Flushing From Multi-compartmented Ballast Water Tanks

Alistair Grieg, Ian Eames and Liora Malki-Epshtein
University College London, Gower Street, London WC1E 6BT

Ballast water is essential for international trade but it also leads to Non Indigenous Species being transported over large distances. The impact is detrimental economically and ecologically. In this paper we review the efficiency with which ballast fluid is diluted and how flushing depends on the geometrical aspects of the ballast tank. We use a three-dimensional acrylic scaled model of a ballast tank to study these processes experimentally, using a dye attenuation technique to estimate the mean dye concentration which remains in the whole tank and different compartments and set out a new methodology to quantify flushing.

KEY WORDS
Ballast water; multi-compartment flow; Non Indigenous Species.

INTRODUCTION

Ballast water is essential for the safe operation of ships; it ensures stability and structural integrity by maintaining shear stresses and bending moments within acceptable limits. The mass of ballast water transferred annually worldwide has been estimated to be at least three billion tonnes and may be more than twice that. Some ships carry little ballast water while others such as bulk carriers and tankers transport tens of thousands of tonnes (Endresen et al. 2004).

Ballast water provides a vector for the transportation of harmful aquatic organisms throughout the whole world at a much greater rate than any other physical process. It is estimated that at least 7000 marine species are transported daily around the world either attached to the hull or entrained within the ballast tanks, comprising anything small enough to pass through the intakes and pumps. These species could be bacteria, microbes, as well as small invertebrates, eggs, cysts and larvae. The relatively few species that survive the journey can flourish when discharged to at a foreign location if there are no natural predators to control their population. These non indigenous species (NIS) cause ecological disturbance and damage the biodiversity. The impact of NIS is severe, mostly irreversible and financially detrimental. There are numerous of examples of serious aquatic bio invasions around the world and the International Maritime Organization (IMO) has published a list with the "ten most unwanted" organisms (Niimi 2004, Rigby and Hallegraff 1994).

The Eueopean Zebra mussel (*Dreissena polymorpha*) is native to the Black Sea but has been introduced to the Eastern half of North America where it has had a massive impact, infesting over 40% of the internal waterways. It fouls all available hard surfaces in high numbers, causing severe problems to ships and land based infrastructure including power stations where it blocks water intake pipes, sluices and irrigation ditches. It has also displaced native aquatic life, altering the ecosystems of the Great Lakes. Between 1989 and 2000 control measures are estimated to have cost US$1 billion. The Chinese mitten crab (*eiocheir sinensis*) a native to northern Asia, was introduced to Western Europe, the Baltic sea and to the West coast of North America. It experiences mass migrations for reproductive purposes and competition with native fishes and invertebrates has led to the local extinction of some species. Additionally the mitten crab burrows into riverbanks and dykes causing erosion and projecting silt into the water. Some cholera epidemics appear to be associated with the ballast water as well. In 1991, a cholera epidemic started simultaneously in three separate ports in Peru, swept across South America affecting more than a million people and killing more than ten thousand by 1994.

The problem of harmful aquatic organisms was first raised in the IMO in 1988 and since then the IMO has been working hard to address this problem. The IMO recognises that ballast water is indispensable for maritime trade and that the solution is to treat or manage the water itself. The International Convention for the Control and Management of Ships Ballast Water & Sediments was adopted by consensus at a Diplomatic Conference at IMO in London in 13th February 2004 and will enter into force 12 months after it is ratified by not less then 30 states with a combined total of not less than 35% of the World's fleet. As 31st October 2008 the IMO states that a total of 14 countries have ratified it representing 14.24% of the World's fleet (IMO 2008). However in its more detailed breakdown the IMO lists 15 countries, see Table 1. Other countries including Australia, Canada, New Zealand and USA require ships to manage their ballast water prior to discharging of ballast in their waters this includes mandatory requirements to exchange ballast.

Table 1. Countries listed by IMO that have ratified the Ballast Water Management Convention 2004 (IMO 2008)

Barbados	Norway
Egypt	St Kits and Nevis
Kenya	Sierra Leone
Kiribati	South Africa
Liberia	Spain
Maldives	Syrian Arab Republic
Mexico	Tuvalu
Nigeria	

There are two ways to deal with the contaminated ballast water; to perform ballast water exchange with mid ocean water or to treat the ballast water itself. The former is still the most effective practical method and is based on the fact that deep mid ocean water contains few organisms, and those taken from the coastal or fresh water environment will not survive in the ocean environment. The related BWC regulation B-4 Ballast Water Exchange mandates all ships whenever possible to conduct ballast water exchange at least 200 nautical miles from the nearest land and in water at least 200m deep. Under circumstances where this is not possible the ballast water exchange should take place as far as possible from the nearest land and in all cases at least 50 nautical miles from the nearest land and in water at least 200m deep.

Ballast water exchange currently provides the best available method to reduce the risk of transfer of NIS. It will be used until at least 2016 and maybe beyond because although many researchers are developing technologies for removal or destruction of NIS they are struggling with producing an effective, cheap, safe and reliable system that can be scaled up to deal with the massive volume and flow rates required.

Ballast water exchange and treatment

There are two methods of ballast water exchange either the flow-through or the sequential method (Wright and MacKey 2006). The flow-through method requires three volume changes of each ballast water tank to meet the standard described. If perfect mixing takes place within the entire tank then 95% of the original water will be removed. If there is a significant density difference then displacement flushing is more likely and the original water can theoretically be removed in a single volume exchange. In practice the flow within the tank is not uniform, different mixing mechanisms exist and the NIS distribution does not follow the water distribution or dispersion.

