Systems Approach For Effective Control Of GHG Discharge From Sea Transportation

Eiichi NISHIKAWA

Professor Emeritus of Kobe University of Mercantile Marine
(Home address) Fuseya 4-3-22, Izumi, Osaka 594-0031, Japan
e-nishikawa@dab.hi-ho.ne.jp

Makoto UCHIDA
Faculty of Maritime Sciences of Kobe University

ABSTRACT

The concentration of green house gas (GHG) in the global atmosphere is continuously increasing year by year, and the control of anthropogenic GHG discharge is becoming a very significant problem for the human world. The Kyoto Protocol adopted by UNFCCC/COP3 requires IMO to make a GHG emission control plan of international sea transportation by 2005. This paper studies on some key issues such as emission index, control target, technological measures for CO_2 emission control, etc. from the viewpoint of systems approach. The study indicates that emission factor EF, which is defined as the CO_2 emission amount per unit transportation quantity, is appropriate for indexing the emission from ship. Regarding the emission control plan, the paper investigates some important issues from both technological and institutional aspects. The paper derives some useful formulas for EF, which represent clearly the effects of each component composing the ship system on EF. Those equations could be used for carrying out research and development systematically and effectively in order to improve the EF.

1. Introduction

The concentration of green house gas (GHG) in the global atmosphere is continuously increasing year by year, and the control of GHG anthropogenic discharge is becoming a very significant problem for the human world. As well known, the Kyoto Protocol, which has been adopted by COP3 in 1995, and is the first international plan of GHG discharge control Though the Kyoto Protocol is not yet put in force at the present of July 2004, it is the most important international plan for GHG discharge control intending to reduce the GHG discharge quantity by 6% compared to the quantity of 1990 by the commitment period from 2008 to 2012. As for the GHG discharge from the international sea transportation, the Kyoto Protocol requires IMO to make an international control plan by 2005. The IMO/MEPC, therefore, is now carrying out the investigation in the working group specially organized for this task.

[Note] COP: The conference of the parties. The parties are the nations who have signed the United Nations Framework Convention of Climate Change (UNFCCC), which has been adopted at the Rio-Summit in 1992. The COP has being held every year since 1993. The COP3 is the 3rd session of COP held in Kyoto, Japan.

In advance of GHG control, the NOx and SO_2 emission regulation is going to enter in force (19 May 2005) by the IMO MARPOL73/78 ANNEX VI. The GHG control, especially CO_2 control, however, would be more serious compared to the SO_2 and/or NOx control. Because, in the case of CO_2 emission control, there would be no measure but to reduce fuel consumption so far as ships are dependent on fossil fuels. In order to respond the CO_2 problem, therefore, it is needed to construct an international plan based on the integrated technological measures from the viewpoint of total system.

The Kyoto Protocol has designated six materials of CO_2, CH_4, N_2O, hydro fluorocarbons (HFCs), per fluorocarbons (PFCs), sulphur hexafluoride (SF_6) as the GHGs. In the case of GHGs discharged from ships, CO_2 has the overwhelming contribution compared to the rest as seen in Table 1. This study focuses, therefore, its attention on the CO_2 discharge, and firstly investigates various factors which influence the CO_2 discharge of sea transportation system. Based on this investigation, secondly, some key issues of technology and institution for CO_2 are considered from the viewpoint of total system.

Table 1 Contribution of each GHG discharged from international sea transportation (equivalent CO_2 % counted by green house effect (S&O 2001))

GHG	CO_2	CH_4	N_2O	Others
Discharge percentage as CO_2 equivalent	96-97 %	1.0 %	0.8 %	1.2-2.2 %

2. Present situation of CO_2 discharge from maritime transportation

The transport sector shares the dominant part 57% of world final oil consumption in 2001 (IEA), and continuously increasing year by year. This enormous amount of oil consumption is mostly due to road transportation, and, as for maritime transportation, its consumption part is not so large. So the CO_2 discharge from maritime transportation is relatively not large viewing from the ratio to the world total, but it could not be said that absolute discharge amount is small according to the estimation by S&O (2001) as seen in Table 2.

