ENERGY EFFICIENCY BASED OPERATION OF COMPRESSED AIR SYSTEM ON SHIPS TO REDUCE FUEL CONSUMPTION AND CO_2 EMISSION

(DOI No: 10.3940/rina.ijme.2019.a2.532)

C Dere, **C Deniz**, Istanbul Technical University Maritime Faculty, Turkey

SUMMARY

Energy efficiency subject has been gaining importance in maritime sector. The compressed air is a valuable energy source in operational manner, by the reason of intrinsic lack of efficiency in pressurization process. Operational pressure and leakage rate are the major variables which affect operational efficiency of the system. This study aims to reveal potential energy saving for the compressed air system. To this end, several pressure ranges, 29-30 bars to 14-18 bars, and different leakage rates 2.4% to 45% are evaluated. After the data was obtained from ships, thermodynamic calculations had been carried out. Optimization of pressure saves 47.3% in daily power requirement, 58,2% in compressed air unit cost, 18.4 and 57.4 tons of reduction in fuel consumption and CO_2 emissions in a year respectively. High leakage rates can cause 2.7 times more power and fuel consumption. Finally, operating load, as an important indicator of compressor, makes imperfections identifiable.

NOMENCLATURE

IMO	International Maritime Organization
MEPC	Marine Environment Protection Committee
EEDI	Energy Efficiency Design Index
EEOI	Energy Efficiency Operational Indicator
SEEMP	Ship Energy Efficiency Management Plan
GHG	Greenhouse Gas
P	Pressure [kPa]
V	Volume [m^3]
m	Mass [kg]
R_u	Universal Gas Constant $[\frac{kJ}{K}]$
R	Individual Gas Constant $[\frac{kJ}{kg\ K}]$
M_{air}	Molar weight of air
T	Temperature [Kelvin]
$\dot{m}_{air\_leak}$	Air leakage rate $[\frac{kg}{h}]$
P_{system}	System pressure [bar]
m_{air_out}	Total air consumption $[\frac{kg}{h}]$
$\dot{m}_{air\_cons}$	Air consumption $[\frac{kg}{h}]$
P_{c_out}	Comp. outlet pressure [bar]
P_{c_in}	Comp. inlet pressure [bar]
T_{c_out}	Comp. outlet temperature [K]
$T_{c_{in}}$	Comp. inlet temperature [K]
n	polytrophic constant
$\dot{W}$	Comp. work [kW]
$\dot{m}_{air\_in}$	Air rate in comp. $[\frac{kJ}{kg}]$
Δh_{out-in}	Enthalpy diff. $[\frac{kJ}{kg}]$
$\dot{W}_{elec}$	Electrical power demand [kJ]
μ_{comp}	Comp & e-motor efficiency
C_p	Constant press. Spec. heat $[\frac{kJ}{kg\ K}]$
$\dot{E}_{loss}$	Energy loses [kJ]
$\dot{H}_{air\_out}$	Outlet air total enthalpy [kJ]
$\dot{H}_{air\_in}$	Inlet air total enthalpy [kJ]

1. INTRODUCTION

Energy efficiency has been very popular subject for many years in maritime transportation as well as in industrial areas. The energy efficiency policy aims to both reduction of energy costs in whole operation and decrement of hazardous emissions emitted to atmosphere. Restricted emission limits in maritime sector, governed by International Maritime Organization (IMO) and Marine Environment Protection Committee (MEPC), prompted operators to pay attention on this subject. Fuel consumption in the operation is evaluated by Energy Efficiency Operational Indicator (EEOI) (IMO, 2009a). This issue starts with the beginning of design stage of ships that Energy Efficiency Design Index (EEDI) (IMO, 2009b) became a mandatory regulation for new ships together with the Ship Energy Efficiency Management Plan (SEEMP) (IMO, 2009c). The primary objective of these amendments is mitigation of emissions by reducing fuel consumption (IMO Web Site, 2018, IMO, 2011). High level of fossil fuel usage to generate electrical energy or propulsion power in ships, makes efficiency consideration more vital phenomena for the both economic and environmental aspects. Each action which can be done while considering fuel saving, has a reaction on emission reduction. It would both give great advantages on mitigation of carbon emissions and preserving money accompanying with the fuel reduction. CO_2 as a greenhouse gas (GHG) has noxious impact, as climate change, on environment. It is shown in studies carbon finance will gain in importance in future (Chang, 2016). For this reason, there are some implementations of novel technologies to reduce emissions as usage of alternative fuels (Deniz and Zincir, 2016) or renewable energy usage (Pflanz, 2000, Nuttall et al., 2014, Schmitman, 2003, Borden and Smith, 2008). While occasional concept designs enable alternative & renewable energy usage on board, there are very limited samples in practice usage of renewable & alternative energy to generate electricity on ships.

Starting with the new and efficient design of ships, many other practices have been applied operations of aged ships to minimize fuel consumption such as, slow steaming, route optimization, on board efficiency managements, adaptation of novel technologies (Seediek, 2015) and maintenance planning which cover overall metrics. All of these plans must extend main energy flow lode to capillaries. All possible and feasible efforts have to be undertaken at the whole ship equipment. Utilization of energy in an efficient way is the cheapest and rapid solution for efficiency issue. These solutions comprise, increasing efficiency of processes, production, conversion and conservation together with diminishing excessive consumption (Bilgen and Sarıkaya, 2016). In this context, all energy consumer equipment must be evaluated in term of efficiency concept. Since, the most economical energy is the energy you never waste, consumption and conservation of energy in an efficient manner are two main objectives which must be focused on in efficiency considerations (Bilgen and Sarıkaya, 2018). One of the most inefficient equipment is compressed air system in engine room by virtue of having natural ineffective process; nonetheless, starting air system is indispensable equipment for an engine room of a ship which is propelled by a large marine diesel engine. By increasing the pressure of the air, the starting air bottle is qualified to start to the reciprocating motion of large bore diesel engine by means of pneumatic way. Compressed air is a kind of energy storage method which uses potential energy of the gas. By both reason of the free charge of air before compression process and no contamination or penal sanction in the case of any leakage, a particular attention is not paid on this matter. However, after compression process the air is qualified with a pressure and gets a valuable expense. It must be emphasized that, pneumatic output power of compressed air only 5-10% of consumed electrical power (V. M. Brodyansky et al., 1994, Taheri and Gadow, 2017). Therefore, compressed air is a high cost energy source for all applications. Independent of the types of compressors not only efficiency level, but also control type, storage strategy and leakage volume of the system are also highly related with the total outcome of compressed air system efficiency. After all, misconception about cost of the air must be cleared up and efficiency measures must be taken into consideration in production, storage and utilization stages.

