mussel colonization during peak settlement season can exceed 35,000 individuals/m² and biomass can exceed 100 kg/m². They can withstand wide fluctuations in temperature and salinity. Previous work has shown that a conventional biofouling control measure such as chlorination is not very effective against these bivalves, unless applied continuously for extended periods of time. We require more efficient, environmentally compatible methods of biofouling control. The paper discusses these issues in the context of the perceived invasion potential of *P. viridis*.

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1. INTRODUCTION

Water is extensively used in industries, where it is considered a coolant par excellence. In fact, among its various uses in the industry, its use as a coolant is most substantial. Electric power generation using steam-water cycle accounts for a major share of the above use. A direct once-through cooled thermal power plant of 2,000 MW(e) capacity typically requires approximately 65 m³ of cooling water every second (Venugopalan et al. 2012). Most of this water is used for steam condensation, whereby the water picks up heat in the condenser before it is discharged back into the receiving water body (Langford 1990). Owing to shortage of coolant water in inland locations, newer power plants are increasingly being located at coastal sites, with the intention of using seawater as a coolant. Coastal power plants generally use cooling water in a once-through mode. In this case, the seawater is drawn from a suitable location, used for steam condensation and then discharged back into the same water body via a carefully designed outfall system. The physical features of the seawater intake system and the associated cooling water pipelines of the power plants are extremely favourable artificial habitats for colonisation of a variety of marine benthic organisms, such as mussels, barnacles and other macro-invertebrates. Hard surfaces provide excellent sites for attachment, and high flow rates ensure a constant supply of food and oxygen as well as removal of metabolic wastes (Venugopalan et al. 1991). Bivalve mussels are among the major constituents of the biofouling communities that colonise power plant cooling water systems all over the world (Jenner et al. 1998).

In tropical regions, the green mussel *Perna viridis* is a predominant bivalve fouling species in seawater intake systems (Rajagopal et al. 1996). Biomass levels as high as 411 tonnes have been reported from intake pipes of a power station (Rajagopal et al. 1991). *P. viridis* is widely distributed in the Indo-Pacific region, extending from Japan to New Guinea and from the Persian Gulf to South Pacific Islands (Siddall 1980). Apart from the Indo-Pacific region, the species has been reported from the Caribbean and several areas of the North and South America (NIMPIS 2002; Rajagopal et al. 2006). In North America, it has been reported from coastal Georgia and Florida (Power et al. 2004), while in the Caribbean region, the mussel occurs in Trinidad and Tobago, Jamaica and Venezuela (Agard et al. 1992, Rylander et al. 1996, Benson et al. 2002, Buddo et al. 2003). Being a biofouling species of considerable nuisance value, it is important to keep a watch on its northward spread to cooler areas, aided by global climate change.

2. CHARACTERISTICS OF *PERNA VIRIDIS*

Perna viridis is a fairly large (8–10 cm), commercially important mussel species (Vakily 1989). It lives in areas where the temperature and salinity are in the range of 11–32°C and 18–33 psu, respectively. Sivalingam (1977) reported that the species survives in the temperature range of 10–35°C and has an optimum temperature range of 26–32°C. *P. viridis* commonly occurs on hard substrata such as rocks in the mid-intertidal to subtidal region. As it has the ability to withstand wide environmental fluctuations, *P. viridis* can spread rapidly after its introduction to new environments (McFarland et al. 2015). In general,

Figure 1. Mussel colonisation in various parts of a coastal power station on the east coast of India. (A) colonisation in the intake well, (B) colonisation inside a concrete pipe and (C) shells of mussels removed from the system during a maintenance shutdown.