Table 2 CO_2 discharge from ships and its share to total world discharge in 1995 and/or 1997

	Discharge Quantity 10^6 tones	Percent to total world discharge
Total quantity from all ships including those for domestic transport, fishing vessels, recreational boats etc.	554.2(1995)	2.4 %(1995)
Ships for international transportation	394.7(1995), 373(1997)	1.7 %(1995) —

In the Kyoto Protocol, the domestic water transportation is discriminated from the international one, and the emissions from domestic segment are counted among individual national emissions, and, as for emissions from navy ships and non-commercial state-owned ships, those are also counted among national emissions. The emissions from fishing vessels are counted into the category of “Agriculture/Forestry/Fisheries”. The ships concerned for IMO are, therefore, those ships engaged in international sea transportation.

Since all ships for international transportation use the bunkers delivered internationally, the total quantity of CO_2 emitted from international sea transportation could be calculated by the use of the data of bunkers delivered. The total emission quantity of 394.7 million tones in Table 2 was estimated by the just mentioned manner using the data of IEA Energy Statistics. The total emission quantity might be used for setting a general target of the emission reduction, but it could not give useful information required for investigating the emission control measures. In order to make a plan for emission control, it is needed to investigate the emission process of CO_2 from sea transportation systems. The Ship & Ocean Foundation has carried out a comprehensive investigation on the CO_2 emission by the procedure of summing up the fuel consumption of individual ships. The obtained results, which have been reported in S&O (2001), give the useful information. There are many kinds of ships. How does each of them contribute to the CO_2 emission? Table 3 shows the estimation of S&O (2001) mentioned above. It can be read out from Table 3 that 3 kinds of tankers, bulkers, and containers, have dominant contribution to the CO_2 discharge of international sea transportation.

Table 3 Fuel consumption and CO_2 discharge of various ships (1997)

Kind of ships	Fuel consumption (10^6 tones/y)	CO_2discharge (10^6 tones/y)	Ratio (%)
Tankers	35	105	28
Bulkers	37	111	30
Containers	45	135	36
Others	7	22	6
Total	124	373	100

3. Technological issues for planning the CO_2 control

3.1 Importance of emission factor EF as emission index

The CO_2 emission quantity Q can be expressed as follows,

$$Q = EF \times (Wc \times L) \qquad (1)$$

where, EF ; emission factor which is defined as the CO_2 discharge quantity when a ship transports 1unit cargo by 1 unit distance, that is, kg/(ton×km),

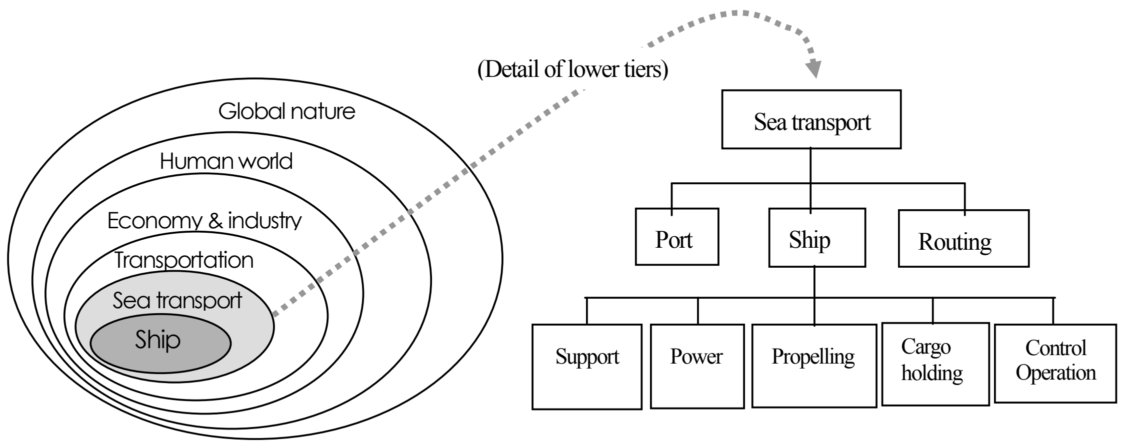
Wc; transportation quantity of cargo,

L; transportation distance.