Many more studies carried out to reveal the compressed air costs in land industrial areas. This cost is highly depended on electrical costs of the company 0,15-0,25$ per kW (Taheri and Gadow, 2017). But in commercial ships the most convenient energy source is fuel oil, accordingly cost of generating electric power via diesel engines in ships much more expensive than land industries because of limited efficiency of internal combustion engines. In industrial areas, compressed air is cached as an underground energy storage, by the reasons of large scale, long life-time, low operational and maintenance costs, thereby it can be considered cheapest energy storage technology in terms of unit cost (Chen et al., 2009). Despite the industries have a great advantage of cost of electricity and feasible energy production aid as renewable energy usage that, several studies had been carried out to improve compressed air systems energy efficiency (Luo et al., 2016, Kaya et al., 2002, Benedetti et al., 2017). These systems are operating under desired profit widely to diminish risk potential of the system (Neale and Kamp, 2009). By taking into account these studies, it is essential to realize why this subject need more attention in maritime sector too. As a results of the studies, system efficiency is highly dependent on the isentropic efficiency, operating pressure and cooling performance of system (Luo et al., 2016). Operating pressure must be well-adjusted within optimum range for the efficient use of compressor. It directly affects isentropic efficiency. Furthermore, leakage rate is another factor for overall efficiency of the system.

This paper analyses impact of operating pressure range variation and leakage rate factors that have major impact on efficiency of the system together with being identifiable and adjustable by marine engineers, on power consumption of compressor and its equivalent fuel consumption with carbon dioxide emissions.

2. ANALYZING AND MODELLING OF COMPRESSED AIR SYSTEM

The compressed air system enables to start main engine, auxiliary engines, emergency generator, and also enables to perform hydraulic and pneumatic tools as exhaust valves motion, cleaning filters or sea chest, back flash filter, cargo operation, horn, fire pumps or a control air, etc. Furthermore, many more technologies can be utilized by compressed air system, powered by service air. A simplified schematic representation of a compressed air system is given in figure 1.

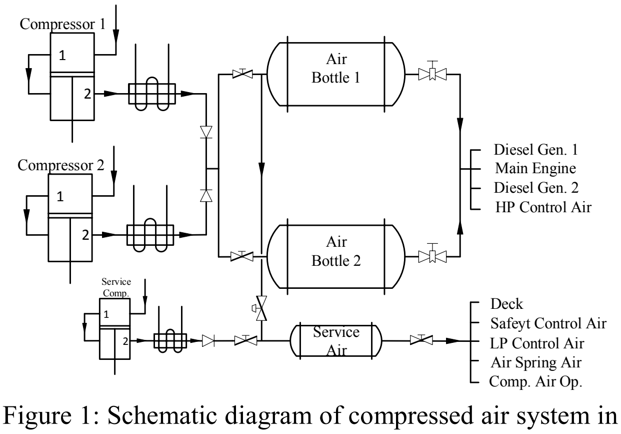

Figure 1: Schematic diagram of compressed air system in ships.

These abilities increase air consumption on board. Compressed air is consistently in use in any commercial ship, qualified and available at any time during the navigation. By the reason that, operating of appropriate systems by pneumatic way provides low initial cost and operating cost for them. Even in this case, operational energy cost is much more than initial and maintenance costs of compressed air system (Mousavi et al., 2014). The proposed evaluation method in this study realizes why attention must be paid to compressed air system optimization.

The compressor is operated on a ship to meet the air demand used by whole ship systems. The air is supplied by air bottles stored in by air compressors. Starting equipment (air bottles) rules have been specified by classification societies. Germanischer Lloyd, as a technical regulatory and supervisory authority, declared minimum requirements for starting air system, for instance, appropriate air bottle capacity, accepted minimum and maximum operating pressures (9-30 bars) and maximum demanded time to fill up air bottles at atmospheric pressure to maximum operating pressure (30 bars) (Germanischer Lloyd, 2015). Air bottles have safety pressure at 31 bars which has critical mission. Compressor operating condition is set at 30 bars. Whenever pressure of air bottle reaches 30 bars, the compressor is automatically shut down by controller, even a case, if automatically shut down control disabled safety valves opens at specified safety pressure. The system contains minimum two compressors and two air bottles except service air bottles and reduction valves. There is an uncomplicated system configuration for compressed air, and not many more system equipment for it. There is no peremptory rule to increase the efficiency of compressed air system, just an advice by MEPC, pay attention to minimize fuel consumption during operation (IMO, 2016). Keeping compressed air system in a good condition and operating at optimum range contribute energy efficiency matter on ships. The compressor efficiency is heavily depended on compressor operating load and decreases with the higher loads of compressor. The load changes with the air discharge pressure, which must be higher than tube pressure that, can be set to a specific value as a peak pressure to control. Operating range adjusted by control parameters and control method of the system. Naturally, control of the system affects the efficiency of the operation directly. Many type of control systems are in use in the compressor operation, according to air demand, minimum pressure limitation, and complexity of the system. Types of control systems are start/stop, load/unload, modulating inlet, variable displacement and variable speed controls (Compressed Air Challenge, 2010). Most of these systems change the load on the compressor by considering discharge air pressure only except start/stop control type. Start/Stop control type is widely service in small-scale compressors. This type of control is the most energy efficient control type for these compressors, by the reason of start/stop control shuts off the compressor automatically when the pressure reaches the desired value (Chris and Kelly, 2003). The conventional and the most convenient control system is this the type of control system in ships too, because of uncomplicated system requirement and controlled by operating ranges of pressure.

A virtual sample of any system can be simulated via computer program to demonstrate outputs and responses of the system, which must be close to real values. For a prosperous model, theoretical knowledge has to be combined with a mathematical model and experiences (Sapietova et al., 2017). In this study, compressor is modelled and operational process is simulated to reveal potential savings in the compressed air system operation. The process simulation includes air leakages, artificial demand and cooling process of compressed air. Furthermore, the modelled compressor parameters, comprises energy consumption, air flow, pressure and temperature values and these are also validated from the data obtained from ships. The results which are considering these issues and obtained from the model are demonstrated in this study.