The sequential method uses the empty then refill approach. This process can remove most of the aquatic organisms with one volumetric exchange. It is a more hazardous procedure as it can compromise a ship's stability especially if done incorrectly. Incorrect ballast transfer is thought to be the case of the near capsize for he Cougar Ace. Emptying a ballast tank increases the shear stresses and bending moments and can place severe stress on the ship girder. The continuous flushing method requires mid ocean water to be pumped into the bottom of the ballast tank and allowing overflow through vent pipes (Armstrong 2007). This method is much safer than the sequential method but not as effective. The ballast tanks remain full, which eliminates concerns about the stability, stresses and fore/aft drafts. For new builds designs are being developed for ballast free ships (Kotinis et al. 2004).

STRUCTURE OF A BALLAST TANK

Dry bulk carriers, tankers and LNG carriers require large quantities of ballast water, primarily for unladen, return journeys. Bulk carriers account for 39% and tankers account for 37% of the global ballast water transported annually. Containerships, ferries, etc. generally require much smaller amounts of ballast water and account for the remaining 24%. Consider two examples;

- 138,500 DWT Cape size bulk carrier (length 266.5m, breadth 42.97m) normal ballast condition of 57,575m^3 This bulk carrier is equipped with two ballast pumps whose total capacity is 2500 m^3/hr.
- 250,267 DWT tanker (length 319m, breadth 54.5m) normal ballast water capacity of 99,578.6m^3). The ballast water tanks are large and have a simple box design. The pump capacity is 3000m^3/hr.

The shape and intricate internal geometry of the tanks is driven entirely by structural considerations of the vessel, customized for maximum cargo capacity and practicality. Ballast water tanks are typically divided into port and starboard tanks to reduce hydrodynamic instability due to roll. The interior design of a ballast tank is structurally complex and is composed of interconnected bays, longitudinal and transverse stringers and stiffeners, Fig. 1 shows the interior geometry of a typical ballast water tank.

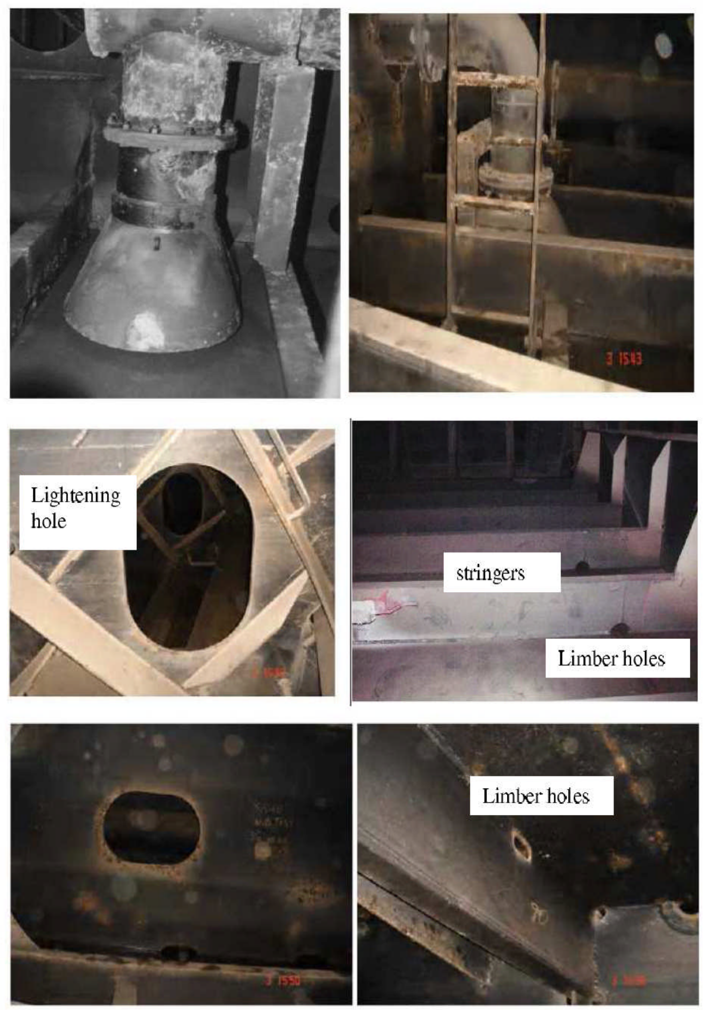

Figure 1: Photographs of the interior geometry of a ballast tank. Courtesy of Captain Galitopoulous (Brave Maritime Corp. Inc.).

SCIENTIFIC QUESTIONS

The introduction has given an overview of the importance of ballast water for marine trade and the steps being taken by industry in mitigating this problem. Although the continuous flushing mode will eventually be replaced, understanding the flow within tanks will still be necessary for the new technologies. Some of these treatments will not change the density of the ballast water (e.g. UV) but other technologies, including heat treatment, change the composition of the water and introduce density effects. So, both the current methodology and future technologies require a general insight into the types of flows generated and the efficiency of flushing.

Ballast tanks have complex internal geometries especially for large tankers. The larger tanks tend to have multi-compartments regions. The current approach is to use simple bulk diagnostics (such as the average concentration in the tank) or point measurements of dye concentration. A major problem here is the lack of a methodology for understanding inertial flows in complex interconnected spaces. In order to improve flushing technologies and to have an impact on the internal design of ballast tanks, it is necessary to understand how the concentration in each compartment changes with time.

The purpose of this paper is to examine

a) the effect of multi-compartments regions in a ballast tank

b) develop a methodology to study these issues

c) propose methods to improve flushing.

In this paper we do not consider the effect of density contrast which is discussed by Eames et al. (2007).