In order to reduce Q, any of 3 factors in the right side of eq.(1) and/or all of them have to be reduced. If the industrial society is recognized as a hierarchical system as shown by Fig.1, Wc and L, that is, the transportation demand is dominantly determined by the economic and industrial systems, which are the higher tiers than the tier of sea transportation system in Fig.1. Wc and L are, therefore, not controllable and should be considered to be the given conditions from the standpoint of the tier of sea transportation. When the planner is investigating a reduction plan at the tier of sea transportation, therefore, there can be only one controllable factor, which is the EF in eq.(1). That is the reason why EF is very important and should be defined clearly from both aspects of quality and quantity.

EF can be expressed as follows by the introduction of fuel consumption FC,

$$EF = f_{CO2} \cdot \frac{FC}{Wc \cdot L} \qquad (2)$$



Structure of upper tiers — Structure of lower tiers of sea transportation

Fig.1 Hierarchical structure of human industrial society

where, f_{CO2} ; ratio of CO_2 emission quantity to fuel consumption,
FC ; fuel consumption for transporting the cargo of $Wc \cdot L$.

As for marine oil fuel, f_{CO2} shows a little variation among various kinds of fuels. That is, f_{CO2} can be approximated as constant with acceptable errors for various marine fuel oils. EF, therefore, can be considered to be approximately proportional to FC. Accordingly the EF control is actually nothing but the FC control. FC has the direct effect to fuel cost, and Fuel cost is the most significant cost for shipping. Therefore the importance of EF would be understandable for the persons concerned in the sea transportation.

Thus above, viewing from both points of quality and quantity, the EF defined by eq.(2) is considered to be a reasonable and appropriate quantity as an emission index.

3.2 Technological expression of EF

What technological factors are affecting the value of EF? In order to understand the relation between EF and ship systems, here, the transportation energy performance TEP, which is defined as the fuel consumption per unit transportation quantity, that is, (kg of fuel)/(ton·km). TEP can be expressed by the next equation (Nishikawa2002).

$$TEP = \frac{FC}{Wco \cdot L} = \frac{P}{Wco \cdot V} \cdot SFC \qquad (3)$$

where, Wco ; cargo loading capacity of ship,
P ; power of engine system, $FC = P \cdot (L/V) \cdot SFC$,
V ; ship velocity,
SFC ; specific fuel consumption of engine system.

Then EF can be expressed as follows,

$$EF = f_{CO2} \cdot TEP \cdot \frac{Wco}{Wc} = f_{CO2} \cdot \frac{P}{Wco \cdot V} \cdot SFC \cdot \frac{1}{\gamma} \qquad (4)$$

where, γ; load factor, that is, the ratio of actually loaded cargo quantity to full loading capacity.
As can be seen, EF is strongly related with TEP. TEP is the most important technological factor affecting

the ship operation cost, so that the all persons concerned in sea transportation are always making efforts for improving TEP. The data of P, V, Wco, SFC, f_{CO2} for each ship could be obtained easily, and therefore EF could be estimated easily for each ship when the load factor $\gamma$is informed. As for Wco, DWT (dead weight tones) could be applied instead of Wco for tankers and bulkers, and, for container ships, it would be better to adopt the containers' number Nc instead of Wco.