2.1 MODELLING OF SYSTEM DYNAMICS

The unit energy cost of compressed air is depended on many factors as, storage pressure, compressor efficiency, cooler efficiency and the source of power generator which can be a shaft generator or diesel generator for a ship.

Modelled compressor algorithm is applied on a ship operation to observe the energy consumption of the system. Efficiency and any other outputs of the system could vary depending on compressor type, capacity, condition of the system, system requirements and operational control type. To calculate energy efficiency of the compressor, measurement of energy consumption and pressure trace of the air bottles are considered. With the relation of air bottle capacity and the pressure trace allow to calculate, how much air stored in air bottle. By considering trend of pressure increase, mass of air pressurized to air bottles can be calculated. Modelled system uses these relations and the power signatures to simulate the operational efficiency of the system. The manufacturer instruction manuals can be used for any type of compressor which will be used in ship for this assumption tool.

Ideal gas assumption is applied to compressed air systems to facilitate the calculation mass of the compressed air in the air bottle with a following fundamental equation.

$$P.V = m.R.T \tag{1}$$

Where the units are; P, pressure [kPa], V, volume [m^3], m mass [kg], R individual gas constant of air 0,2871 [kJ/kg.K] which value obtained by dividing universal gas constant to molecular weight of air (R_u/M_{air}) T, temperature [Kelvin].

Volume of a single air bottle can be 5.5 m^3 to 15 m^3 in existing commercial ships and varies ship to ship. Furthermore, as specified in Germanischer Lloyd (2015), maximum permissible operating pressure is 30 bars. In the study, these information was taken in to account for modelled system. All consumers are supplied from this system as service air, or engine starting air. Except from consumption another, a small amount of air consumed via leakage by piping, junction or holes. Air leakage is modelled as a function of pressure inside the air bottles or in system pipes. Leakage is an unavoidable issue in such systems (Cerci et al., 1995). Allowable leakage can be approximately 2-15% as a base leakage according to system capacity where in the system that maintained properly. However, in the case of poor maintenance, leakage, the undesired amount of air consumption, can reach 40-50% of system consumption capacity (Seslija et al., 2012, Dindorf, 2012). The basic amount of leakage can be accepted as a tolerable and unavoidable leakage. More than this value can be expressed as wasted air and depends on number of leakage holes and dimeter of holes, expressed by Compressed Challenge Inc., leakage is totally based on pressure and orifices areas. (Compressed Air Challenge, 2004). For a considered system, the leakage rate is a function of a system pressure, written in equation 2.

$$\dot{m}_{air\_leak} = f\left(P_{system}\right) \tag{2}$$

An estimated cost of air leakage can be calculated via this equation, as well as mass after detection of leakage points. In case of well-known of initial system parameters, as basic consumption and operating pressures, leakage trend can be observed clearly. Additionally, cost of leakages in the system in the specified time intervals can be projected from deviation of specified initial air consumption.

Primary consumers of compressed air were mentioned above. In the operation, the air is provided as a service air from service air bottle or from start air bottle through reduction valve. The pressure of the system controlled around 7-8 bars therefore, the consumption of the air is not highly dependent on start air pressure. However, in some cases, consumption and leakage volume increase in higher pressures. The increased demand will not exist in the case of the absence of the high pressures. If the system can operate its functions with lesser amount of air, the excessive usage of air and excessive leakage amount is called as artificial demand in the system. In a commercial ship, consumption amount of the air by ship can be around 40kg/h to 100kg/h according to system types and consumption volumes. Total operating consumption is expressed by following equation 3;

$$\frac{m_{air\_out}}{dt} = \dot{m}_{air\_cons} + \dot{m}_{air\_leak} \tag{3}$$

Where $\dot{m}_{\mathrm{air\_cons}}$ and $\dot{m}_{\mathrm{air\_leak}}$ are the total consumption by systems and leakages from system respectively. To meet this demand and keeping system in a steady pressure, air compressor feeds up the air bottles at the range high pressures. After a while, compressor stops and runs again to compensate consumption. In such a way, fluctuation in the system can be minimized. Depending on system capacity, total consumption, number and size of the compressors, control type of compressors varies. Main control types are inlet modulation, load/unload, variable displacement, variable speed, start/stop control, listed least efficient to most efficient respectively.

To perform an efficient operation of compressed air system, control type is an important factor but, for small size of compressors start/stop control, in use on ships, is the most efficient method for controlling pressure in the air bottles. The aim of this part to switch compressor control ranges to more efficient range. To achieve this objective operating principles of compressors must be well-known. Applying the knowledge to a mathematical model with a data taken up from ships allows simulate different pressure or leakage conditions. In this regard, effects of different parameters, mentioned above, on power consumption of air compressor or cost of air per unit for ships and also an evaluation can be easily done in terms of emission generation for the production of compressed air. The model allows this kind of calculations and comparing them with each other.

In the modelling of these system compression process is assumed as polytrophic process. The increase of pressure in the compressor described by polytrophic equations, that temperature change in the air can be expressed as a formula below which is assumed as a polytrophic compression as equation 4;

$$\left(\frac{P_{c\_out}}{P_{c\_in}}\right)^{\left(\frac{n-1}{n}\right)} = \frac{T_{c\_out}}{T_{c\_in}} \tag{4}$$

Where n is the polytrophic superscript constant used in the compression processes as the value range 1 to 1.4. The value has been assumed as 1.2 or 1.3 (Festo, 2016, Taheri and Gadow, 2017, Yu et al., 2014) in the studies.