MATHEMATICAL MODEL

In the absence of a density contrast between the ballast water and that used to flush the tank, the high aspect ratio of the tank geometry (along the base and the vertical sections), meant that a bulk Peclet number (based on a turbulent diffusivity) was high (>100) so that the transport out of the tank was largely through displacement. This is because the front between the new and existing fluid (perpendicular to the mean flow) was much smaller than the overall distance from the source and exit. When density effects were present they tended to dominate the flow because the characteristic Froude number tended to be small. When denser fluid was pumped into a tank it tended to create displacement flushing where the dense fluid essentially filled up the tank from the bottom up, pushing out the lighter fluid. When light fluid was introduced, a gravity current was generated, bypassing most of the tank and leading to long flush times.

FLOW CHARACTERISTICS

The key bulk characteristics variables for exchange flows with no density contrast are the Reynolds number and Peclet number:

$$\mathrm{Re} = UH/\nu\ ,\ \mathrm{Pe} = UL/D_E, \tag{1}$$

where D_E is the turbulent diffusivity.

The volume flux into a ballast tank is Q. As we move further away from the pipe inlet, the mean flow decays quite quickly. Assuming typical values of $L \sim 100$m, $H \sim 2$m, $Q \sim 0.5$ - $1\mathrm{m}^3$. The mean flow near the jet is $\mathrm{Re}_J = (Q/\pi R)/\nu \sim 10^5$. Based on the closest compartments, $\mathrm{Re}_J = Q//H\nu \sim 10^6$. Up the riser section, $U \sim Q/(HL) \sim 0.01$m/s, so $\mathrm{Re} \sim 10^4$. The turbulent diffusivity scales as $D_E \sim UH$, so that $\mathrm{Pe} \sim L/H \sim 10$.

In trying to understand the effect of the three-dimensional nature of flow, we extend the analysis of Eames et al. (2007) to multiply connected compartments for displacement type flows.

Figure 2 shows a schematic of a general tank configuration, with one, four, nine and many interconnected compartments of the same size. The inlet is located at the bottom right-hand of the tank, while the outlet is at the left-hand side of the tank. In reality, some of the compartments are of different sizes and there may be multiple outlets. But to first develop a framework to understand these processes, we simplify the problem by considering compartments of the same shape and size with similar interconnecting holes.

We use the index notation $\{ij\}$ to denote the i horizontal compartment, j vertical compartment (see Fig. 2). The ballast tank has total volume V. The local concentration in the tank is C. It is useful to define average concentrations within each compartment and within the whole tank itself. The mean concentration in the whole tank is

$$\overline{C} = \frac{1}{V}\int_V C dV\ . \tag{2}$$

The mean concentration in the compartment $\{ij\}$ is

$$C_{ij} = \frac{1}{V_{ij}}\int_{V_{ij}} C dV\ . \tag{3}$$

When the compartments are all the same volume, the mean concentration is

$$\overline{C} = \frac{1}{\left(\sum_i 1\right)\left(\sum_j 1\right)}\sum_{ij} C_{ij}\ . \tag{4}$$

Fluid is pumped into the ballast tank with a volume flux Q. There are two relevant timescales, one associated with filling up the whole tank V/Q and the other for filling up individual compartments V_c/Q. The times and volume fluxes are normalised so that $\tau = 1$, corresponds to a compartment of volume V_c being filled by a flux Q, i.e. $\tau \sim tQ/V_c$. At $\tau = 0$, there is no dye in the tank and $C = 1$ corresponds to the tank filled uniformly with dyed fluid. The timescale for the whole tank to be flushed scales with NV_c/Q, where N is the number of connected compartments.

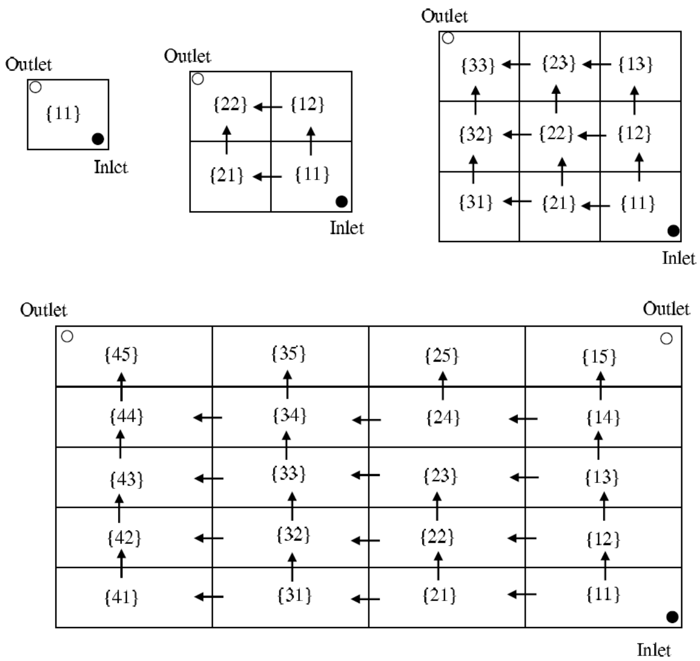

Figure 2: Schematic plan view showing the configurations analysed using a displacement and mixing model for $N = 1, 4, 9$ and 20. The twenty compartment arrangement is a schematic of the model ballast tank used in the experimental study. The inlet and outlet positions are indicated

DISPLACEMENT FLOWS

While the compartment volumes are the same, the location of the outlet and size of the interconnecting lightening holes affect the mean flow into each compartment, which will tend to fill at different rates. This is reflected in the analysis in terms of the fraction of the total volume flux entering each compartment and the connection with neighbouring tanks.

SINGLE COMPARTMENT

For the case of pure displacement from a tank with a single compartment, the mean concentration of dye in the tank increases at a constant rate, until it is filled. This is expressed mathematically as

$$\frac{dC_{11}}{d\tau} = 1, \qquad \max C_{11} = 1 . \tag{5}$$

The solution to this equation is

$$C_{11} = \tau \text{ , for } \tau < 1, \quad C_{11} = 1 \text{ for } \tau \geq 1 \quad . \tag{6}$$

The tank is clearly flushed through full of dye in one exchange volume.

