Design of shell and tube heat exchanger for ballast water treatment applications on ships based on simulation

A Iswantoro, Semin , T Pitana , M B Zaman
Department of Marine Engineering, Marine Power Plant Laboratory, ITS Surabaya, Indonesia

Abstract. Now, environmental issues are the mostly discussed issue and become a top priority in the world. Whether it's environmental damage or environmental pollution. The issue of pollution and damage to the environment and ecology in the region, which have an impact on living organisms, both humans, animals and plants. Environmental damage and pollution can occur on land, water, and air. With various forms of damage and pollution, the methods of handling are different. This research will focus on damage and pollution in waters as well as methods of handling and prevention, especially in marine waters. This research focuses on designing a heat exchanger by varying its types, namely shell and tube heat exchanger. From the modification of model, it will be known which one is more effective in performance. Both temperature exchange, pressure drop, flow rates, dimensions and materials are simulated by software. Where these parameters are influenced by the characteristics of the ship's power of main engine. From 2 model of shell and tube heat exchanger that are one pass-shell and two pass-shell the result for case 1 the effectiveness are 92% & 93%, case 2 are 93% & 94% and case 3 are 94% & 95%.

1. Introduction
Environment issues are mostly discussed issue and a top priority in many countries. The issue of pollution and damage to the environment and ecology in the region, which have an impact on living organisms. Ballast water in the world have become a major cause an ecological imbalance. The International Maritime Organization (IMO) has been actively taking regulated steps to minimize species moved, by adopting the International Convention for Ballast Water Management and Sediments Control in 2004.

1.1 Water Ballast Treatment
In research on ballast water treatment using heat, or thermal treatment, several have been done. As has been done by R. Balaji and O. Yaakob in 2011 with a case study research on the application of Ballast Water Treatment on MT vessels. Bunga Kasturi with engine power of 25090 kW by utilizing heat from the main engine and from a generator with a power of 1020 kW x 3 sets. Resulting in research, the total heat recoverable is 16924.59 kW during sailing. Total heat available 43844.39 kW (unloading). Total heat available 7453.4 kW (loading). [1]
The research was developed in 2014 by R. Balaji and O. Yaakob. One treatment method is heat, which sterilizes ballast water from marine species. Systems that utilize waste heat from ships will provide an economic solution for ballast water treatment. Based on the analysis of waste heat available on existing crude oil tankers, although heat availability is visible, complementary treatment methods are required for high volume treatment. So, combined filtering and heating systems can be combined. Seawater circulating as secondary coolant in the engine is filtered and heated by taking heat from the engine system, rejection steam and exhaust gases. The planned system is a combination of taking heat from multiple sources on board and filtering can be optimized. By considering the components in the
system, it can be ascertained that the specific processes associated with each of them (i.e., heat exchangers and filters) for species mortality/isolation can be carried out. [2]

Then another research, namely the use and utilization of heat from machines to kill microorganisms based on tests and IMO requirements conducted by R. Balaji and O. Yaakob in 2015 resulted in an average heat recovery from exhaust gases, namely between 15% to 33% of the input energy. Tests on species showed >95% will die (mortality) in the temperature range 55°C to 75°C. [3]

R. Balaji and O. Yaakob then began to conduct research on the design of a heat exchanger to be more optimal in the ballast water heating process in 2017. Optimization of the heating design, using engine exhaust gas as a uid fluid, and ballast water as a uid process, was achieved by using the Lagrangian method, the annual cost is an objective function. Limiting the number of variables, the optimal value is calculated by considering the cost for the utility fluid. In total, four optimal designs and three comparative designs were developed. Heat balance data of the tanker, specific fuel consumption values and fuel costs are considered design variables. Designs are compared based on annual costs, optimal exit temperature and optimal mass from the side of the heat exchanger. The heater design for ballast water treatment uses flue gas for the purpose of retrieving waste heat for ballast water treatment, scope for further improvement includes shell and tube side udfs and tubular finned heat exchanger design. The availability and flow limitations of heat depend on the type of vessel, and designs can be worked on for other types of vessels. The increased realization of waste heat will provide a competitive advantage for heat treatment methods, not only in cost but also in increasing the treatment potential of the system. [4]