Thus, the total work of the compressor to air can be calculated with the converting the general formula in equation 5 to equation 6;

$$Q = m.C.\Delta T \tag{5}$$

Where Q is the total heat work, $\dot{W}_c$, expressed in equation 6, done by compressor to the air.

$$\dot{W}_c = \dot{m}_{air\_in}\,\Delta h_{out-in} = \dot{m}_{air\_in}\int_{T_{c\_in}}^{T_{c\_out}} C_p dT \tag{6}$$

The temperature difference can be calculated with the *equation 4,* and *equation 6* can be transformed to *equation 7* to obtain electrical consumption of compressor $\dot{W}_{elec}$, which must include compressor efficiency varies by the forced air flow through to air bottle.

$$\dot{W}_{elec} = \dot{m}_{air\_in}.C_p.T_{in}\left(\frac{\left(\frac{P_{c\_out}}{P_{c\_in}}\right)^{\frac{(n-1)}{n}} - 1}{\mu_{comp}}\right) \tag{7}$$

μ_{comp} is the efficiency of the compressor which is calculated by adopting the relation between compressor output capacity, discharge pressure and electrical power consumption of compressor while in operation besides, this nomenclature includes both electric motor efficiency and compressor efficiency. By relating them, the efficiency expressed as a function of discharge pressure or can be called as adverse pressure of air bottle. However, measuring of compressor output flow requires flow sensors, implementing the measurement system to any ship is impractical. To simplify the matter, air flow can be calculated by using relationship of the increasing air pressure trend in the tube with the time via using mass-pressure balance equilibrium. In this method both compressor working characteristic and air consumption by other systems can be calculated.

To represent μ_{comp}, energy balance equilibrium can be written as in *equation 8;*

$$\dot{W}_{elec} - \dot{E}_{loss} = \dot{H}_{air\_out} - \dot{H}_{air\_in} \tag{8}$$

Where total electric consumption of compressor changes enthalpy of air passes through compressor. $\dot{E}_{loss}$ is the losses which represents, mechanical loses as friction by 10%(Festo, 2016), pressure drop, piping, storing, filter etc. Considering losses, efficiency can be defined by ratio of internal energy change in air and electrical power consumption by compressor. Enthalpy change also can be written depends on temperature difference of air.

$$\mu_{comp} = \frac{\Delta H_{air}}{\dot{W}_{elec}} \tag{9}$$

In compressor catalogues efficiency calibrated as minimum and maximum efficiency level of compressors. Maximum efficiency is accepted as a 100% efficiency for compressors. In this study equations 8 and 9 are used to calculate efficiency which includes all losses as motor losses and compression losses. Compressor model was adjusted via real compressor data and dynamic responses of the system have been changed in the model. If any enhancement of efficiency measures, that the model has capability to adopt to a new system model. The present study was performed to investigate potential energy savings in compressors which are operating in ships. The compressors fitted to ships to meet the required air demand by consumers.

Ships can have different air demands as a result of size of ships or different air consumer systems fed by. The operating data and compressor specifications are demonstrated in Table 1. The power consumed by compressors, measured current and voltage values, air bottle capacities (for each one), actual operating range of the compressors and loaded time (operating time of compressor in a specified time interval for instance; 12 min. in an hour corresponds 20% loaded time) are indicated for four different ships.

Table 1: Four Different compressed air system specifications

Ship Type	Ship A Bulk Carrier	Ship B Container Ship
Power	55.7 kW	44,1 kW
Electric Voltage	440 V	440 V
Electric Current	85 A	65 A
Air Bottle Capacity	9.5 m^3	5.5 m^3
Operating Range	24 - 28 bar	25 - 29 bar
Loaded Time	10.5 %	12,50%
Ship Type	**Ship C Container Ship**	**Ship D Container Ship**
Power	57.5 kW	160 kW
Electric Voltage	440 V	440 V
Electric Current	85 A	267 A
Air Bottle Capacity	12 m^3	15 m^3
Operating Range	27 - 29 bar	28 - 30 bar
Loaded Time	17,00%	18,00%

3. RESULTS AND DISCUSSIONS

According to the data obtained from ship, air bottle capacities, electric current, operating range, operating load and operation time demonstrated in the table 1. Additionally, by using the equation 9 efficiency is calculated in terms of operating pressure denoted as a function in Figure 2.

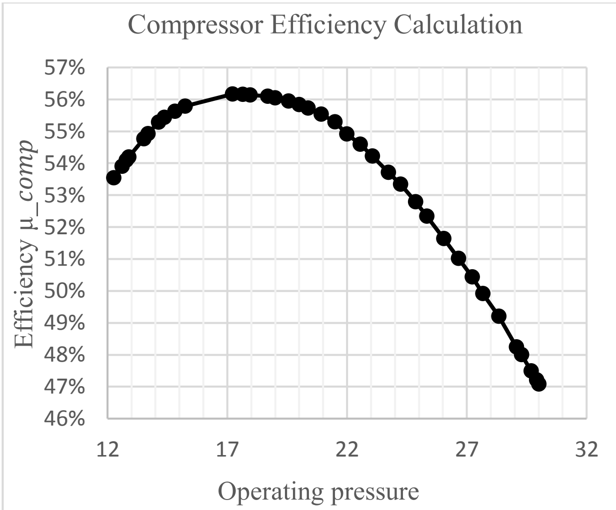

Figure 2: Efficiency of compressor as a function of pressure

The formula which represents compressor efficiency was embedded in the model. The mass of air ($\dot{m}_{air}$) in to the air bottles varies with the pressure by the virtue of intrinsic phenomenon of polytrophic compression process expressed in equation 4. According to the equation, it can be seen that, initial temperature of the air is directly affects efficiency of compressor. Since the variation of air temperature is unavoidable during voyage, effect of inlet temperature of air was not added to model. However, as indicated by Dindorf, reducing inlet air temperature costs less 1% power for per three degrees drop (Dindorf, 2012). Compressor working load is part loaded during operation which is indicated in table 1 between 10-20% time that, additional effort could not be paid to adjust air temperature around compressor all the time in the engine room conditions. That is why temperature effect is not investigated in this study. The simulation gives results according to activities that can be done without the initial investment cost of the selected compressors while considering safety issues or together with least expense solutions.

In the modelled system the simulation was performed according to consumption of air. Air utilization in considered ship systems is 90-95 kg/h and supplied by the compressor which is introduced in the table 1 specified as Ship D. Since the system pressure range is very close to maximum operating pressure which means compressor is not performing at optimum ranges and together with considering electrical consumption and loaded time for the system, these criteria makes Ship D best selection to work on it. Although pressure reduction has unfavourable effect on exergy stored for one cubic meter (Budt et al., 2016), high volume of air bottles in Ship D compensates this in navigational operations. To reveal operational savings and additional variables, pressure range scenario was applied to compressor model in ranges which are 29-30, 28-30, 28-29, 28-24, 28-23, 27-24, 26-23, 25-20, 24-19, 22-18, 22-16, 18-14 bars. As can be seen in the table 1 at other ship types minimum operating pressure is 24 bar but this pressure is higher than minimum required operating value in 9 bars given in DNVGL and sufficient airline pressure 8 bars for system. Minimum operating pressure adjusted to 14 bars in the model. Simulation results gave information with regard to pressure range in specified time interval; on power consumption, air consumption, unit compressed air cost in kW, leakage and consumption rate reduction which is called as artificial demand, fuel & money savings, and CO_2 emission reduction.