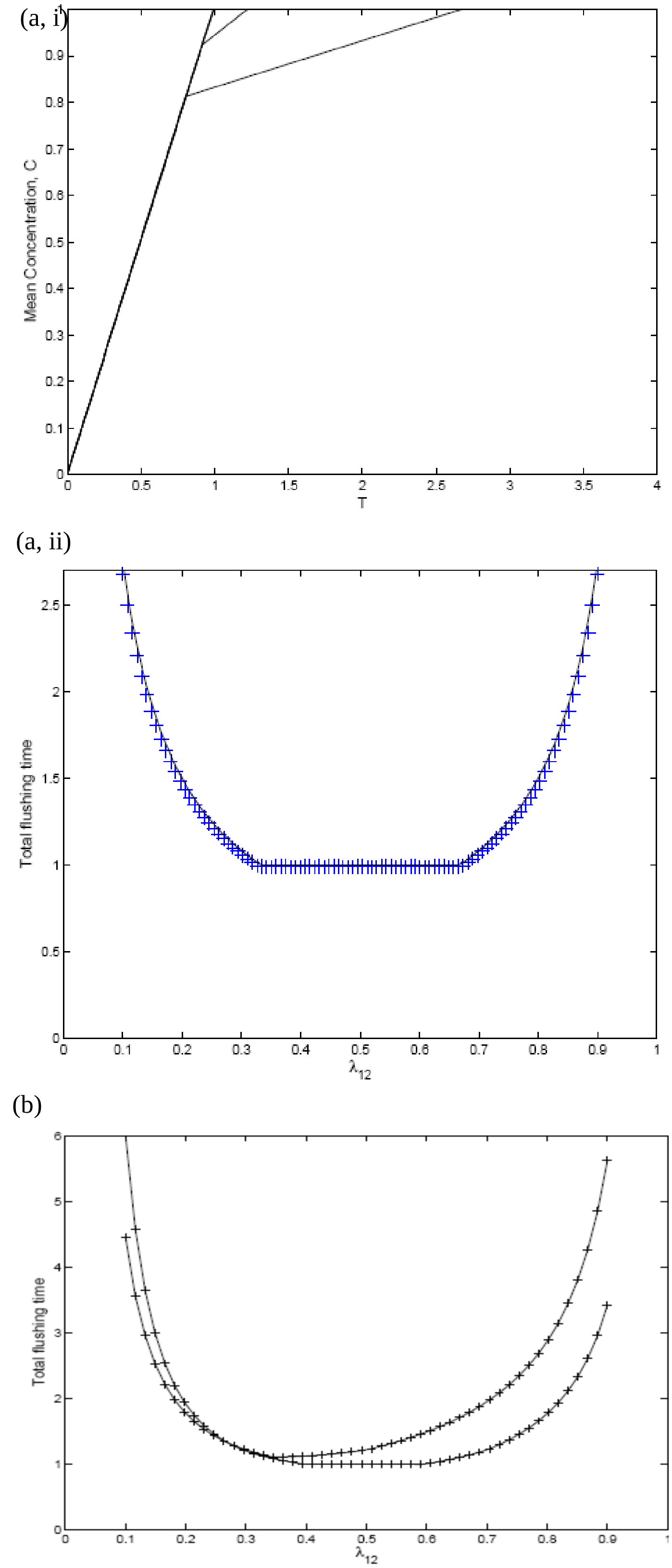

Figure 3: Flushing from a tank with (a) a two-by-two and (b) a three-by-three compartment arrangement.

FOUR COMPARTMENT TANK

Only when there is the possibility of flow bypassing different portions of the ballast tank the analysis does offer some interesting results. Consider four connected compartments, where the fraction of the inlet flow passing from {11} to {12} is λ_{12} and from {11} to {21} is λ_{21}. The system of equations describing the displacement flushing is

$$\frac{dC_{11}}{d\tau} = 1$$
$$\frac{dC_{12}}{d\tau} = \lambda_{12} H(C_{11} - 1) \quad (7)$$
$$\frac{dC_{21}}{d\tau} = \lambda_{21} H(C_{11} - 1)$$
$$\frac{dC_{22}}{d\tau} = \lambda_{12} H(C_{12} - 1) + \lambda_{21} H(C_{21} - 1) .$$

along with $\max_{ij} C_{ij} = 1$. (8)

$H(X)$ is the Heaviside-step function with the properties $H(X) = 0$ for $X < 0$ and 1 for $X \ge 0$. Mass conservation introduces an important integral constraint:

$$\lambda_{12} + \lambda_{21} = 1 . \quad (9)$$

Consider the case when $\lambda_{12} > \lambda_{21}$ or ($\lambda_{21} < 1$). Compartment {11} fills in time $\tau = 1$. Compartment {12} begins to fill at a faster rate than {12} and fills at time $1 + 1/\lambda_{12}$, before starting to fill compartment {22}. When $\lambda_{21} < 1/3$, compartment {22} is filled before compartment {21} and so the total time to fill the tank is $1 + 1/\lambda_{21} > 4$. When $1/3\lambda_{21} < 1/2$, compartment {21} is filled before compartment {22} and then goes on to contribute to filling {22}. The total filling time is then $\tau = 4$. By symmetry, for $1/2 < \lambda_{21} < 2/3$, the filling time is $\tau = 4$ (or $T = 1$), while for $2/3\lambda_{21} < 1$ it is $\tau = 1 + 1/(1 - \lambda_{21})$ or $T = 1/4 + 1/4(1 - \lambda_{21})$.