bivalve molluscs have been recognized as successful invaders all over the world (Morton and Tan 2006; Robinson et al. 2007; Darrigran and Damborenea 2011). It has been reported that in newly introduced areas, *P. viridis* can eventually become the marine equivalent of Asian zebra mussel *Dreissena polymorpha* (Power et al. 2004). The invasion success of the mussel is related to its biological traits (Minchin et al. 2016). Apart from its salinity and temperature tolerance, several aspects of its life history are responsible for its success as an invasive species. Among its life history traits, rapid growth, early onset of maturity and dispersal through a long planktonic stage are important. The well-developed byssus system also is a major factor in the dispersal of the species, as it allows the individuals to stick tenaciously to ship hulls. It has been transported as part of the hull fouling community (Huhn et al. 2015). The filter-feeding nature of mussels is also a supporting factor in that it facilitates feeding of suspended food available in plenty in eutrophic environments of ports and harbours (Olenin and Daunys 2005). Mussel larvae have a long planktonic stage, which makes it possible for them to be transported over long distances in ship ballast water tanks. Goh and Lai (2014) remarked that *P. viridis*, with its susceptibility to temperature increase, might shift to colder regions as the seawater temperatures rise due to global warming. Urian et al. (2011) remarked that though under the current conditions *P. viridis* was at the northern edge of its potential range in the United States, with increasing water temperatures as a result of warming, southerly currents might permit northward expansion of its range. It is necessary to study the consequences of the range expansion of the green mussel in the context of its reported effects on industrial cooling systems (Rajagopal et al. 2006).

3. BIOFOULING IN INDUSTRIAL COOLING WATER SYSTEMS

Mussels are common nuisance organisms on artificial surfaces in the marine environment. Seawater intake and outfall structures, as well as pipelines and culverts of coastal power plants are particularly prone to fouling by mussels. In cooling water systems (CWS) of coastal power stations, mussels are the most dominant organisms (Venugopalan et al. 2012). Though biofouling in cooling water systems of coastal power plants are multispecies communities, it is often seen that only a few species are dominant. For example, in the case of power plants in India, it has been reported that a few mussel species such as *P. viridis*, *P. perna*, and *Brachidontes* spp. were the dominant species (Rajagopal et al. 1991). Green mussels constituted 12.8-16.2% in terms of numerical density and

up to 71% in terms of biofouling biomass in the intake pipe of a coastal power plant in India (Rajagopal et al. 2003a). Compared to barnacles, mussels are reported to be more common in CWS. The probable reasons for this observation are their byssate nature that allows strong layered growth in space-limited environments, long planktivorous larval life (barnacles in comparison have a non-feeding settlement stage that limits their range of colonisation) and ability to relocate and reattach even after dislodgement from a substratum.

Mussels are important fouling organisms in the cooling water systems of power plants. Because of the characteristics mentioned above, mussel colonisation in seawater intake lines of coastal power plants can be very heavy, leading to problems ranging from flow reduction in conduits to complete blockage of heat exchanger tubes. Colonization during peak settlement season can exceed 35,000 individuals per square metre and mature communities can weigh as much as 100 kg/m² (Figure 1). Studies showed that massive infestation of CWS could take place in spite of intermittent chlorination (Rajagopal et al. 1991). *Perna viridis* is a continuous breeder as well as an active filter feeder that grows faster under flow conditions in CWS. This mussel is also a prolific byssus producer with high chlorine tolerance. These characteristics make it a formidable pest species to deal with in industrial systems using seawater as coolant. Figure 2 shows the relative numerical densities of different mussel species on the intake screens of a coastal power station and in ad-

Figure 2. Densities of five mussel species in the coastal waters off Kalpakkam, South India (black bars) and on the intake screens of a power station drawing coolant seawater from the same location (red bars). High flow environment inside intake pipes supports dense mussel settlement.

Figure 3. Valve movement recordings of *Perna viridis* using a Mosselmonitor™. (A) Valve movements of an undisturbed control mussel. (B) Valve movements of a mussel subjected to continuous chlorination of 0.7 mg/L (as total oxidant residuals). The downward arrow indicates onset of chlorine dosing. Note that the mussel opened its valves and started feeding after an initial closure.

joining coastal waters, suggesting preferential growth of these bivalves in the high flow regime of the CWS. Rajagopal et al. (2003a) showed that on continuous exposure to 1 mg/L residual chlorine, *Brachidontes variabilis* (another prolific biofouling species in power plant CWS) took 288 h for 100% mortality, while *P. viridis* took 816 h. In a multispecies scenario, such high tolerance gives the mussel a clear advantage over other co-existing species.