Research was continued in 2017 by R. Balaji and O. Yaakob regarding the use of heat for ballast water treatment, namely the utilization of waste heat from ship engines as a potential source for heating ballast water. Similar to the schematic arrangement of a ship, a laboratory-scale heat exchanger collects waste heat from jacket water and exhaust gases to test mortality rates for marine species. The result is that mortality is in the range of 80-95% for phytoplankton, zooplankton and bacteria, which can be achieved by maintaining a temperature of 60–65°C for 60 seconds. In addition, the effect of centrifugal pump impellers can also increase the mortality of some species. [5]

After that in 2018 by R. Balaji and O. Yaakob regarding the economic level of heat utilization from the main engine, the utilization of waste heat from ship engines could be a potential source for heating ballast water. Similar to the schematic arrangement of a ship, a laboratory scale heat-engine exchanger that collects waste heat from jacket water and exhaust gases to test species mortality rates. Heat treatment is proven to increase mortality in microorganisms and is more economical because it can save costs. [6]

1.2. Microorganism on Water Ballast

In the 1897, biologists had shown that marine plankton (deep-drifting organisms, most of which are microscopic) could pass through pumps into ships’ seawater systems and survive. In 1908 it was reported that in Asia in the North Sea and northern Europe there was an invasion by Chinese mitten crabs believed to be the result of discharging ballast water. It wasn't until the 1970s that scientists began directly sampling the organisms in the ballast water. Many studies have shown that ballast tanks usually contain many species of animals, plants, protozoa, bacteria and viruses, even in quite large numbers. [7]

Small planktonic organisms can be easily pumped in and out of the ballast tank. Plankton can be characterized as holoplankton, meroplankton or tychoplankton. Holoplankton spend their entire life floating in water, and include a variety of bacteria, protozoa, unicellular plants (phytoplankton), and small animals (zooplankton). The latter mainly consist of copepods, mysid shrimp, arrowworms and comb jellies in brine, water fleas and rotifers in freshwater. Meroplankton spend part of their life cycle drifting away in plankton, and include the larvae or eggs of various worms, shellfish, snails, crabs, starfish, fish, and other organisms. Tychoplankton are organisms that usually live on the bottom. Certain other organisms which in the narrow sense are not planktonic can be associated with planktonic hosts, such as certain viruses and nematodes, parasites and flatworms. In addition, some organisms that are non-planktonic in nature can be brought into a ballast tank attached or attached to
wood chips or other floating debris, and small fish or shrimp can be carried in through the ballast channel, shown in table 1. [7]