NINE COMPARTMENT TANK

By looking at nine-interconnected compartments, we can see how the general picture of multiply connected compartments is built up. The first three equations are given by (3-5) and supplemented by six further equations:

$$\frac{dC_{22}}{dt} = \lambda_{12} H(C_{12} - 1) + \lambda_{21} H(C_{21} - 1)$$
$$\frac{dC_{13}}{dt} = \lambda_{13} H(C_{12} - 1)$$
$$\frac{dC_{33}}{dt} = \lambda_{23} H(C_{23} - 1) + \lambda_{32} H(C_{32} - 1) \quad (10)$$
$$\frac{dC_{32}}{dt} = \lambda_{31} H(C_{31} - 1) + (\lambda_{32} - \lambda_{31}) H(C_{22} - 1)$$
$$\frac{dC_{22}}{dt} = (\lambda_{12} - \lambda_{13}) H(C_{21} - 1) + (\lambda_{21} - \lambda_{31}) H(C_{12} - 1)$$
$$\frac{dC_{23}}{dt} = \lambda_{13} H(C_{13} - 1) + (\lambda_{23} - \lambda_{13}) H(C_{22} - 1) .$$

in addition to the requirement that $\max_{ij} C_{ij}(t) = 1$.

Mass conservation requires an additional integral constraint

$$\lambda_{32} = 1 - \lambda_{23} . \quad (11)$$

For a tank of nine interconnected compartments, there are potentially nine unknowns. Using mass conservation reduces this to 2 x 3 - 1 = 5 relationships, giving four free constants. These integral relationships will be examined in more detail in the experimental study. To explore the types of solutions we obtain, we consider the asymmetric case of $\lambda_{32} = \lambda_{21}$, $\lambda_{23} = \lambda_{12}$, reducing the system down to two free parameters.

Time to fill half of {12} is given by $\tau_{12,1/2} = 1 + 1/2\lambda_{12}$, to fill half of {13} by $\tau_{13,1/2} = 1 + 1/\lambda_{12} + 1/2\lambda_{13}$.

EXPERIMENTAL SETUP

The aim was to study how the three-dimensional internal geometry of a ballast tank affects the mixing of the water with which the tank is flushed.

Design of model ballast tank

An acrylic model ballast tank was designed based on generic features of a double bottom and hopper tank from a bulk carrier, see Fig. 4. The key geometrical aspects are the horizontal section (double bottom tank), the turning section (hopper tank), internal geometry with longitudinal and transverse frames, the filling pipes and two overflow arrangements with fixed height. Stringers were not added to the geometry, although they will tend to enhance mixing with each tank. Two limber holes are added at the top and bottom of each interconnecting wall of width and depth 0.8cm.

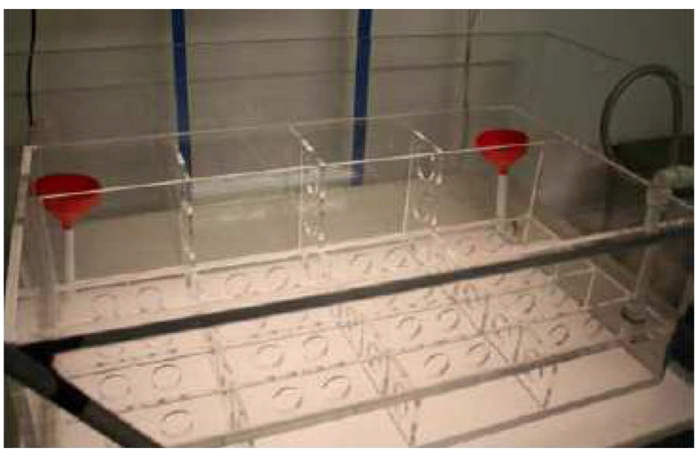

Figure 4: Photograph of the model ballast tank used in the experimental study.

The compartments have internal dimensions of 10cm by 25.8cm and height 10cm. The compartments are connected by circular holes of diameter 5cm, two on the long side and one on the short side. The turning section (hopper tank) consisted of three holes of diameter 8cm on the vertical axes and had a width of 13cm. The tank is of width 57cm, length 1.07m, height on the horizontal section of 10cm and 30cm on the turning section. The fluid was introduced through a 2cm diameter hole at the ceiling of the horizontal section. The overflow arrangements were two funnels fixed at 28cm connected with pipes leading to the outlet on the side base of the turning section. At this height, the model ballast tank has a total volume of 70 litres. Figure 4 shows a photograph of the experimental apparatus.

Experimental methodology

The model tank was filled at a rate $Q = 167\text{cm}^3/\text{s}$ through a vertical pipe of internal radius $R = 1\text{cm}$. This gives a jet Reynolds number of $\text{Re}_J \sim 10^3$ and is turbulent. The model facility is shown in Fig. 4 and was designed to support varying flow rates and two different filling lines; one from a header tank and one from a supply tank. The supply tank has a capacity of 400 litres. Before the flow-meter was fitted a tap to regulate the exit flow from two outlets and keep the flow constant.

The black food dye was mixed uniformly in the supply tank using a pump. A diffuse light source was placed below the model ballast tank and images were captured every 5 seconds using a Pulnix camera and Matrox image capture software. Captured images were filtered, masked and processed using Matlab's Image Processing Toolbox. A calibration test was undertaken by studying the fractional attenuation of images as a function of the total concentration of dye in a water column. The average dye concentration in each tank and in the whole tank was estimated.

EXPERIMENTAL OBSERVATIONS

The experimental variables are the relative flux through the two outlet pipes and the volume flux into the tank. To reduce the number of experimental variables, we fixed the volume flux Q into the tank to be 10 litres per minute.

