Estimation of Air Pollutants Emission from Ships in the Kaohsiung Harbor Area

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Kaohsiung Harbor is adjacent to Kaohsiung City, a metropolis that has long suffered from air pollution. The annual releases of air pollutants such as SO_x, NO_x, CO_x, PM, and HC from stationary and land-based mobile sources in Kaohsiung city have recently been thoroughly studied. However, emissions from vessels (another mobile source) have not been extensively investigated and understood. Evaluating ship emissions in Kaohsiung's harbor waters may be crucial to controlling air pollution in Kaohsiung city. This work, therefore, estimates the emissions of air pollutants from ships in 1997 and evaluates their contributions to total emissions in the city of Kaohsiung. Various approaches of estimation based on different databases and assumptions yielded different results. The emissions of NO_x, PM, HC, and CO were 13786, 341, 713, 1684 ton/yr, respectively, from vessels in Kaohsiung's harbor waters, as estimated by Ship Operation method/Cargo method. Emissions of SO_x and NO_x were 4055 and 9125 ton/yr, respectively according to Lloyd's emission factor/fuel consumption approach and emissions of SO_x and NO_x were 4837 and 5114 ton/yr, respectively, according to ship exhaust measurement/calculation. The contributions of SO_x and NO_x from shipping in the Kaohsiung city area were significant. Around 10~22% of the total NO_x and 10~12% of the total SO_x emissions in Kaohsiung city were attributed to ships in the harbor waters of Kaohsiung.

Keywords: ship emissions, air pollutants, SOx, NOx

1. Introduction

The extent to which air pollutants emitted from shipping impact the environment has not been of general concern until recent years, perhaps owing to that international shipping has caused less air pollution than land-based sources have. This is despite the fact that ships carry most of the world's traded goods (80% in 1998) (Kesgin and Vardar, 2001). This relatively new concern for emissions

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from vessels has been expressed by the International Marine Organization (IMO, 1997). The IMO did not attempt to address air pollution from ships until the mid-1990s (Corbett and Fischbeck, 1997). In 1997, the IMO adopted the "Protocol of 1997" to amend MARPOL 73/78, by adding a new Annex (Annex VI) on the prevention of air pollution from ships (IMO, 1997). International ships in which have been installed diesel engines with a power output of over 130 kW on or after 1 January 2000 have been required to comply with the applicable NO_x emission limits set by Regulation 13 of the Annex. The emission of SO_x is regulated by Regulation 14, which also limits the fuel sulfur level to 4.5% in general and 1.5 % in a SO_x Emission Control Area, respectively. In spite of these limitations, a measurable reduction in NO_x and SO_x emissions from ships will not occur for several years assuming a 1.5% yearly fleet replacement rate (Corbett and Fischbeck, 1997).

Kesgin and Vardar (2001) reported that the NO_x emission from public passenger ships in the Istanbul Strait was about 4% of that from motor vehicles in Istanbul. They also stated that international shipping globally contributed approximately 7% and 4% of NO_x and SO_x emissions respectively, as reported by the International Chamber of Shipping; these values were double those reported by the American Bureau of Shipping. However, emissions from ships can significantly contribute to local pollution in regions of high shipping volume along congested waterways (Streets et al., 2000). Ships accounted for about 17% of nationwide NO_x emission and Goteborg harbor contributed around 45% and 15% of the total SO_2 and NO_x emissions of the city of Goteborg in Sweden in 1996 (Isakson et al., 2001). Streets et al. (1997 and 2000) estimated that SO_2 emissions from shipping in Asia waters have grown by 5.9% per year between 1988 and 1995, representing only 0.7% of total continental Asian emissions in 1988, resulting in approximately 20% atmospheric loading in the vicinity of ports and heavily traveled waterways. In addition, the routes Singapore/Taiwan and Taiwan/Japan together contributed about 40% of the total SO_2 emissions on Asian shipping routes in 1995.