As mentioned above, extensive mussel colonisation in power plant CWS has been reported in spite of intermittent chlorination (James 1967). Bivalve mussels have the ability to close their shells and protect their soft body parts from chlorinated water, sustaining themselves on anaerobic metabolism. It has been reported that bivalves can overcome short time periods of low dissolved oxygen content, though they are vulnerable to prolonged oxygen deficiency (deZwaan 1977; Chen et al. 2007). Once settled, they can withstand low dose chlorination for considerable lengths of time. Holmes (1970) showed that mussels that settled during gaps in an intermittent chlorination regime were able to resist subsequent exposures to chlorine. Previous studies have also shown that intermittent chlorination is inadequate to control mussel fouling (Rajagopal et al. 1996; 2003b). Adult mussels were largely unaffected by residuals as high as 0.7 mg/L TRO in laboratory experiments using a Mosselmonitor™ (Figure 3) which can record the valve movements in bivalves. After an initial stage of valve closure following the onset of chlorination at 0.7 mg/L level, the mussels opened their valves and continued to feed uninterrupted. Higher levels of chlorine (1.0 mg/L) were required to inhibit normal feeding. For other fouling mussels such as *Mytilus edulis*, as well as the dreissenid bivalves *Dreissena polymorpha* and *Mytilopsis leucophaeata*, chlorine concentrations at which valve movement (and thereby feeding) is affected lie in the range 0.3 to 0.6 mg/L (Pollman and Jenner 2002). A report by Rajagopal et al. (1996) indicated that if chlorination were to be employed as the antifouling measure in a fouling community, where five species of the mussels co-existed (*P. viridis*, *P. perna*, *Brachidontes striatulus*, *B. variabilis*, and *Modiolus philippinarum*), *P. viridis* would be the last to get eradicated, due to its ability to withstand chlorine stress. It may be recalled that the residual chlorine levels legally permitted in the discharged water is about 0.5 mg/L or less (0.2 mg/L in some countries). Therefore, increasing the chlorine concentration above the presently dosed levels is not a feasible option. It is obvious that the sublethal levels of chlorine administered in power plant CWS will have little effect on established *P. viridis*.

However, continuous low dose chlorination (CLDC, 0.2 to 0.4 mg/L as total residual oxidants) has been shown to be quite effective for mussel control (Murthy et

al. 2011). CLDC works on the principle of deterring the settlement of plantigrades. In once-through cooling systems, where coolant water is drawn from the sea, passed through the condensers and released back into the sea, CLDC works by preventing settlement of young mussels. Propagules (pediveligers and juveniles) entering the cooling water circuit do not find the environment conducive for settlement and, therefore, exit the system along with the outgoing water; hence the term exomotive chlorination (Lewis 1985). Occasional breaks in chlorination, owing to poor equipment reliability of the chlorine dosing system (which is a common issue because of the corrosive nature of chlorine) can permit mussel colonisation to take place, with the result that the settled mussels are unlikely to be killed by the sublethal doses of chlorine employed and, therefore, continue to feed and grow, despite chlorination.

Work carried out at Kalpakkam (southeast coast of India) has shown that *P. viridis* fouling on surfaces could be prevented by low dose continuous chlorination such as being practised at power stations. Test panels exposed at the intake point (non-chlorinated site) of the power plant were completely fouled by green mussels in about 7-8 months, while those exposed at the pump house of the power plant (chlorinated site, 0.2-0.4 mg/L TRO) were practically free of green mussels (Venkatnarayanan et al. in preparation). This indicated the effectiveness of exomotive chlorination, which discourages settlement of young mussels. However, established adult mussels in the seawater coolant system (which had settled during previous breaks in chlorination) continued to survive despite the low doses being employed continuously. These observations highlight the need to have a fool-proof system for reliable operation of the chlorine dosing system, given the fact that green mussels are continuous breeders and their young ones are available in coastal waters almost throughout the year (Soon and Ransangan 2014).

4. CONCLUSIONS

Perna viridis is a major fouling species in seawater cooling systems of coastal power plants in the tropics. Compared to other fouling mussel species, it is relatively more tolerant to chlorination, though colonisation of young mussels can be prevented by the use of continuous dosing of low levels of chlorine. The mussels are extremely difficult to get rid of using intermittent chlorination and adult mussels can withstand continuous chlorination even beyond permitted levels for several days. These mussels, by virtue of their life cycle traits, have the ability to colonise new areas, as have been reported in recent literature. There is a need to monitor the distribution of the

green mussels and to develop better, environmentally compatible methods to prevent biofouling by them.

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