Figures 5, 6 and 7 show the depth-averaged concentration field of the dye in each chamber for $T = 0.1$, 0.2, 0.41, 0.83 and 1.25 for the near exit open, the far exit open and both exits open respectively. The average concentration in the tank, $\overline{C}$ is shown as a function of T for the there cases in Fig. 8, the solid straight line is the case for ideal displacement flow and the solid curve for perfect mixing. In the absence of density effects, the high-aspect ratio tends to ensure that up until $T = 0.75$, that is when 75% of the tank is filled with dye, the undyed fluid is essentially pushed out, behaviour typical of displacement flow. This is because the mixed region has yet to exit the ballast tank. When both outlets are open (Fig. 7), the displacement mode occurs until $T = 0.80$. When the nearest outlet is open (and the furthest outlet is closed), the tail off in the mean concentration is largely due to the increased mixing and smaller flow in compartment {41}. The intermediate case is when the furthest exit is open, Fig. 6.

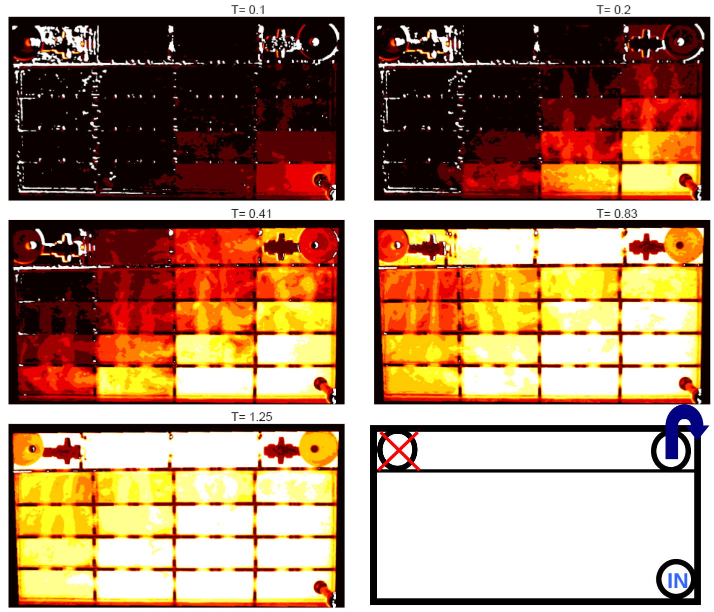

Figure 5: Concentration field for the case when the nearest exit is open. The images are for T = 0.1, 0.2, 0.41, 0.83 and 1.25.

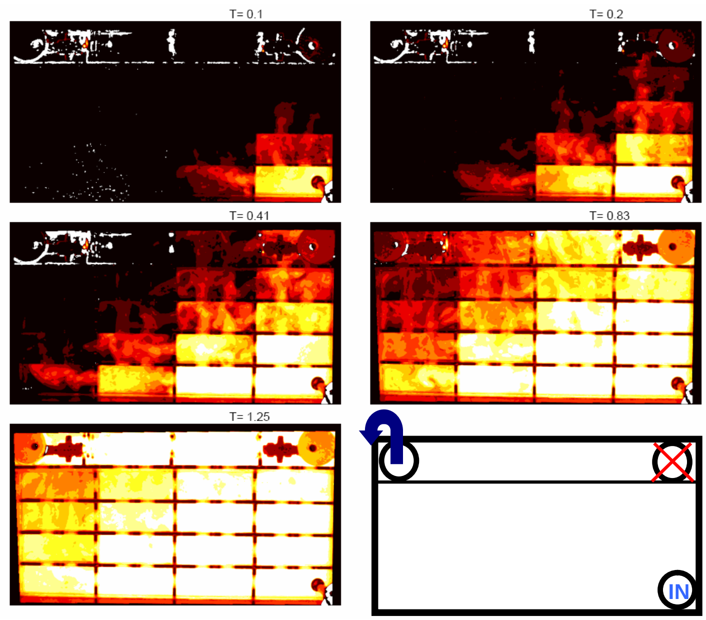

Figure 6: Concentration field for the case when the furthest exit is open. The images are for $T = 0.1$, 0.2, 0.41, 0.83 and 1.25.

More information can be extracted by studying the concentration in each of the separate compartments. The mean concentration in each compartment $\overline{C}_{ij}$ was determined by masking off individual compartments and analysing, from above, how a diffuse light source passing through the tank was attenuated. From each time sequence, we determined $T_{1/2}$ the time when the concentration reached half the maximum (corresponding to fully filled with a homogeneous body of dyed fluid). In order to relate the measurements with the displacement model, we also applied a linear fit to the data in the region $0.4 < \overline{C}_{ij} < 0.6$. The fitting line was

$$\overline{C}_{ij,\,fit} = 0.5 + (T - T_{1/2})\alpha_{ij}\,. \qquad (12)$$

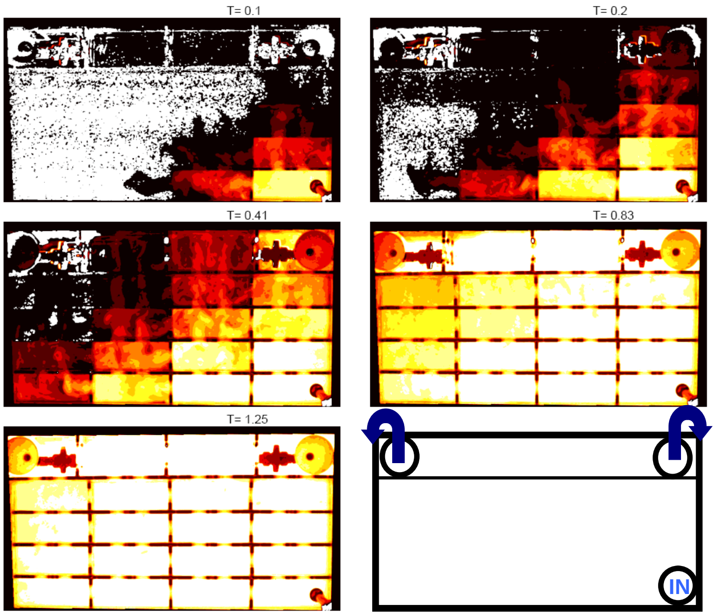

Figure 7: Concentration field for the case when both exits are open. The images are for T = 0.1, 0.2, 0.41, 0.83 and 1.25.