The Kaohsiung Harbor, in the middle of the Singapore/Japan shipping route, is Taiwan first largest and the world's third or fourth largest volume port. It has been responsible for the carriage of more than half of the containers and cargo in Taiwan for many years. According to Taiwan's Ministry of Transportation and Communications (2001), Kaohsiung harbor accounted for 70% of Taiwan's container carriage and 67.6% of its cargo shipping in 2001. From 1997-2001, the average annual growth rates of containers and cargo handled at Kaohsiung harbor were 7.3% and 4.8%, respectively. Given this large volume of container and cargo handling, the air pollutant emissions due to shipping at the port of Kaohsiung have recently become of concern.

Most of the world's commercial ships, powered primarily by diesel engines, use fuels with (about 3 to 5%) more sulfur than in the fuels used in land diesel engines (Corbett and Fischbeck, 1997; Street et al., 1997; USEPA, 1999). Kaohsiung harbor is an area of Kaohsiung which has long suffered from industrial/traffic air pollutants such as SO_x, NO_x, CO_x, PM, and VOCs (KCEPB, 2000). Emissions of these common air pollutants from shipping in Kaohsiung harbor may be significant for Kaohsiung area. Accordingly, this work assesses the SO_x, NO_x, CO_x, and PM emissions from shipping in Kaohsiung Harbor and the local contributions of each to Kaohsiung city.

A variety of factors, including power source (steam or diesel), engine size, fuel type, operating mode (cruising, maneuvering, hoteling), and load govern the emission of air pollutants from shipping (Trozzi et al., 1995; USEPA, 1998; Cooper and Andreasson, 1999; Kesgin and Vardar, 2001). The use of fuel or energy consumption to estimate ship emissions must generally incorporate emission factors. For example, Lloyd's emission factors (fuel-based) determined by ship operation mode testing were adopted to estimate the SO_x, NO_x, CO, and PM emissions from shipping (Corbett and Fischbeck, 1997; USEPA, 1998). These factors were reported to be similar to those of AP-42 for land diesel engines. Some researchers have used emission factors in units of mass per kW-hr or Gj, obtained by sampling/monitoring ship exhaust gases (Cooper and Andreasson, 1999; USEPA, 2000; Kesgin and Vardar, 2001). However, the methodological uncertainties of using emission factors to estimate ship emissions have been rarely reported. Cooper and Andreasson (1999) indicated that the calculated errors incorporating emissions factors for NO_x and CO_x emissions were 9 to 11% in exhaust measurements using the continual emission monitoring systems regulated by IMO.

In this work, Ship Operations Method and Cargo Method developed by Corbett and Fischbeck (USEPA, 1998) were used to estimate the emissions of domestic and foreign vessels operating in Kaohsiung waters, respectively. For comparison, Lloyd's emission factors (fuel-based) are also used to estimate directly the ship emissions of SO_x, and NO_x. Lastly, emissions are estimated from ship exhaust measurement and the contribution of air pollutants from ships to the pollution of Kaohsiung City is presented as well.

2. Sampling and Analysis

This work investigated 30 vessels. For convenience, a portable gas auto-analyzer (IMR 3000 P) was used to measure SO_x, NO_x, and O_2 concentrations in vessel stack flue gases, with accuracies of 0-20% ± 1%, 0-20% ± 1%, and ± 0.2%, respectively. The analyzer was installed with a pre-filter to removal particles carried by the flue gases and a pre-cooling system to prevent high temperature from influencing the measurements. Five side-by-side analyses of SO_x and NO_x were also performed by conventional methods (NIEA A413.71C for SO_x and NIEA A411.71A for NO_x) to validate the measurements. The samples were taken from five stationary sources (stacks) and ten samples (five for each pollutant) were compared. The results (with concentration corrections) showed that the readings obtained by the conventional methods were 1.1 to 1.4 of those recorded by the gas auto-analyzer for NO_x and 1.1 to 1.5 for SO_x. The temperatures of the flue gases were also recorded. The measurements of flue gas velocities were based on NIEA A101.7 (equivalent to 40 CFR, Part 60 App. A, Meth.1, USEPA, 1990) (Taiwan EPA, 1994). Recorded temperature and O_2 concentrations were used to correct the final concentrations of SO_x and NO_x.