3.3 Measurability of EF

As mentioned above, the EF defined by eq.(2) is recommended here as the CO_2 emission index. One important characteristic required for the emission index is to be able to be measured reliably with satisfactory accuracy for individual ships in actual service. The EF could also meet to this requirement. As can be seen in eq.(2), the definition is very simple. If the data of fuel consumption and transportation quantity over a certain period, say a year, could be informed, EF can be calculated easily. As for the FC, ANNEX VI of MARPOL73/78 for NOx and SOx regulation, which will be entering in force at 19 May 2005, could be very useful. SABSTA (2004) have described as follows regarding the data of fuel consumption,

> **"According to regulation 18 of Annex VI…**
>
> **…after the entry into force of Annex VI, data will be available from 'all ports' for 'all bunker loading'. From these data a national collation could be made. The data will give: ship ID (hence type/GT/etc.), date and place of bunkering, and quantity of type of fuel oils loaded. Each delivery will only generate one bunker receipt; so double counting will be avoided. However, the following fuel supplies will not be covered:**
>
> **(a) Fuel delivered only for intra-national non-commercial usage**
> **(b) Fuel for recreational, national only usage**
> **(c) Fuel for military and non-commercial state-owned ships, because governments in most countries buy, store and deliver fuel for such usage. However, such data may be available from other national sources (i.e. Ministry of Defense or other national authorities).**

Though the description indicates some problems as (a)-(c), those are considered to be not so serious that the data of FC of each ship could be available owing to ANNEX VI of MARPOL73/78. As for the transportation quantity, every ship should make the documents of cargo drop-offs and pick-ups at each calling port. Therefore, if any appropriate soft ware tool and data management system for the collection of those documents have been developed, the data of [Wc·L] could be also available by the use of those collected transportation documents. The ratio f_{CO2} of fuel oil, as mentioned by SABSTA (2004), does not vary so much that average value of f_{CO2} could be applied for all marine fuels. For example, S&O (2001) has adopted the value of 2.999kg- CO_2/(kg of fuel) for bunker oils.

Thus above, the emission factor EF would be available for individual ship by the use of her bunker receipts and cargo transportation documents.

4. Institutional issues for CO_2 emission control

4.1 Decision of emission control target

As for the emission control target of whole international sea transportation, its decision seems to be not so difficult, because it could be decided corresponding to that of Kyoto Protocol both for quantitative target and time schedule. Following the decision of whole target, the next step is to assign the individual target to each ship according to the whole target. This assignment to each ship would not be so simple as the whole target decision. Here two points are discussed. One is the method for setting the individual target of each ship, and two is who should be responsible for managing the emission of each ship according to the target.

4.1.1 Use of EF for target of each ship As for the whole target, it would be possible to decide the target by the emission amount, but as for individual ship target, it is considered to be appropriate to adopt not an emission quantity but a value of EF. Because working condition and transportation quantity of each ship are varying now and then. Target setting of EF should be made taking into account of the relation with the whole target. Introducing the following quantities,

Qt□b, Qt□t ; the total CO_2 emission amount at base year and target year, respectively,
EFave□b, EFave□t ; average value of EF for all ships at base year and at target year, respectively,
(Wc□L)b ; total transportation amount at base year,
(Wc□L)t ; estimated total transportation amount at target year,

then, the next relation can be derived from eq.(1). The ratio Qt□t/Qt□b , which should be of course less than 1, corresponds to the whole target of emission control.

$$\mathrm{KEFave}^* = \frac{EFave\square t}{EFave\square b} = \frac{Qt\square t}{Qt\square b} \square \frac{(Wc\square L)b}{(Wc\square L)t} \qquad (5)$$

KEF* is the ratio of EF at target year to that at base year. It would be better to adopt not the value of EF but the ratio KEF* as the target. If the future transportation amount (Wc□L)t is predicted to increase compared to the base year, the target ratio KEF* should be decided to be more strict corresponding to the increase of transportation quantity as expressed by the above equation.