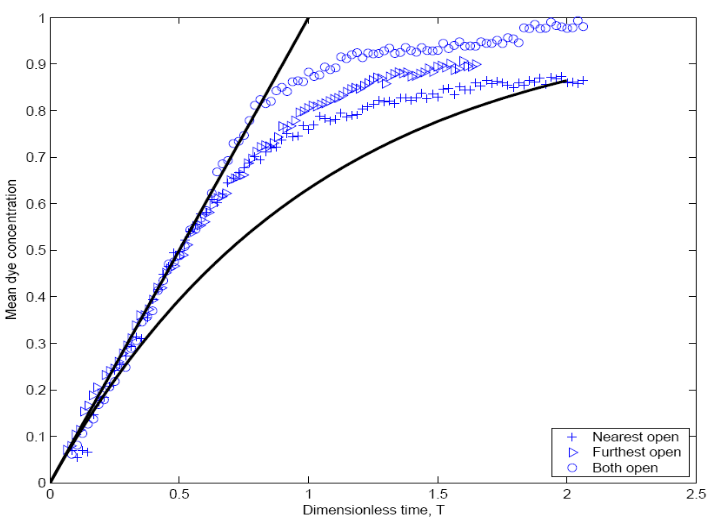

Figure 8: Mean concentration in the entire tank for (a) furthest exit open, (b) closest exit open, and (c) both exits open.

For perfect displacement, the parameter α_{ij} gives the approximate rate at which fluid enters the compartment and corresponds to λ_{ij}.

Figure 9i shows how the concentration in each compartment varies as a function of time while column (ii) in Fig. 9 shows α_{ij} plotted against $T_{1/2}$. The data for {11} is not included. When the furthest outlet is closed, the majority of the flow by-passes the left-hand side of the tank, so that the rates of flushing are significantly reduced to about 10% of the mean tank flow. When the furthest outlet is open, the rate of flushing through the left-hand side of the tank is increased, as can be seen in the general increase in α_{ij} in these regions. When both outlets are open, the values of α_{ij} in the top row of compartments have broadly similar values.

In the inlet tank, since dyed fluid is being introduced at a constant rate, $\alpha_{ij} = 1$ and the half-time flushing is $T_{1/2} \sim 2/70$. In the adjacent compartments {12} and {21}, when the flow is evenly split between them, so that $\alpha_{12} \sim \alpha_{21} \sim 0.50$ (i.e. $\lambda_{12} \sim \lambda_{21} \sim 0.50$). This is clearly seen in all the graphs. For the furthest outlet open, we would expect the flow to broadly advect the dye towards the outlet, though there is a flow along the right-hand side wall and passes into the larger chamber. For this case, we would expect $\alpha_{31} \sim \alpha_{22} \sim \alpha_{13} \sim 0.25$ and α_{14} etc. to have values of ~ 0.125. Again, this is broadly confirmed by Fig. 9(bii). When both outlets are open, the flow tends to be long the bottom row of compartments and then vertically towards the larger compartment. If the majority of the flow in compartments {14} to {44} is towards the vertical turning section, then $\sum_{i=1}^{4} \alpha_{i4} = 1$ and $\alpha_{i4} = 0.25$. Again, this is broadly seen, with the rates of flushing in all the compartments (except {11}, {21} and {12}) to be of similar orders of magnitude.

CONCLUSIONS

In this paper we have reviewed the current and future guidelines which are being developed by the IMO for the removal of contaminants from ballast water tanks. The complex structural considerations and general geometry of ballast tanks has been described.

Both the mathematical models and experiments in this paper focused on when the injected water and initial ballast water had the same density. The mathematical models we have developed for displacement spreading in multiple interconnected compartments in a ballast tank shows that for a small number of compartments, the contaminated water is displaced by clean fluid with slightly more than one exchange volume even when the exchange coefficient between different compartments is not symmetrical. However, for large number of compartments, bypassing will occur, requiring more than one exchange volume.

The laboratory study employed a model ballast tank with twenty compartments and lightening and limber holes, and used a light attenuation technique to assess the average concentration of dye in each compartment. We examined the broad influence of varying the fraction of discharge from two asymmetrically placed exits, with water either leaving at a nearby outlet, an outlet placed diametrically opposite, or with water leaving from both outlets. The experimental results show that when both outlets were open, 90% of the total contamination was removed in one exchange volume. But when only the nearest outlet was open, significant by-passing occurred with a reduction in the efficiency of flushing. Even with the recommended three exchange volumes, a significant fraction of the initial contaminant remained. These results were interpreted both in terms of the mean concentration in the entire tank, Fig. 8 and the rate of loss of dye from each compartment, Fig. 9.

The main conclusions from this study are that the placement of the outlets has a crucial effect on the efficiency of mixing and that their location must be considered when designing ballast tanks. The results presented here did not consider density effects and these could have significant impacts of the efficiency of removal of the original fluid especially if less dense fluid is injected into ballast tanks. This is an area currently under investigation. This research shows that structural considerations, changes in density (due to the method of purification, which might involve heating) must both be considered. Our future task will be to combine this information to assist in developing rational protocols for cleaning ballast water.