The fuel used by each ship was analyzed to measure its fuel sulfur content. The measurements relied on NIEA A443. 70B equivalent to D4294-98 in ASTM (KCEPB, 2000). The examined fuel oils were classified into two categories - A class and C class. The sulfur contents of A and C class fuel oils were 0.1~0.95% (average 0.48%) and 2.15~3.04% (average 2.68%), respectively. These data were used to estimate the emissions of sulfur oxides from shipping..

3. Results and Discussion

Emissions of SO_x, NO_x, CO_x, PM, and HC from vessels were studied. SO_x emissions depend solely on fuel sulfur content while emissions of NO_x, are mainly related to the type of combustion (Corbett and Fischbeck, 1997; USEPA, 1998). In the USEPA's report, prepared by Energy and Environmental Analysis Inc. for the analysis of commercial marine vessels' emissions and fuel consumption data, the SO_2 emission factor was evaluated solely from the fuel sulfur flow, since all SO_2 emissions were fuel-derived whereas the

Table 1. Vessels distribution with CI marine engines by USEPA Category

Count of Ships	Category				Count of
Vessel Service	1	2	3A	3B	Ships
Container	-	4	-	-	4
Fishing	1469	392	41	-	1902
Passenger	-	-	1	-	1
RoRo[a]	-	3	-	-	3
Transport	10	9	-	-	19
Tug	-	27	-	-	27
Utility	47	6	-	-	53
Count of Ships	1526	441	42	-	2009

a. RoRo: Roll-on/Roll-off vessels including ships carrying vehicles and other large non-containerized items.

Table2. Daily fuel consumption per ship

Fuel use per day-ship (adjust for max load = 80% max power)	Engine Category			
Vessel Service	1	2	3A	3B
Container	-	15	-	81
Fishing	7	14	18	14
Passenger	14	-	14	29
RoRo	-	18	70	59
Transport	12	18	45	42
Tug	8	14	35	45
Utility	8	13	29	18

Source: Commercial Marine Emissions Inventory for EPA Category 2 and 3 Compression Ignition Marine Engines in the United States Continental and Inland Waterways (USEPA, 1998)

emission factors of NO_x, CO_x, PM, and HC were statistically related to the fractional loading of a rated engine output. Therefore, in this work, the emissions of SO_x were separately estimated from the emissions of NO_x, CO_x, PM, and HC. Ship operations method (SOM) and cargo method were used to estimate these latter four pollutants; Lloyd's emission factors and the fuel consumption approach were applied to estimate the SO_x. SO_x and NO_x emissions were also estimated from on-site sampling data.

3.1 Estimation of Emissions by the Ship Operations Method (SOM) and the Cargo Method

As mentioned above, Corbett and Fischbeck proposed the ship operations method and the cargo method to estimate the emissions from U.S. flag vessels that were operating in U.S. waters, and the emissions from foreign flag vessels that were carrying cargo on U.S. navigable waterways, respectively for compression ignition (CI) engines above 37 kilowatts (kW) (USEPA, 1998). According to their results, no single approach, with currently available data, could yield a comprehensive inventory of ship emissions in U.S. waters. Foreign shipping carried significant volumes of cargo from/to U.S. ports, as is also true for Kaohsiung. Therefore, this work adopted the same approach. Both methods rely on two databases: (a) the common database of registered ships with information on propulsion type, break horsepower, and engine specifications and (b) the database of marine diesel emission factors reported by Lloyd's Register Engineering Services. These emission factors are similar to the current USEPA emission factors in AP-42. For NO_x, they are 87 and 57 kg pollutant/tonne fuel at slow and medium speeds, respectively; for particulate matter (PM), 7.6 and 1.2 kg pollutant/tonne fuel at slow and medium speeds, respectively; for hydrocarbons (HC), 2.4 kg, and for carbon monoxide (CO), 7.4 pollutant/tonne fuel, for all CI marine engines (USEPA, 1998). According to the USEPA, categories 1, 2, and 3 (A and B) of marine CI engines correspond to engines with propulsion engine displacements per cylinder of < 5, 5~20, and $\geq$ 20 liters, respectively. Categories 1 and 2 were assumed to use medium-speed emission factors; half of category 3A was assumed to use medium-speed, and half to use slow-speed factors in the calculations of pollutant emissions per day-ship.