3.1 POWER CONSUMPTION

As can be seen at figure 3, in all cases power consumption of compressor is decreasing with the lower pressure ranges. These low consumption values depend on both increasing of compressor efficiency and decreasing of air usage in the systems. For the continuous operation (24 hours) in a day, day-wise power consumption is demonstrated. While operating pressure between 29-30 bars, the power consumption of compressor 518.9 kW/day, in the case of reduction in operating pressure, power requirement decreases. At minimum operating pressure range, power consumption can be reduced to 273.2 kW/day at the same conditions.

The increased efficiency of the compressor is effective in the required power. The efficiency increases 9.0% approximately near the operating pressures 17 bars.

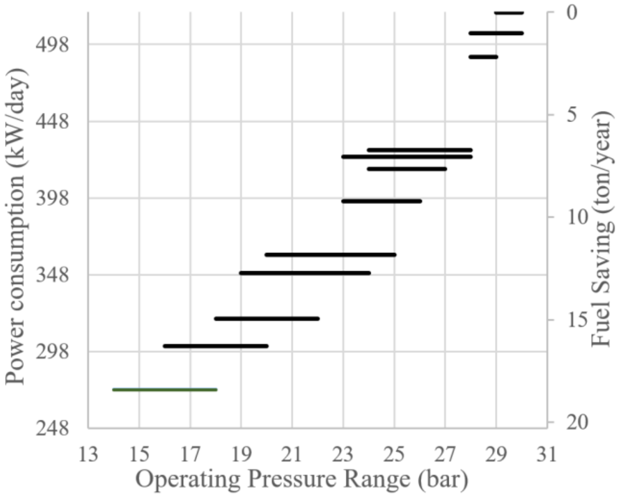

Figure 3: Power Consumption variation as a function of pressure in a day.

3.2 AIR CONSUMPTION

Total air consumption which comprises both system leakages and air utilization, is demonstrated in figure 4. The amount of air utilization is slightly affected by operating pressure range. The total consumption of air is decreased from 94 kg/h to 87 kg/h in specified case for an hour. The air consumption reduction is about 8.0% for maximum and minimum operating pressures. Despite the slight decrease of the air consumption, the reduction in power requirement is 47%. It can be said that a small part of power saving comes from saving in air utilization. The phenomenon is called as artificial demand that higher operating pressures cause higher air consumptions.

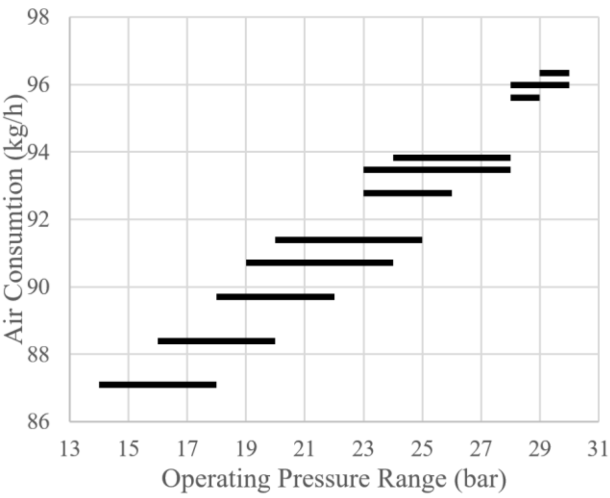

Figure 4: Air Consumption variation as a function of pressure

Since air consumption is resultant of consumption of air leakage and air utilization, variation in both parts are investigated separately in another case.

3.3 REDUCTION IN AIR UTILIZATION AND LEAKAGE

The air leakage measurement was carried out during without any air consumption by systems. The pressure reduction in the air bottle is assumed as leakage rate. The amount of leakage rate is much smaller than the amount of air utilization when compared. Typically, 2.3kg/h leakage amount measured when total air consumption is 94kg/h approximately at specified operating pressure range. With the decreased operating pressure, the leakage rate decreases. The reduction in both air utilization and leakage rate demonstrated in terms of percentage of initial usages. It is assumed as 100% both usage of air and leakage in maximum operating pressures. With the drop in operating pressures, both of the incorporated consumptions could be performed with lower amount of air. On the basis of this reduction is reducing the artificial demand for the system.

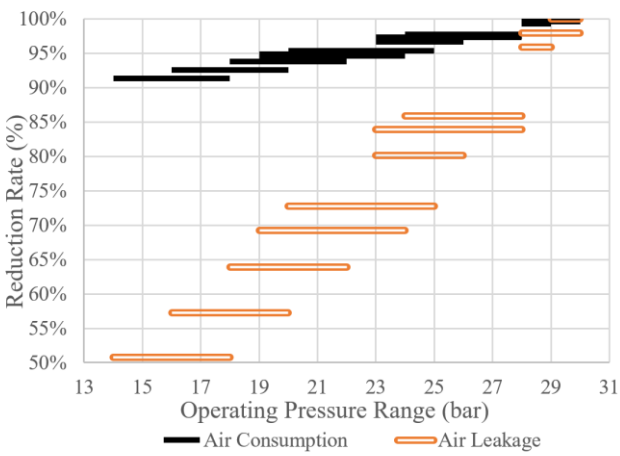

Figure 5: Reduction of artificial demands as a function of pressure

It is indicated in figure 5, reduction ratio in the leakage rate is much more than reduction in air utilization. While consumption rate of leakage is 50.8% of initial leakage amount, the air utilization is 91.3% of initial air consumption at minimum operating pressures. This representation shows air leakage depends on operating pressures more than air utilization for systems. The figure indicates that, ship system's air usage requirement is about 91.3% of total air usage at maximum operational pressures. The consumption amount can be accepted as a baseline. 8.7% of utilized air reduction is expressed as artificial demand and also can be eliminated by operating pressure reduction. Reducing pressures also gives a great advantage to reduce leakages. Halved leakage rate could be achieved with the reduced operating pressures, However the amount of the lowered leakage is relatively low when compared with the air utilization reduction. Additionally, variations of leakage conditions were investigated separately in next section.