How should the individual target be assigned to each ship? It seems to be reasonable and feasible to adopt the KEFave* as the average target for all ships. But EFs of individual ships would be scattering. Some ships have better EF and the others have worse EF compared to the average. Therefore, it would be reasonable that individual target of each ship is assigned taking into account her EF at base year. In order to do so, it would be convenient to introduce a weighting coefficient α for assigning the individual target KEFind*, that is,

$$\mathrm{KEFind}^* = \alpha\square\mathrm{KEFave}^* \qquad (6)$$

α could be given by the value proportional to the deviation of each ship's EFind from EFave□b, for example, by the use of the below relation,

$$\alpha = k\square\square EFav\square b \;\square\; EFind\square b\square \qquad (7)$$

The constant k would be arranged from political aspect rather than technological aspect.

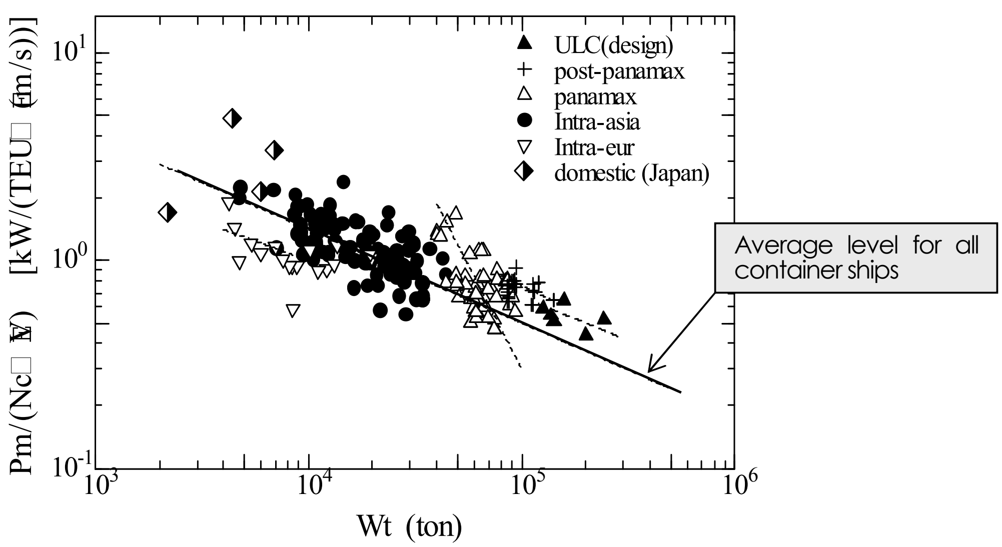


Fig. 2 Relation between Pm/(Nc□V) and Displacement Wt for container ships

The EFave□b can be obtained according to the statistical analysis of many ships' data. As an example, let us investigate the data of container ships. EF is expressed by eq.(4). In eq.(4), f_{CO2} is almost constant and SFC is the engine performance, so that the most important term affecting EF is P/(Wco□V). Fig.2 shows the trend of this term of container ships. In the figure, loading capacity Wco is expressed by container number Nc (TEU), and P is represented by main engine power Pm. The data plotted in the figure were collected from those references of Containerisation International Yearbook, Lloyd's Register of Ships, Data Book of Japan flagged ships. As seen, ship-size is very effective on Pm/(Nc□V) so that EFave□b has to be treated as a function of ship-size. As for the value of EFind, it could be made clear by the method mentioned previously in Section 3.3. Finally, as for load factor γ in eq.(4), annual average value of all containerships over base year could be applied.

Once the individual KEFind* has been assigned, then its value should be labeled as the individual value of each ship regardless of her owner, her flag state, her operator, etc.

4.1.2 Who is responsible for controlling the EF of individual ship? Recently the structure of international sea transportation systems has been changing drastically. Formerly one shipping corporation had its own ships and crews, and operated and managed them by itself, that is, the shipping corporation took a comprehensive role integrating necessary functions such as ownership, ship operation, ship management, manning, etc. Nowadays, however, those component functions for international sea transportation have been individually separating from each other, and becoming to be left individually to separate corporations. The international sea transportation system is becoming a complicated transnational, trans-subjective system. This situation brings about a problem that it is becoming difficult to identify who and/or which corporation is responsible for the CO_2 emission control. The general management of CO_2 emission control plan would be carried out by IMO as the same procedure with MARPOL73/78 ANNEX VI. Actual tasks for emission control, however, have to be carried out not by IMO but by those who engaged directly in the international sea transportation. It is important, therefore, that the regulation system should be constructed by taking into consideration of the situation mentioned above.