Table 3. Estimated annual emissions of NOx, PM, HC, and CO for CI engines in the Taiwan fleet (ton/yr)

Vessel Service / Pollutant	Category 2	Category 3	Categories 2 and 3 Total
Container			
NO_X	45	-	45
PM	1	-	1
HC	2	-	2
CO	6	-	6
Fishing			0
NO_X	3922	1348	5270
PM	83	.82	165
HC	165	187	352
CO	509	72	581
Passenger			
NO_X	-	26	26
PM	-	2	2
HC	-	4	4
CO	-	1	1
RORO			
NO_X	41	-	41
PM	1	-	1
HC	2	-	2
CO	5	-	5
Transport			
NO_X	117	-	117
PM	1	-	1
HC	5	-	5
CO	15	-	15
Tug			
NO_X	270	-	270
PM	6	-	6
HC	11	-	11
CO	35	-	35
Utility			
NO_X	56	-	56
PM	1	-	1
HC	2	-	2
CO	7	-	7
Total			
NO_X	4450	1374	5824
PM	92	84	176
HC	187	191	378
CO	578	73	651

3.1.2 Estimate of Emissions from Taiwan Flag Vessels by Ship Operations Method

An inventory of ships was first established by counting the ships by USEPA category, to estimate using SOM, the emissions from Taiwan flag vessels that were operating in Kaohsiung harbor waters (Table 1). Data concerning the daily fuel consumption per ship, calculated from the ship's brake horsepower and the engine brake-specific fuel consumption were obtained from USEPA (1998) (Table 2). The daily emissions per ship were multiplied by the number of ships and service days per year to estimate annual emissions. However, this estimate was modified by a conservative service/underway factor of 0.1 for annual emissions based on visit surveys. In fact, some Taiwan flag vessels spend some operating time outside Kaohsiung harbor waters. Therefore, the annual emissions were corrected by assuming a 48% reduction and another factor of 0.52 was then applied. Table 3 presents estimates for each pollutant by type of vessel and by USEPA category. The estimated emissions of NO_x, PM, HC, and CO were 5824, 176, 378, 651 ton/yr, respectively. About 90% of total NO_X, 94% of total PM, 93% of total HC, and 89% of total CO were attributed to the emissions from fishing boats because 95% of investigated Taiwan flag vessels were fishing boats.

Table 4. Summary of cargo movements in Kaohsiung harbor waterway

Region	Distance[a] (km)	10^6 tons moved[b]	10^9 ton-km
Harbor outside	209	276	415
Harbor inside	18	276	5
Total	-	-	420

a: data derived from vessel navigation waterways (KHB, 1996).
b: data from Kaohsiung Harbor Bureau (KHB, 1999).