3.4 COMPRESSED AIR COST

It is important to specify evaluation factor as "compressed air cost" from the point of view in kW/kg to make a neutral assessment. By the normalization of all factors as leakage rates and consumed amount of air, required power to produce per unit (kg) of air in terms of kW becomes a reliable indicator for observers. In the evaluated system, demonstrated in figure 6, compressed air cost 0.22 kW/kg at maximum operating pressures 29-30 bars. The value of compressed air cost could be reduced to 0.13kW/kg that provided in the case of operating pressure drop at 14-18 bars. Unit cost is independent of the air amount consumed in the system, it is an indicator of cost of qualified air which is capable of performing same systems.

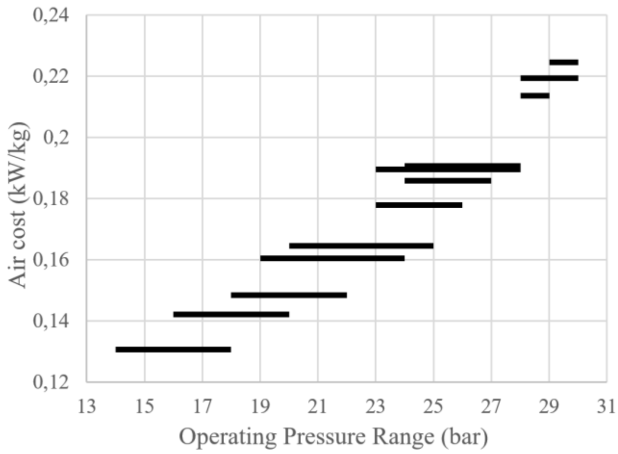

Figure 6: Reduction of Compressed air cost as a function of pressure

The minimized air cost is 60% of the initial cost. However total required power is 47% of the initial power requirement for the same operating pressure ranges. The favourable difference is caused by lowered leakage and air consumption rates.

3.5 SAVINGS IN FUEL AND FUND

Total possible saving in fuel is demonstrated in figure 3. The corresponding saving in dollars can be calculated from price of fuel. The savings calculated from simulation model and assumed that 300 voyage days' navigational operation for a ship in a year. Savings in fuel and fund assumed as 0% at maximum operating pressures. By the reduction of pressure steps, fuel and money savings could reach 18.4 tons of fuel and 7600 USD respectively for the fuel oil type with 380 cst and $413.5/ton price (Ship&Bunker, 2018). The values can be seen as small amount of savings when compared with annual operating cost of a ship. The results should be considered under the perspective that the study carried out without the initial investment cost. Such a perspective will enhance applicable area of these savings.

3.6 CO_2 EMISSION REDUCTION

Energy efficiency applications and saving fuel have positive effect on emission reduction. Since ships have only one energy source as fossil fuels, operational energy reduction directly saves both fuel and money together with taking care environment. Reduced emission value reaches 57.4 tons of CO_2 in a year in optimized operation of compressed air. Taking into account that global merchant fleet in the world exceeds 50k ships, adaptation of saving such methods in this perspective, without extra expenditure, an effortless attention can be paid for environmental aspect.

3.7 LEAKAGE ANALYSE

Leakage is crucial matter in compressed air systems in all facilities. This problem becomes more critical issue that ship has a moving and stretching structure. Because of the dynamical forces in sea conditions, compressed air system which includes numerous of pipes and junctions, prone to leak compressed air to outside. The acceptable value of leakage rate can be 2%-10% of the total air usage. In the ships leakage rates can exceed the acceptable values because of mentioned reasons. Air leakage does not leave any trace such as oil leak or water leak. It is very difficult to be noticed. Higher leakage rates cause the compressor to operate more and consume more power than desired. In the study the leakage rate is specified as 2.4% of utilized air which is assumed basic leakage from measured values and also used in previous section. The variation of leakage rates 5% – 10% – 25% – 35% – 45% were simulated in the model. The results as power consumption, leakage rate variation amount, air consumption, leakage flow and compressor load factor are investigated in terms of both variable operating pressure and increased leakage rates. Results are demonstrated in Figure 7-8-9.

The variation of leakage rates is given in Figure 7. The figure indicates that leakage amount decreases with the operating pressure drop in the all leakage rate cases. The maximum rate of the leakage is 45% could be lessened to 24.7% in low pressure operating conditions of compressed air system. The eliminated leakage amount is considerable for high initial leakage rates.