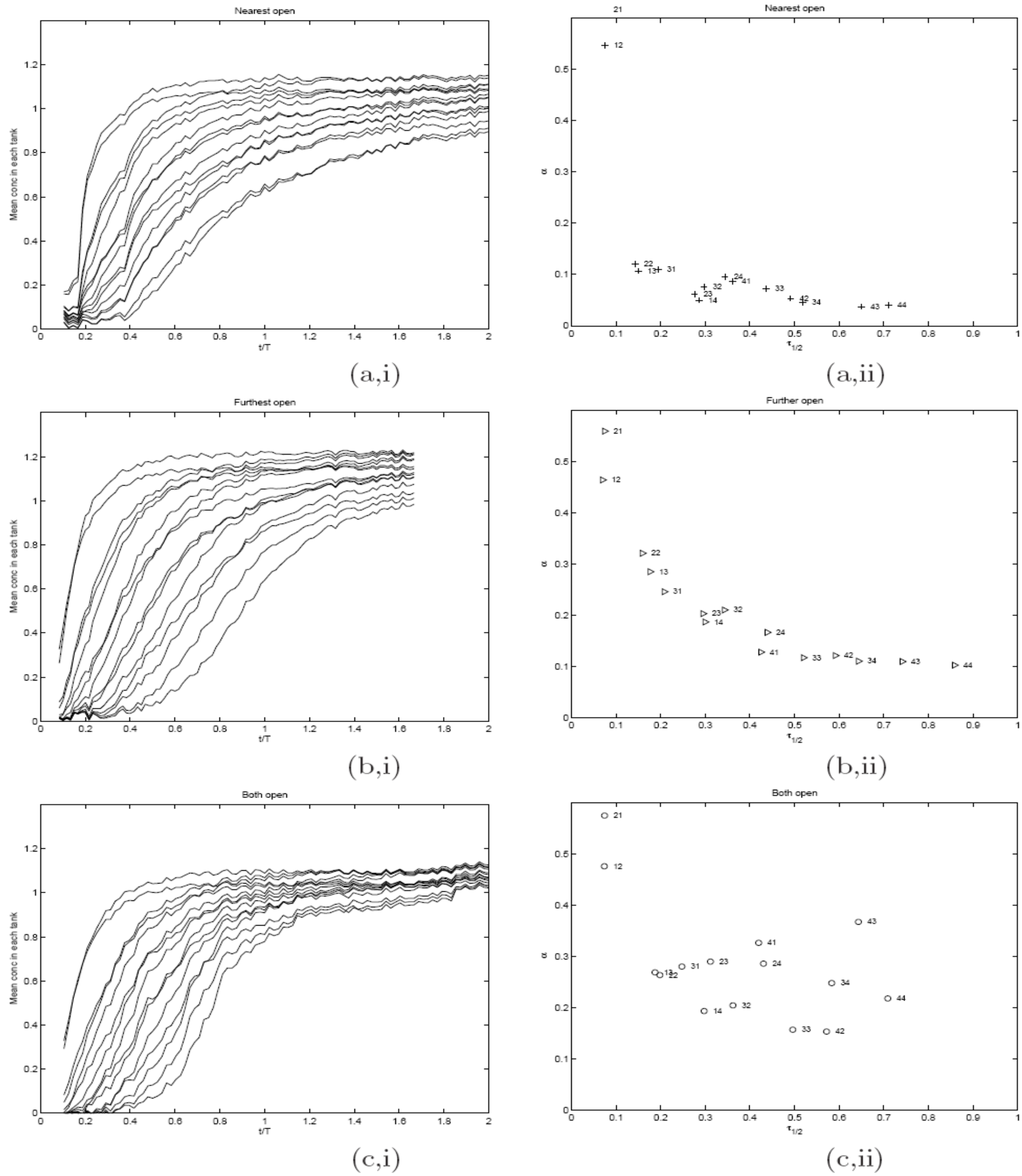

Figure 9: The results in (a), (b) and (c) correspond to the results from the 15 compartments ({1,1} excluded) when the nearest exit is open, the furthest exit is open and both are open. (i) and (ii) correspond to the mean concentration in each compartment versus time t/T and the rate of increase in the mean concentration α_{ij} defined in the text and the time to fill the half the compartment $T_{1/2}$.

REFERENCES

Armstrong, G. 2007 Ballast system design for flow-through exchange of ballast water; Trans IMarE, Vol 109, 257-269.

Eames, I., Landeryou, M., Greig, A. & Snellings, J. 2007 Continuous flushing of contaminants from ballast water tanks. Marine Pollution Bulletin. 56, 250-260

Endresen, O., Behrens, H.L., Brynestad, S., Andersen, A.B. & Skjong, R. 2004 Challenges in global ballast water management. Marine Pollution Bulletin. 48, 615-623.

IMO 2008. www.IMO.org, status of conventions by country.

Kontinis, M., Parsons, M. G., Lamb T. and Sirviente A. 2004 Development and investigation of the ballast-free ship concept. Trans SNAME **112** pp. 206-240.

Niimi, AJ. 2004 Role of container vessel in the introduction of exotic species. Marine Pollution Bulletin. 49, 778-782.

Rigby, G.R. & Hallegraeff, G.M. 1994 The transfer and control of harmful marine organisms in shipping ballast water: behaviour of marine plankton and ballast water exchange on the MV "Iron Whyalla"; J. Marine Env. Eng. 1: 91-110; 1994

Wilson, W., Chang, P., Verosto, S. Atsavapranee, P., Reid, D.F. Jenkins, P.T. 2006 Computational and experimental analysis of ballast water exchange; Naval Engineers Journal.118, 25-36.

Wright, D.A., & Mackey, T.P. 2006 Shipboard and dockside trials of ballast water treatment technology. Naval Engineers Journal. 118, 37-43.