3.1.3 Estimate of Emissions from Foreign Flag Vessels by Cargo Method

The cargo method uses cargo movements and waterway data to calculate the total tons and ton-km moved annually by ships in and around Kaohsiung harbor. The average numbers of cargo ships needed to carry these volumes were estimated, and the emissions per ton-km derived for these hypothetical cargo ships (USEPA, 1998). Kaohsiung harbor waters were classified into two

Table 5. Average speed (in m/min) of cargo ships

Vessel Service	CI Engine Category 1	2	3A	3B	Weighted Average
Container	-	154	-	308	308
RoRo	185	247	308	308	278
Transport	154	216	247	247	216
Weighted Average	154	216	278	278	278

regions - inside harbor and outside harbor (within 20 nautical miles (about 37 km) of coastline). The waterway length of inside harbor is 18 km. The outside harbor region includes several links (navigation routes) with distances of 4 to 17 km (average 12 km) calculated over a 0.25 by 0.25 nautical mile grid. In each region, the cargo movements in ton-km were calculated by summing the product of the number of tons shipped along each link in a region, by the length of that link. Table 4 summarizes the results

Combining the daily emissions per ship (from SOM), the average deadweight tonnage (DWT), the cargo capacity factor, and speed data, yields the emissions per ton-km. The ratio of deadweight tonnage to gross tonnage is typically 5/3 and the DWT data were multiplied by 0.8 to yield an estimate of the maximum cargo weight that could be carried. Consequently, the average DWT of foreign cargo ships was 22519 tonnes/ship. Moreover, a cargo capacity factor of 0.5 was applied to vessels that operated on ocean routes, since most ships carry average cargo loads of 50% to 60%. Average speeds for cargo ships used in this study were obtained from USEPA (1998) (Table 5). Accordingly, the emissions per ton-km and emissions per year were calculated using the following equations.

$$E_{TM} = E_d \div (DWT * CCF * V * 24) \quad (1)$$

E_{TM} = Emissions per ton-km

E_d = Emissions per day (data from Ship Operation Method)

DWT = Average DWT per ship

Table 6. The estimation of cargo ship emissions for Kaohsiung harbor inside and outside waters

Water region	NO_x (ton/yr)	HC (ton/yr)	CO (ton/yr)	PM (ton/yr)
Harbor inside	79	3	10	25
Harbor outside	7883	332	1023	140
Total	7962	335	1033	165

CCF = Cargo capacity factor (0.5)

V = Average speed of vessel across duty cycle (adjusted for max BHP)

24 = Hours per day to convert ship speed to ship km per day

$$E_Y = E_{TM} * TM_Y \quad (2)$$

E_Y = Emissions per year

TM_Y = Ton-km per year (from Table 4)

Table 6 presents the results calculated by the cargo method for foreign vessel emissions, assuming that all of the foreign flag fleet were cargo vessels. The estimated emissions of NO_x, PM, HC, and CO were 7962, 165, 335, 1033 ton/yr, respectively. The emissions of cargo ships inside harbor were much lower than those outside harbor because the navigation distance inside harbor is much shorter than that outside harbor.

3.1.4 Estimate of Total Emissions from Commercial Shipping by SOM and Cargo Method

Summing up Taiwan flag fleet emissions (calculated from SOM) and foreign flag fleet emissions (calculated from cargo method) yields an estimate of the total emissions from commercial shipping in Kaohsiung harbor waters (Table 7). According to this table, the air pollutant emissions, particularly those of NO_x and CO, from the foreign flag fleet, exceed those from the Taiwan flag fleet.

Table 7. Emissions (ton/yr) from commercial shipping in Kaohsiung harbor waters estimated by Ship Operation Method and Cargo Method

Pollutant	Category 2 engine	Category 3 engine	Categories 2 and 3 Total
Taiwan flag fleet			
NO_x	4450	1374	5824
PM	92	84	176
HC	187	191	378
CO	578	73	651
Foreign flag fleet			
NO_x	7962	-	7962
PM	165	-	165
HC	335	-	335
CO	1033	-	1033
Total			
NO_x	12412	1374	13786
PM	257	84	341
HC	522	191	713
CO	1611	73	1684

The foreign fleet accounted for 58% of total NO_x and 61% of total CO emissions from shipping in Kaohsiung harbor in 1997. The total emissions of NO_x, PM, HC, and CO were 13786, 341, 713, 1684 ton/yr, respectively.