4.2 Methodology for forwarding the emission control plan

MARPOL73/78 ANNEX VI will be entering in force at 19 May 2004 for NOx, SO_2 control. The same methods for NOx, SO_2 control could be applied also for the management of CO_2 control. In order to facilitate individual ships for achieving their emission target, it might be desirable to introduce a procedure similar to that provided by the Kyoto Protocol, called as "emissions trading". That is, when a ship could achieve her emission reduction in excess of her target, she can transfer a part of the emission reduction quantity to another ship and/or, to the contrary, a ship can acquire some emission quantity from another ship and can add the quantity to her emission reduction quantity. Of course, this emissions trade should be allowed as far as the trade can contribute to promote the emission control of international sea transportation.

5. Technological measures for EF control

It could not be avoided that all ships will be required to reduce CO_2 emission in near future, so that it is important to investigate technical factors affecting the EF improvement. Let us investigate a bit more precisely the technological meanings of previous equation (4). Ship resistance R, and engine power P can be expressed by next equations, respectively,

$$P=(R \cdot V)/\eta \qquad (8)$$

$$R = Ct \cdot (\rho/2) \cdot Sw \cdot V^2 \qquad (9)$$

Introducing these relations to eq.(4), then,

$$EF = f_{CO2} \cdot \frac{R}{Wt} \cdot \frac{1}{\eta} \cdot \frac{Wt}{Wco} \cdot SFC \cdot \frac{1}{\gamma} \qquad (10)$$

$$= f_{CO2} \cdot \frac{\rho}{2} \cdot \frac{Sw}{Wt} \cdot Ct \cdot \frac{1}{\eta} \cdot \frac{Wt}{Wco} \cdot \frac{1}{\gamma} \cdot SFC \cdot V^2 \qquad (11)$$

Further, the following relation can be derived,

$$\frac{Pm}{\ } = \frac{\rho}{\ } \cdot \frac{Sw}{\ } \cdot \frac{Ct}{\ } \cdot \frac{Ct}{\ } \qquad (12)$$

$Wt\square V^3 \quad 2 \quad Wt \quad \eta \quad \eta\square\square^{1/3}$

where, Ct ; total ship resistance coefficient,

Pm ; power of main engine

R ; total resistance of ship,

SFC ; specific fuel consumption of engine system

Sw ; hull wetted area

Wt ; total weight, that is, displacement tones of ship

η ; efficiency of propulsion system

ρ ; density of sea water,

Δ ; displacement volume

The technological meaning of each term in the right side of eqs.(10,11) are as follows,

R/Wt ; **Resistance performance**. It is influenced by the hull design and, further, when a ship is in service in actual sea area, it is influenced by various conditions such as wave motion corresponding to sea state, hull surface fouling, etc. So, those measures such as weather-routing, hull maintenance, propeller maintenance etc. are effective for EF improvement.

η; **Total propulsion efficiency**. It is influenced by propeller efficiency, transmission efficiency, hull efficiency, and propeller roughness.

Wco/Wt ; **Cargo loading performance**. In case of those ships transporting low density cargoes such as container ship, car carrier, ferry, design considerations of hull structure are very important for the improvement of this performance.

SFC ; **Powering performance**. It is nothing but the efficiency of engine system. The engine system should be considered to be included, here, all machines installed on board not only main engine but also auxiliary engines and boilers.

V ; Ship velocity affects strongly EF. Speed-down is one of most effective and easy measure for EF improvement. On the other hand, since speed-down induces the increase of time cost for transportation, speed-down measure would require the cooperation of operator and shipper.