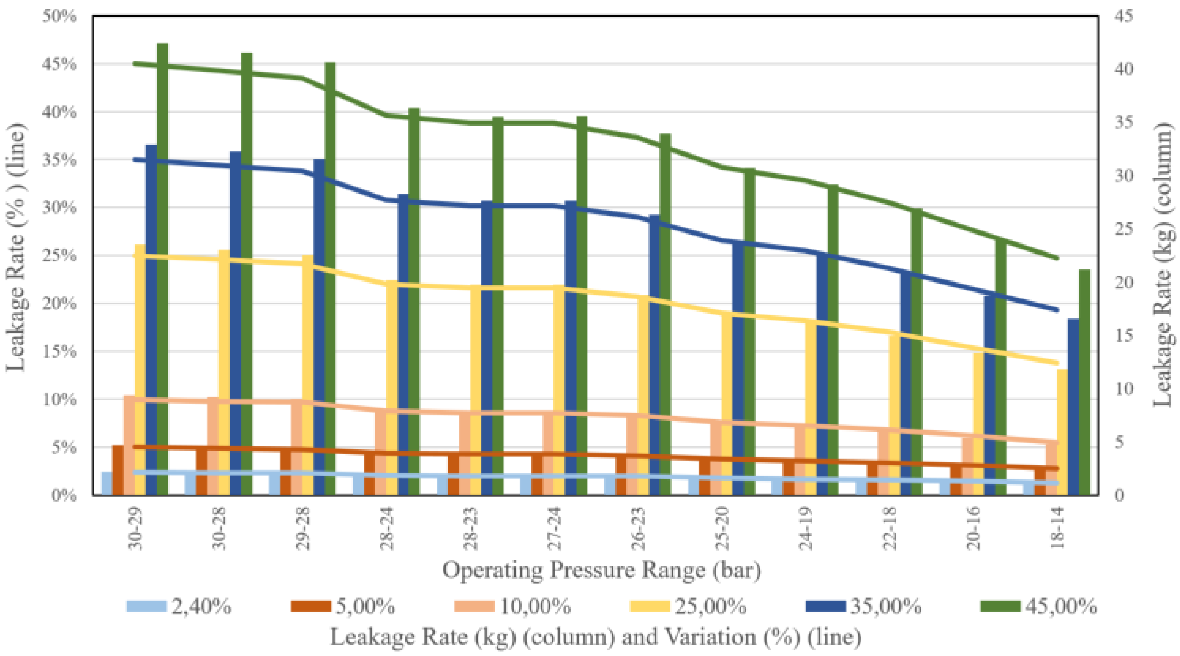

Figure 7: Leakage rate variation against operating pressure

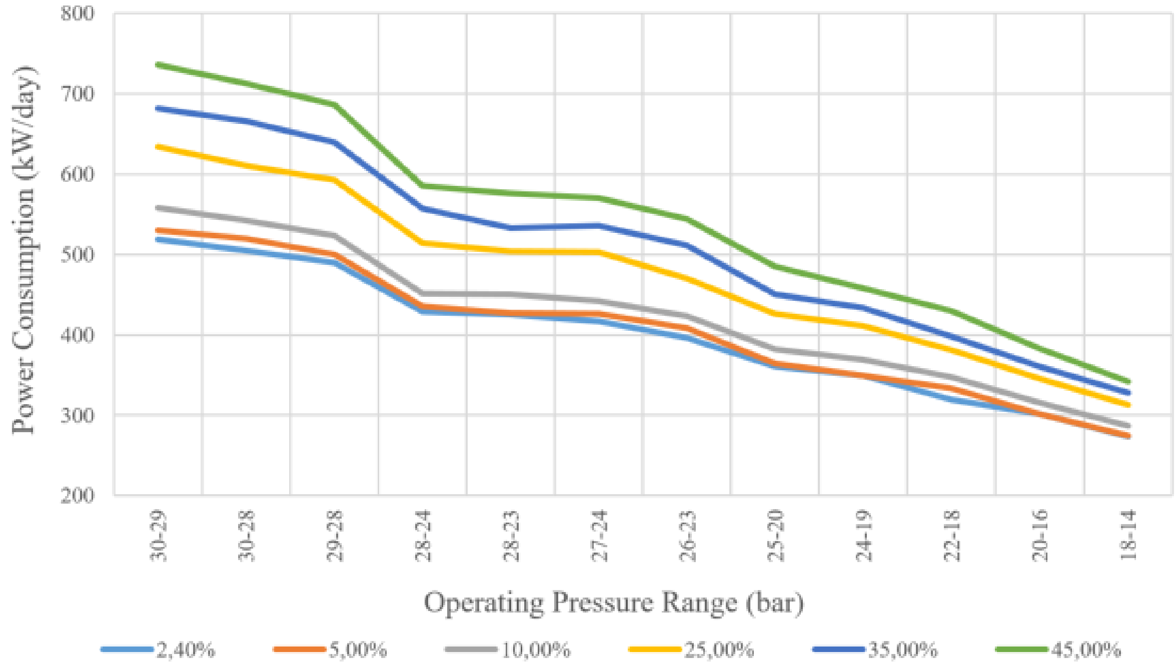

Figure 8: Daily power consumption with respect to pressure ranges and leakage rates.

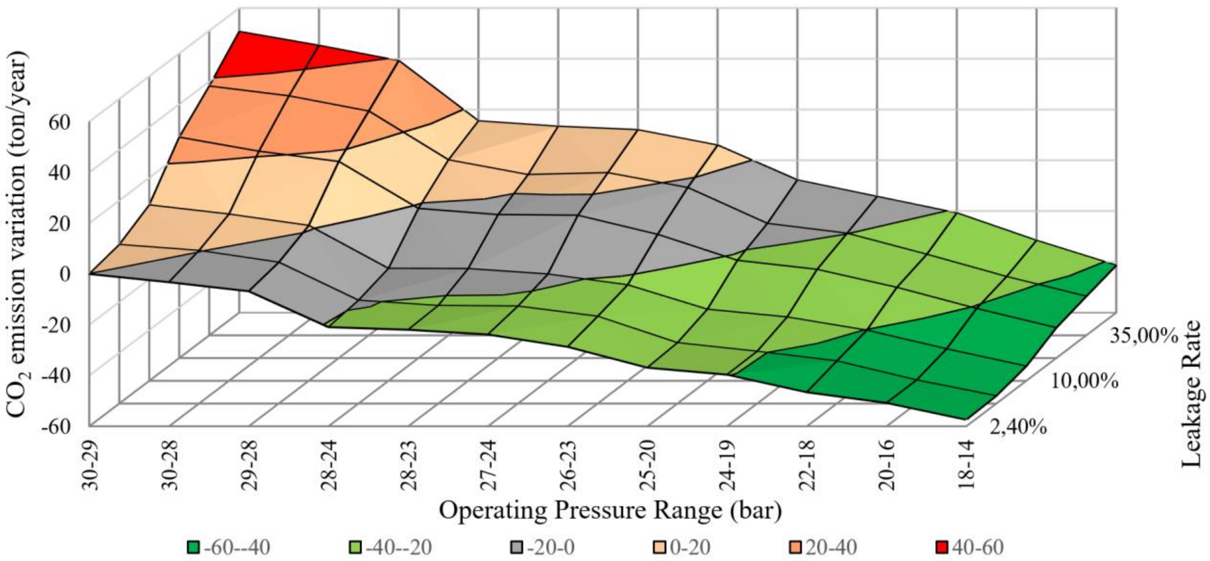

Figure 9: Amount of CO_2 emission change with the variation of Leakage rate and operating pressure.

Power consumption values increased at high leakage rates, given in figure 8. At the maximum operating pressures daily power consumption of compressed air system rises from 518.9 to 735.8 kW with an increase of 41.7%. The percentage indicator shows effect of the operational pressure at different leakage rates. While in the case of operating pressure 28-24 bars the ratio is 36.2% and for the minimum operating pressures, the power need rises 273.2 to 341.8 kW with a ratio of 25% which is the comparison of minimum and maximum operating pressures. If it is considered that the 45% leakage rate, the power requirement drops 735.8 kW to 341.8 kW, which also means lesser than half power. The values reveal that the pressure effect gains in importance at high level of leakages. While additional power requirement is 216.8 kW in the maximum operating pressure, the power need 155kW, 110kW and 68kW for the 28-24, 22-18 and minimum operating pressure ranges, respectively.