3.2 Estimation of Emissions from Lloyd's Emission Factors and Fuel Consumption

The USEPA report did not include an SO_x emission database for either the SOM or the cargo method. Therefore, SO_x emission was roughly estimated by the approach of using Lloyd's emission factors and that incorporate a fuel consumption calculation.

The average energy density consumed by vessels is 143.4 kcal/ton-km in Taiwan waters (KCEPB, 2000). 1 kg ship fuel generates 9000 kcal of energy (Trozzi et al., 1995) corresponding to a fuel consumption of 0.016 kg per ton-km of cargo moved. The total annual fuel consumption and the annual SO_x emission can be calculated as follows.

$$M = W \times 0.016(\text{kg/ton-km}) \times D \times 10^{-3} \quad (3)$$

M: total annual fuel consumption (tonne fuel/yr) (1 tonne $=10^3$ kg)

W: total annual inbound and outbound cargo shipped (ton)

D: effective distance of cargo movement (km)

$$E_s = M \times F \times 10^{-3} \quad (4)$$

E_s: Annual emission (tonne of pollutant/yr)

F: emission factor (kg pollutant/tonne fuel)

According to KCEPB (2000), the effective distance moved by cargo can be estimated from the stage of operation of a ship. A ship has four operating stages – 1) cargo handling, 2) warm-up of engine, 3) navigation inside harbor, and 4) navigation outside the harbor. The corresponding effective distances estimated from vessel operating time and speeds, in the four stages were 12, 15, 25, and 50 km, respectively, resulting in a total effective distance of 102 km.

Lloyd's SO_x (as SO_2) emission factor is $20\times(S\%)$, where (S%) is the sulfur content of the fuel; additionally, the sulfur content in the vessel fuel varies from 2.1 to 5% by weight (Corbett and Fischbeck, 1997). The sulfur content of Asian fuel is 3%; the global average is 2.8% (Street et al., 2000). A and C class diesel oils are frequently used in Kaohsiung waters; the measured average sulfur contents of these two different fuels were 0.48% and 2.68%, respectively. Vessels generally use C class fuel when navigating outside the harbor, in Kaohsiung waters. The port authority requires that all vessels that operate inside Kaohsiung harbor area use A class fuel. However, 10% of vessels investigated did not comply with this regulation. The SO_x emission increases if more vessels use C class fuel inside the harbor, because SO_x emission is linearly proportional to the emission factor/fuel sulfur level, according to Eq. 4. This work also verified the approximately linear relationship between SO_x emission rate and fuel sulfur content. The weighted sulfur content of the vessel fuel was about 1.6% corresponding to the effective operating distances inside and outside the harbor. The total cargo shipped annually was 77654594 tonnes. Consequently, the estimated annual SO_x emission was 4055 tonnes (as SO_2). Similarly, the annual NO_x emission was estimated as 9125 tonnes, using an average emission factor of 72 (= (87+57)/2 in Section 3.1) kg pollutant/tonne fuel.

3.3 Estimation of Emissions from Ship Exhaust Measurements

Ship exhausts were measured to verify the vessel emissions estimated by the above methods. The respective average emission rates of SO_x and NO_x were 0.35 and 0.37 kg/hr, obtained from the measurements of 30 ship stacks. For simplicity, the ships' operating modes were not considered. The emissions can be approximately estimated as follows.

$$E_m = E_r \times T_s \times N \qquad (5)$$

where E_m is the emission of the pollutant, E_r is the pollutant emission rate in kg/hr, T_s is the average ship residence (dwelling) time in Kaohsiung harbor waters in hours/ship, and N is the total number of inbound and outbound vessels. The average ship residence time in Kaohsiung harbor waters was approximately 5 days. Data concerning inbound and outbound vessels and tonnage by vessel were obtained from the Kaohsiung Harbor Bureau (KHB, 1999). The pollutant emission rate was assumed to be linearly proportional to vessel tonnage for ships with a tonnage of at least 5000 tonnes; the rate for vessels with a tonnage of 4999 tonnes or less was consistent. Table 8 lists the estimated ship emissions.