| No. | Location & year | Results |
|-----|-----------------|---------|
| 1   | Australia 1973  | Plankton sampled in 1 ship from Japan included polychaetes, copepods, amphipods, ostracods and chaetognaths (Medcof 1975). |
| 2   | Australia 1976-1978 | Plankton and fish in 23 woodchip carriers from 13 Japanese ports included 61 species; most common were copepods, molluscs, larvaceans and barnacles. Sediments from 9 woodchip carriers from 7 Japanese ports yielded 32 crustaceans and polychaetes (Williams et al. 1988). |
| 3   | Montreal and St. Lawrence River 1980 | Plankton samples from 46 ships that had ballasted outside the northwest Atlantic included 132 phytoplankton, 7 protist and 35 invertebrate species (Bio-Environmental Services 1981) |
| 4   | North Atlantic 1981 | Australia 1981 |
|     | Identified 4 fish and reported mysids in ballast water of a domestic bulk carrier (Middleton 1982). |
| 5   | Coos Bay, OR 1986-1991 | Plankton samples from 159 woodchip carriers from 25 Japanese ports included 402 species in 24 animal, plant and protist phyla, with the most common being copepods, diatoms, polychaetes, barnacles, molluscs and flatworms (Carlton & Geller 1993; Pierce et al. 1997) |
| 6   | Australia 1987-1993 | Sediment from ballasted cargo holds in 12 Japanese woodchip carriers arriving in Tasmania in 1987-88 yielded 56 phytoplankton species, including abundant diatoms in 4 ships and dinoflagellate cysts in 7 ships (Hallegraeff et al. 1990). Sediments from 31 out of 83 mainly Japanese woodchip, wheat and ore carriers arriving in Australia in 1987-89 (including the 12 already mentioned) contained dinoflagellate cysts, with toxic species in 4 ships (Hallegraeff & Bolch 1991). 343 ships were sampled by 1990, with sampling continuing through at least 1993 (Hallegraeff & Bolch 1992). |
| 7   | Great Lakes and upper St. Lawrence River 1990-1991 Japan 1991 | Plankton samples from 86 ships included 110 species of zooplankton in 11 phyla, mainly copepods, cladocerans and rotifers; and 100 species of bacteria, phytoplankton and protists, mainly diatoms and dinoflagellates including 21 bloom-forming, red tide and/or toxic species (Locke et al. 1991, 1993; Subba Rao et al. 1994). |
| 8   | Washington state 1991 | Samples from 6 Japanese woodchip carriers arriving at Tacoma and Port Angeles in 1991 yielded 21 species of phytoplankton and protists from incubated sediments; and at least 8 orders of organisms in ballast water from 3 ships (Kelly 1992, 1993). |
|     | Gulf of Mexico | Ballast water samples in 5 of 19 ships yielded Vibrio cholerae, which genetic analysis found to be identical to the strain responsible for the 1991 South American cholera epidemic and found in oysters in Mobile Bay, Alabama (McCarthy & Khambaty 1994). |
|     | Germany 1992-1995 | Plankton sampled in 189 ships, along with organisms in sediment, fouling organisms on tank walls, and larger crabs and fish where possible, included over 350 species, mainly unicellular algae, |
copepods, other crustaceans and molluscs (Gollasch et al., in press).

| Year | Location | Samples/Findings |
|------|----------|------------------|
| 1993-1994 | Chesapeake Bay | Plankton net, whole and bottom water samples in 70 ships from foreign ports yielded 275 plant, protist & animal species; and 4 species in sediment from 5 ships (Smith et al. 1996). |
| 1994-1995 | Hong Kong | Plankton samples from 5 ships from both sides of the North Pacific included 82 species of invertebrates and protists, with copepods being the most common (Chu et al. 1997). |
| 1994-1995 | Scotland | Plankton sampled from 32 ships and sediment from 24 ships yielded dinoflagellates, diatoms and other organisms. This study is ongoing (Macdonald, in press). |
| 1995 | Baltimore, MD | Plankton samples from 1 coal carrier from Israel yielded 23 species of dinoflagellates and invertebrates, numerically dominated by copepods, bivalves, polychaetes and gastropods (Wonham et al. 1996). |
| 1995-1997 | New Zealand | Plankton and bottom water samples from tanks with foreign ballast water in 50 container ships, bulk carriers and break bulk carriers arriving at Lyttelton and Nelson yielded live phytoplankton in 80% of tanks, dominated by diatoms, heterotrophic flagellates and dinoflagellates, and live invertebrates in 83% of tanks with arthropods, molluscs and annelids occurring most frequently (Hay et al. 1997). |
| 1996 | Valdez, AK | Plankton from 16 domestic and 1 foreign oil tanker included 68 taxa (Ruiz & Hines 1997). Cultured ballast water and sediment samples from 17 ships yielded at least 198 heterotrophs (reported as flagellate, pseudopodial and ciliate forms), plus diatoms, cnidarians, turbellarians, nematodes, rotifers, gastrotrichs, polychaetes and copepods (Galil & Hülsmann 1997). |
| 1996 | Israel | Studies are under way or being undertaken in Chesapeake Bay, Long Island Sound, the Port of Morehead City in North Carolina, the Port of Long Beach in California, the Port of Honolulu in Hawaii, the Gulf of St. Lawrence, British Columbia, Sweden and Wales (Gauthier & Steel 1996; Walton & Crowder, 1998; Eldredge 1998; J Carlton, pers. comm.). |

