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Journal of ETA Maritime Science

JEMS JOURNAL

Editorial (ED)

We are pleased to introduce JEMS 8(1) to our valuable followers. There are valuable and endeavored studies in this issue of the journal. We hope that these studies will contribute to the maritime industry. I would like to mention my gratitude to authors who sent their valuable studies for this issue, to our reviewers, to our editorial board, to our section editors, to our foreign language editors who provide quality publications by following our publication policies diligently and also to layout editors who spent great efforts in the preparation of this issue.

Your Sincerely.

Editor-in-Chief
Prof. Dr. Selçuk NAS

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Journal of ETA Maritime Science
JEMS JOURNAL

Understanding IMO 2020

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In 2020, the International Maritime Organization (IMO) required bunker fuel used by the global shipping industry to lower sulfur content from 3.5% to 0.5%. As a result, fuels will require blending with low sulfur products like diesel. Followed by radical changes and significant costs to all players. We experienced the IMO 2020 sulfur regulations significantly increased pricing for global transportation fuels broadly. This stands to benefit those who can most efficiently produce low sulfur refined products (complex refiners) while potentially creating inflationary costs for global transportation and consumers.

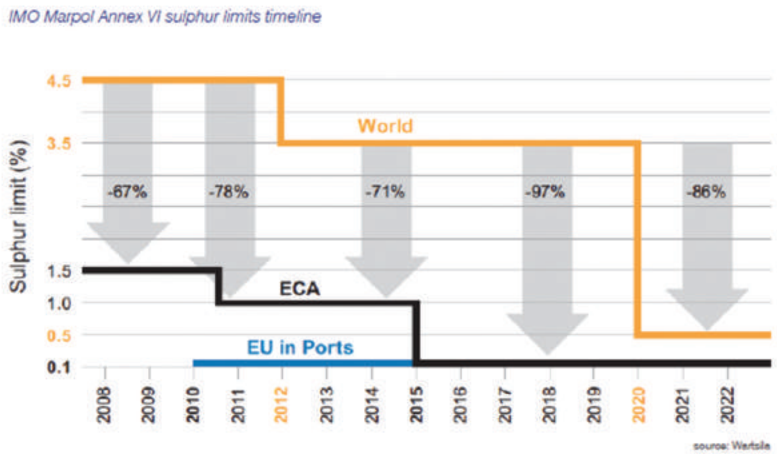

Figure 1. *IMO Marpol Annex VI sulphur limits timeline*

Emission standards rules were first discussed in 1973 during the International Convention for the Prevention of Pollution from Ships (MARPOL), and since 1997, these standards have become progressively more stringent, on a country-by-country basis, focusing on reducing greenhouse gas emissions (GHG).

Efforts have focused on regulating the sulfur levels in fuels used while ships are operating in defined coastal areas defined as Emission Control Areas (ECAs). These are generally located in high traffic coastal regions adjacent to Europe and North America (dark blue areas in the map below) and sulfur thresholds in these areas have systematically been

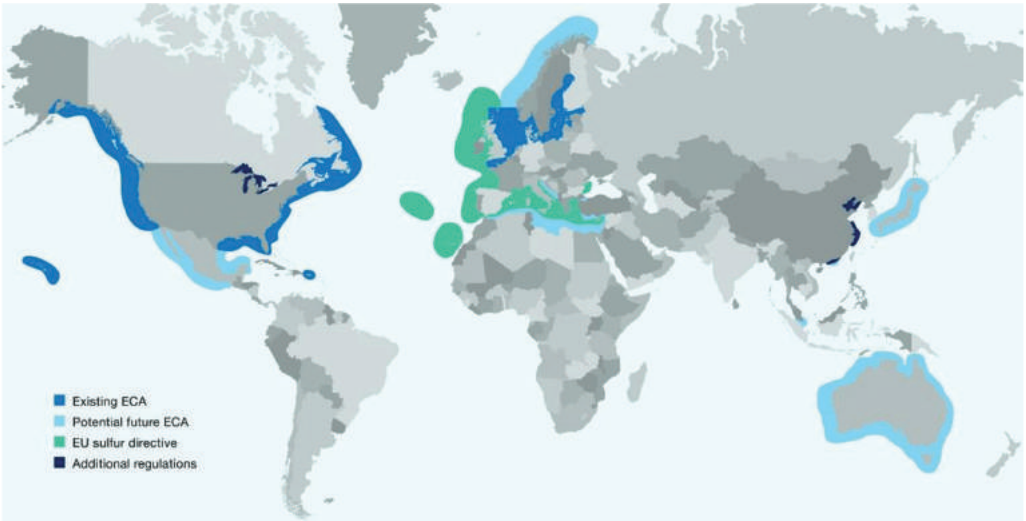

Figure 2.*Current and future Emission Control Areas (ECA)*

reduced until the latest update in 2015 which reduced this limit to 0.1% sulfur.