γ; When fully loaded, γ=1. In case of tanker and bulker, γ□1 in in-voyage, but γ=0 in out-voyage, so average value of γ equals nearly to 0.5, so that, for tankers and bulkers, the possibility of γ improvement would be little for EF control. For container ships, however, making efforts for γ improvement is very important and effective for EF improvement.

The term $Pm/(Wt\square V^3)$ of eq.(12) expresses the combined performance of resistance and propulsion of ship. In case of tankers and bulkers, there is almost no room for improvement of cargo loading performance Wt/Wco, so that the performance $Pm/(Wt\square V^3)$ is very important for them. Fig.3 shows the data of tankers, bulkers, and container ships. The performance of tankers and bulkers is almost same with each other. On the other hand, the performance of container ships is better compared to tankers and bulkers. Size-up is very effective, as well known, for improving this performance for all ships.

Almost all components composing the ship system are expressed clearly and can be understood how they affect the EF by eqs.(10-12). These equations, therefore, would be useful for the effective and systematic considerations in order to improve the EF.

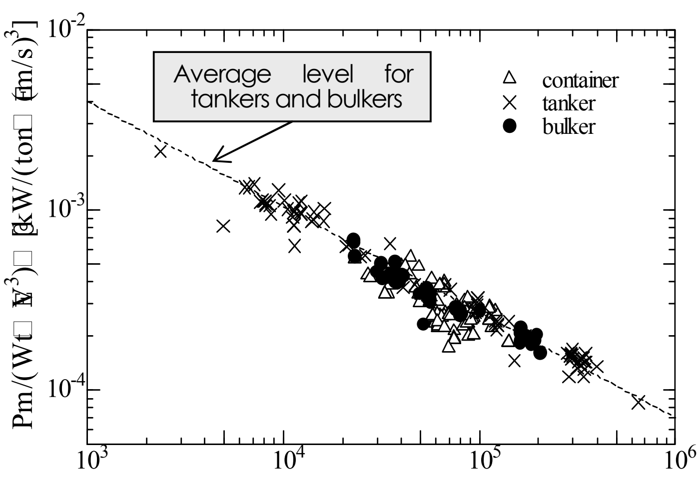


Fig.3 Resistance and propulsion performance of tanker, bulker and container ship

6. Conclusion

Kyoto Protocol of UNFCCC has required IMO to make the GHG control plan of international sea transportation by 2005. From the viewpoint of systems approach, a study was carried out here about some key issues such as CO_2 emission index, control target, technological measures for CO_2 control. The results are summarized as follows.

* The emission factor EF defined by emission amount per unit transportation quantity is considered to be an understandable and reasonable emission index.
* As for emission control target, KEF*, which is the ratio of EF at target year to EF at base year, seems to be an appropriate scale, and the target value KEF* should be decided taking into account the trend of future transportation quantity.
* Equations(10-12) have been derived. These equations express clearly how any component of ship affects the EF. Those equations could be useful for carrying out research and development for EF improvement.

Taking into consideration the recent situation of climate change due to GHGs pollution, the GHG control will be becoming an inevitable task for sea transportation in very near future. The study carried out here could propose only some fundamental ideas for the CO_2 emission control of international sea transportation. In order to make a control plan and to put the plan into practice, further concrete and practical investigations are required. It is hoped that above results obtained here could be useful for those further investigations.

References

IEA(2003), Key World Energy Statistics

Nishikawa (2002), E., et al, Analysis of propulsion performance of ships in service by the use of AB-LOG data, J. of Japan Institute of Marine Engineering, vol.37, no.11, pp.830-83, (in Japanese).

Ship & Ocean Foundation (2001), Report on the reduction measures of GHG discharge from ships, (in Japanese)

UNFCCC/SBSTA (2004), Report on the 20th Session of SBSTA, Methodological issues relating to emissions from international aviation and maritime transport, FCCC/SBSTA/2004/INF.5 (27 May 2004).