1.3. Ballast Water Treatment Method

From year to year, ballast water treatment technology has developed and many kinds. Related companies have even carried out mass production to meet market needs. Figure 1 below are the methods and technology as well as the manufacturers of ballast water treatment equipment.[8]

![Ballast Water Treatment Method](image-url)

**Figure 1.** Ballast water treatment method
In this research, ballast water treatment will be carried out using heat, so that it is included in the mechanical method category. Table 2 below are some references obtained from previous research. [9][10]

| Method                  | Capacity       | Microorganism              | Effectiveness |
|-------------------------|----------------|----------------------------|---------------|
| UV                      | NR*            | *Gymnodinium* sp.          | <6%           |
|                         |                | *Alexandrium* sp           |               |
|                         |                | *Chattonella* sp           | <40%          |
| UV                      | 2 m³ h⁻¹       | Chlorella                  | 87%           |
| UV                      | 0.2 – 1.6 m³ h⁻¹| Various                   | 78 – 100%     |
| UV                      | NR*            | Phytoplankton              | 40 – 99%      |
|                         |                | Zooplankton                |               |
|                         |                | Bacteria                   |               |
| UV/hydrocyclone         | 312 – 350 m³ h⁻¹| Phytoplankton             | >85%          |
|                         |                | Zooplankton                |               |
|                         |                | Bacteria                   |               |
| UV                      | Regal Princess | *Artemia salina*          | 99.50%        |
|                         | (100 – 3000 m³ h⁻¹)| *Dinoflagellate Prorocentrum* | 84.70%       |
|                         |                | *Tetraselmis* sp           | 87.60%        |
| UV/Filtration           | Vessel Coral Princess (NR*) | Phytoplankton     | >70%          |
|                         |                | Zooplankton                |               |
|                         |                | Bacteria                   |               |
| Heat                    | Iron Whyalla vessel | Phytoplankton           | >98%          |
|                         | (50,000 of ballast water) | Zooplankton            |               |
|                         |                | Bacteria                   |               |
| Heat                    | Various tests  | Phytoplankton              | >99%          |
|                         |                | Zooplankton                |               |
|                         |                | Bacteria                   |               |
| Heat                    | 85 L min⁻¹     | Zooplankton                | 90%           |
|                         |                | Bacteria                   | 95%           |
| Heat Microwave          | 1 – 2 L min⁻¹  | Microalgae                 | Complete inactivation |
|                         | (Nannochloropsis oculata) | *Oyster larvae*     |               |
|                         |                | (Crassostrea virginica)    |               |
| Heat Microwave          | 1 – 2 L min⁻¹  | *Artemia* cysts            | 100%          |
| Heat Ultrasound         |                | *Artemia salina*          |               |
|                         |                | larvae stage               | 100%          |
|                         |                | adults                     | 85%           |
|                         |                | cysts                      | 60%           |
|                         |                | *Dunaliella tertiolecta*   | 40%           |
2. Methods

2.1 Literature review and collecting data
Problem identification is carried out based on problems that occur in the field, in this case, the problem of pollution due to ballast water. Then from this problem then conduct a literature study and data collection. With the aim of obtaining basic knowledge and data from previous studies that can be used as a reference for further research. At this stage, a study of references contained in papers, journals, proceeding, conferences and supporting books is carried out. The collection of various kinds of references serves to strengthen the theoretical basis of thermal ballast water treatment.

2.2 Heat exchanger modeling
The next step after conducting a literature study and gap analysis is to model the heat exchanger with the collected data. Data related to ship engine power and ship speed, this data is used for the input of heat exchanger modeling, so that it will be seen which heat exchanger has the best performance.