While the sulfur limits for bunker fuel usage in the ECA's are tight (tight enough that they can only effectively be met by using marine diesel), their impacts have not been substantial because total usage in these areas is quite small. A much bigger impact is expected when the new standards for "openwater" transit come into effect ("Global cap" in the chart below).In 2008 the International Maritime Organization (IMO) voted to reduce the global cap on sulfur emissions for international shipping to 0.5% (from the 3.5% which has been in effect since 2012)starting from 1 January 2020. In October 2016, the IMO reiterated the 2020 deadline, reducing the odds of a last-minute deferral. The latest figures provided by the IMO showed that the yearly average sulfur content of the residual fuel oils tested in 2015 was 2.45%. As a comparison, the worldwide average sulfur content for distillate fuel is 0.11%.

The change will have dramatic consequences on the refining industry and both crude oil and product prices. Normally, refineries don't make bunker fuel but instead they produce fuel oil (mostly vacuum tower bottoms and other related streams). Bunker fuel is primarily produced by blending terminals which purchase fuel oil from refineries along with distillates to produce a variety of bunker grades. Industry consultants have indicated that this market structure has the potential to constitute another source of problem for the industry in the 2020 transition.

Global fuel oil production was ~8mmb/d in 2016, of which ~4mmb/d (~38%) was used as bunker fuel, which represents the main application. Fuel oil is also used for electricity generation (a key area of potential future demand growth), heating and a variety of industrial purposes. The global oil product bunker market is dominated by residual fuel oil, accounting for ~80% of the market (with the rest being
marine gasoil).

Forecasted Product Portfolio Post 2020

This to provide a perspective on the bunker industry as it is today/currently, and a view of what the industry could look like after 2020 is in full implementation mode.

Prior to 2020

Simple product selection – in reality ship owners have two considerations to make: Do I need fuel that complies with Emission Control Area (ECA) specifications (0.1%) or do I need a fuel that is for international waters HSFO 3.5%. Of course some ship owners also have the option to go for higher viscosity fuels like RMK 500, 700, etc. or even less viscosity, e.g. RMG 180. However, there is not too much complexity around the fuel choices. We also operate in a market where from a supply perspective, the market is quite balanced.

Supplier / Customer relationship heavily relies on pricing – competitive pricing or cheapest price will win the deal 10 out of 10 times!

Credit is very liquid - partly as there are too many suppliers in the market and each bring a portion of credit to the market!

Connected to the credit point, is the fact that barriers to entry for new suppliers/ bunker traders are not very hard to overcome. Therefore, we have a very crowded competitor landscape (too many suppliers!).

Post 2020

There will be a very wide range on price differentials (spreads). Buyers must realize that poor bunker planning may result in having to buy the most expensive fuel option to comply with the new regulations. ”Fuel Oil Not Available Report” (FONAR) can not help when MGO is available at a port and the preferred fuel choice for the ship owner is VLSFO and VLSFO is not available at the port. Under this situation, they will have to buy the compliant fuel that is available, pricing is not one of the criteria to use a FONAR.

Having to deal or plan for multiple fuel options will be more relevant and as mentioned on the price differentials, this will have a very serious impact to customers if they have to buy the most expensive fuel due to poor planning.

With the introduction of VLSFO 0.5%, and the fact that the majority of the VLSFO fuels will be blended, understanding quality specifications will be critical in minimizing the potential challenges around compatibility and stability, among others like a wide range of viscosity.

As we mentioned, the supply

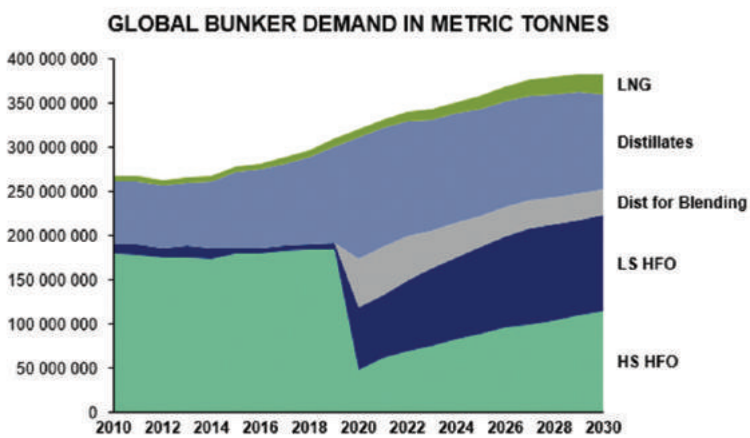

Figure 3.*Global Bunker Demand in Metric Tonnes.*

availability will be more complex. We are not predicting that there will be massive supply disruptions. However, buyers should anticipate that there could be times that their preferred fuel is not available and will end up having to wait for the next avails or having to buy the most expensive fuel.