Table 8. Estimate of NO_x and SO_x emissions from vessels by measurement/calculation

Vessel Tonnage	≦ 1000	1000 to 4999	5000 to 9999	10000 to 19999	20000 to 24999	≧ 25000	Total
Number of vessels	2571	9027	6122	6580	1032	7353	32685
Average SO_x emission rate (kg/hr)	0.35	0.35	0.70	1.40	2.10	2.80	-
Average NO_x emission rate (kg/hr)	0.37	0.37	0.74	1.48	2.22	2.96	-
Annual SO_x emission (ton/yr)	108	379	514	1105	260	2471	4837
Annual NO_x emission (ton/yr)	114	401	544	1169	275	2612	5114

Assumptions: the pollutant emission rates were consistent for vessels ≦4999 tonnages; the emission rates were double for vessels with 5000 to 9999 tonnages; and the emission rates for vessels with 10000 to 19999 , 20000 to 24999, and ≧25000 tonnages were 2-, 3-, and 4-fold of that for vessels with 5000 to 9999 tonnages, respectively.

The calculated annual NO_x emission, determined from sampling, was 5114 tonnes lower than 9125 and 13786 tonnes estimated by directly calculating the emission factor/fuel consumption (Section 3.2) and by applying the SOM/Cargo Method (Section 3.1), respectively. In contrast, the measured annual SO_x emission was 4837 tonnes slightly above that (4055 metric tons) estimated by directly calculating emission factor/fuel consumption. The results differed from those obtained by the other two approaches, since different databases and assumptions were used. A more detailed investigation is necessary to achieve more reliable estimates.

3.4 Local Contribution to Air Pollution from Shipping Emissions

Kaohsiung harbor is a part of Kaohsiung city that has suffered from air pollution for years. Whether pollutants emitted from vessels that operate in Kaohsiung harbor waters significantly contribute to the air pollution of Kaohsiung city is a matter of concern. Kaohsiung city's non-shipping emissions of SO_x, NO_x, PM, HC, and CO were 36874, 49183, 27345, 67545, and 100876 tonnes/year, respectively, in 1997; they are 41480, 52902, 19145, 60146, and 372425 tonnes/year at present (KCEPB, 2000; KCEPB, 2002). The contributions of PM, HC, and CO from shipping to Kaohsiung city were negligible (< 2% each), but shipping emitted about 10~22% of the total NO_x and 10~12% of the total SO_x in Kaohsiung city. Control of total NO_x and SO_x emissions in Kaohsiung city should include shipping emissions.

4. Conclusions

The estimated annual emissions of PM, HC, and CO were 341, 713, and 1684 tons in 1997 based on Ship Operation Method/Cargo Method. These contributions to Kaohsiung City's pollution are negligible.

The annual NO_x emissions were 13786, 9125, and 5114 tons, as estimated by the SOM/Cargo method, directly calculating emission factor/fuel consumption, and sampling/calculation, respectively. The annual NO_x emissions from shipping contributed 10~22% of the total NO_x in the city of Kaohsiung in 1997. Directly calculating the emission factor/fuel consumption and the sampling/calculation approach yielded estimated annual SO_x emissions of 4055 and 4837 tons, respectively. Around 10~12% of the total SO_x emissions in Kaohsiung city were attributed to ship emissions.

The volume of container and cargo transportation at the port of Kaohsiung has increased steadily in the past decade. Although this increase of container and cargo carriage was small in 2001, the shipping emissions related mainly to container and cargo carriage did not decline. For Kaohsiung city, the emissions of the five investigated air pollutants increase year by year. The results of this work support the consideration of vessel emissions in controlling air pollutant, especially SO_x and NO_x emissions, in Kaohsiung city.

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