2.3 Heat exchanger simulation
After the calculation and modeling process has been carried out, a simulation can be performed. Simulations are carried out based on the data obtained and mathematical calculations.

2.4 Data analysis
The final step is to analyze the result data from heat exchanger modeling. The variable of concern is the performance of the heat exchanger based on thermal efficiency and pressure drop.

3. Results and Discussion
Before doing modeling, there are several things that need to be done first, namely the simulation design. In this case there are 2 calculations, that are for one pass-shell and two pass-shell. Calculation for energy conservation and heat transfer rate equation:

\[ q = C_k (t_{h,i} - t_{h,o}) = C_c (t_{c,o} - t_{c,i}) \]  \hspace{1cm} (1)

\[ q = UA\Delta t_m = \frac{\Delta t_m}{R_o} \]  \hspace{1cm} (2)

Where:
- \( \Delta t_m \): true mean temperature difference (MTD)
- \( C_c \): capacity rate of cold fluid
- \( C_h \): capacity rate of hot fluid
- \( t_{ci} \& t_{co} \): cold fluid terminal temperature (in & out)
- \( t_{hi} \& t_{ho} \): hot fluid terminal temperature (in & out)
- \( R_o \): overall thermal resistance

The overall energy balance for any two-fluid heat exchanger is given by:

\[ m_h c_{p,h} (t_{h,i} - t_{h,o}) = m_c c_{p,c} (t_{c,o} - t_{c,i}) \]  \hspace{1cm} (3)

Where:
- \( m_h \& m_c \): mass flow rate of fluid
- \( c_{p,h} \& c_{p,c} \): heat capacity of fluid

The expression for maximum possible heat transfer rate \( q_{max} \) is:

\[ q_{max} = C_{min} (t_{h,i} - t_{c,i}) \]  \hspace{1cm} (4)

The total of heat transfer rate from hot to cold fluid is:

\[ q = \varepsilon C_{min} (t_{h,i} - t_{c,i}) \]  \hspace{1cm} (5)
Where:

\( \varepsilon \) : heat exchanger effectiveness

\( C^* \) : heat capacity ratio

\( \text{NTU} \) : number of transfer unit

Whereas the following is a formula for finding the Log mean temperature difference:

\[
\text{LMTD} = \Delta t_{\text{lm}} = \frac{\Delta t_1 - \Delta t_2}{\ln(\Delta t_1 / \Delta t_2)}
\]  

Based on calculation and simulation can be the following results were obtained.

For case 1: the power of engine 1000 kW for one pass-shell & two pass-shell:

For case 2: the power of engine 2000 kW for one pass-shell & two pass-shell:

![Figure 2](image1.png)

(a) result for one pass-shell, (b) result for two pass-shell

![Figure 3](image2.png)

(a) result for one pass-shell, (b) result for two pass-shell
For case 3: the power of engine 3000 kW for one pass-shell & two pass-shell:

4. Conclusion
Based on calculation and simulation, can be take conclusion that:

One pass-shell
With an engine power of around 1000 kW, to get effectiveness 92%, the dimensions of the length of the heat exchanger are 4 meters with 150 tubes. With an engine power of around 2000 kW, to get an effectiveness 93%, the dimensions of the length of the heat exchanger are 5 meters with 150 tubes. With an engine power of around 3000 kW, to get effectiveness 94%, the dimensions of the length of the heat exchanger are 6 meters with 150 tubes.

Two pass-shell
With an engine power of around 1000 kW, to get effectiveness 93%, the dimensions of the length of the heat exchanger are 4 meters with 150 tubes. With an engine power of around 2000 kW, to get an effectiveness 94%, the dimensions of the length of the heat exchanger are 5 meters with 150 tubes. With an engine power of around 3000 kW, to get effectiveness 95%, the dimensions of the length of the heat exchanger are 6 meters with 150 tubes.

5. References
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