The air consumption is not affected by leakage volumes. Hourly leakage amount which is given in figure 7, increased 2.2 kg to 42.4 kg for an hour at maximum operating pressures. By the decreasing of operating pressures leakage amount drops. The leakage reaches 21.2 kg at minimum operating pressure with a maximum leakage rate. Leakage can be cut in half with operating pressure drop which also leads 216kW power reduction.

CO_2 emission generation demonstrated in figure 9 which changes by variation of pressure and leakage parameters. In the figure emission generation is compared with the initial condition as 2.4% leakage 29-3,0 bars operating pressure.

By the increase of leakage 2.4% to 45% CO_2 level climbs 50.7 tons more, demonstrated "red (+)". Reduction of operating pressure has favourable effect on emission. Operating pressure around 25 bars neutralize 45% excessive leakage which corresponds 29-30 operating pressure at minimum leakage rate. At minimum operating pressure condition, emission reaches maximum reduction level 57.4 ton, demonstrated as "green (-)" in the *figure 9* which was mentioned previous section and this favourable effect was smoothed over by increased leak rate about 16 tons. If considered case 45% leakage rate, operating pressure has a great effect on emission which differs 92 tons of CO_2. At the other hand, at minimum operating pressure range leakage effect is 16 tons while at maximum range 50.7 tons that another favourable effect of operating pressure at higher leakage conditions.

Compressor load is an important indicator of exceptional cases. In the case of any leakage, excessive consumption or inefficiency of compressed system, it can be foreseen any defectiveness existence. Load factor which means ratio of operating time to elapsed time includes both operating and idle time.

$$Load\ Factor = \frac{Time_{loaded}}{Time_{loaded} + Time_{idle}} \tag{10}$$

Time interval of compressor switch on period is another indicator of load factor. For instance, while in a proper running system, load factor can be 10 minutes, in a problematic system it can drops even further which means increase of load factor. Load factor variation is demonstrated in figure 10. By comparing of time intervals of activation of compressor operational efficiency can be realized.

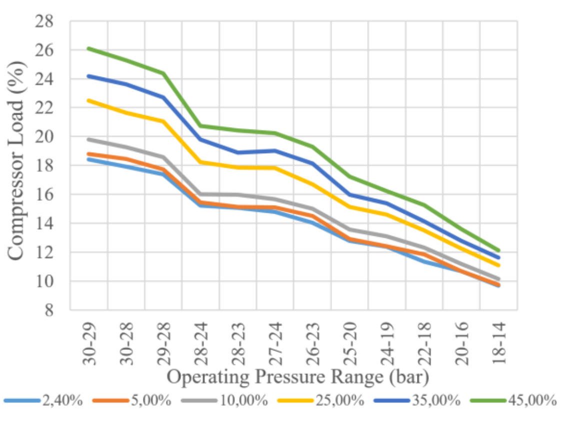

Figure 10: Compressor load variation with the leakage rates

Increase of the load factor from 18.4 to 26 responds as a power consumption increment from 518.9kW to 735.8kW per day, in maximum operating pressures as mentioned in previous section. At the other operating pressure ranges, load factor decreasing with pressure drop and increasing with leakage increment. Reduction in operational pressure has more advantage at higher leakage rates both on diminishing the amount of and keeping compressor at similar loads. It can be clearly seen that changing in load factor is a response of the any imperfection in the compressed air system. An estimation can be accomplished by considering and comparing load factor with base conditions.

4. CONCLUSION

To accomplish energy efficiency plan in an extensive manner, all energy consumers must be analysed in a deeply conception. Energy efficient operation of compressed air is investigated in this study. According to analysed system, a low-cost method, reduction in operational pressures, carried out in system model to reveal possible operational savings. System air consumption and leakage rate data were embedded in to model. Except manoeuvre and departure from port operations, excessive pressures are not required for compressed air system. By considering of operating priorities and safety issues, different pressure ranges performed on the system. Results of the simulation indicate power need of compressor, leakages and compressor load were diminished while air consumption slight decrement which can be ignored at lower operating pressures. Leakage is un avoidable matter in compressed air systems. Rate of the leakage in acceptable range up to 10% and excessive leakage up to 45% were performed in the model. Leak amount, consumption change, and compressor operational load were observed. Power requirement and compressor load are increasing, while air utilization has stable value at higher leakage rates. It seems compressor load is an essential indicator of imperfection of the system. To avoid excessive leakages, leaks must be detected. To identify location of leaks, it is easy to use mobile ultrasonic acoustic devices, that can detect hissing noises and have capability of diagnosing high frequency noise sources.

Operating of compressor in high time-loads has unfavourable effect on compressor components as valves etc. and lessen efficiency of the operating duration of these components. As an additional outcome, economic life of the equipment and components must be considered in such conditions. This operation not only comes out with an inefficient operation and wasting energy together with emission generation but also reduces of economic life time of the components. Efficient operation of compressed air systems has non-energy benefits on life time of components need more research to reveal (Nehler, 2018).

The results, taken from the model, may seem inconsiderable when compared with the total operating costs of ship however, the higher saving values can be attained by the combination of solutions without initial investment cost and such applications with low expenses. To achieve desired energy saving rates in total, energy consumption routines of people should be modernized (Bilgen and Sarıkaya, 2018). If global fleet capacity is considered, implementation of these type of actions has world-wide consequences on substantial amount of fuel saving and emission reduction. Implementation of such applications in maritime industry will enhance efficiency policy in both cases of design and operation (SEEMP&EEDI&EEOI). By figuring out of these applications by MEPC as an advisory opinion or as an enforcement, considerable amount of reduction can be achieved at first step just with operational tricks without initial investment or with low expenses. Since the modelling, which used in this study, enables growth that capabilities of model can be enhanced with embedding additional data in it. The results of such simulations allow mariners to be aware of potential savings at operations thus, the results are useful for training and workshops and encourage engineers pay more attention to, measure efficiency of systems, minimization of loses and monitoring.

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