We see the relationship moving from pricing (transactional) to a relationship based more on trust and how reliable your supplier is (emotional).

Credit liquidity will be challenged, and in a way it could be very similar to what we are projecting for fuel supply.

Pricing-Spread Analysis

Prior to 2020

Simple product selection – in reality ship owners have two considerations to make: Do I need fuel that complies with Emission Control Area (ECA) specifications (0.1%) or do I need a fuel that is for international waters HSFO 3.5%. Of course some ship owners also have the option to go for higher viscosity fuels like RMK 500, 700, etc. or even less viscosity, e.g. RMG 180. However, there is not too much complexity around the fuel choices. We also operate in a market where from a supply perspective, the market is quite balanced.

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I see the relationship moving from pricing (transactional) to a relationship based more on trust and how reliable your supplier is (emotional).

Credit liquidity will be challenged, and in a way it could be very similar to what we are projecting for fuel supply.

QUALITY IMPACT

From the supply side:

Challenge of handling multiple grades: MGO, VLSFO, HSFO but in addition the different specifications within the VLSFO blended fuels, different viscosity and other characteristics.

From the demand side:

Very similar to the supplier, prepare and be ready for procuring and handling multiple grades: MGO, VLSO, HSFO and how important it will be in the future to properly for bunkers. Poor planning can lead to having to buy the most expensive compliant fuel available and additional operations on board the vessel to handle the fuel switch over.

Advises to Shipowners and Academicians;

Blending and feedstock strategies. The best short-run source of low-sulfur fuel for shippers in marine gasoil (or a combination of marine gasoil and fuel oil), and, in our view, this will be the compliance strategy of choice for most of the shipping companies, at least in the early years. From a technical perspective, shipping companies are saying that technically it should be relatively easy to switch to a combination fuel (even if switching to pure gasoil may present challenges in some cases), with only minimal operational changes and no significant capital expense or time out of service. The two fuels combined could see an incremental demand of 1.2-1.5 MBD. Gasoil blending is the option of choice for Maersk. The largest benefit of this short-run option is flexibility, or capability to adjust to market dynamics. The largest negative could be lack of viscosity that impairs tanker engine performance with long duration untested fuel options.

Non-compliance / cheating. The IMO has no authority to monitor or enforce its own regulations, but rather has relegated compliance to the member states. Currently, both direct and indirect methods are used to monitor compliance in ECAs. These include in-port verification of bunker fuel paperwork and the monitoring of vessel smokestack emissions at sea using aeroplanes and, more recently, drones There are also large differences between the penalties imposed on non-compliant vessels in ECAs. The penalties imposed in North America are more severe than elsewhere. See Table 1 for this.

Scrubbers. Shipping companies can decide to equip vessels with exhaust gas cleaning systems (ie. scrubbers) which spray alkaline water into a vessel's exhaust, causing the removal of sulfur dioxide. The advantage of this approach is that it allows burning high sulfur fuel oil (set to become increasingly cheaper from 2020). The disadvantages is the high upfront investment requirement ($2-10m) per vessel (including the lost income during the installation phase), it is less proven on 2- stroke and 4-stroke engines (used in large shipping vessels), and increases opex by ~$400k per vessel per year (e.g. requires specialized personnel). There are also several uncertainties associated with this solution: firstly, if MARPOL legislation proceeds along the same lines as has legislation regulating the emissions from terrestrial motor vehicles, then future legislation can be expected to impose limits on pollutants such as nitrous oxide (NOx) and particulate matter that are not filtered by scrubbers. It also raises the issue of waste water disposal. Industry estimates suggest that only 300-400 KBD of the 2.5MBD high sulfur bunker fuel consumption can be absorbed by scrubbers in 2020. Further, while spreads may incentivise scrubbers as an option, the available dry dock capacity

Table 1.*Penalties for non-compliance to sulfur regulations in selected countries*

Country	Maximum financial penalty
Belgium	Eur 6 million
Canada	CAD 25,000
Denmark	No maximum
Finland	Eur 800,000
France	Eur 200,000
Germany	Eur 22,000
Latvia	Eur 2,900
Lithuania	Eur 14,481
Netherlands	Eur 81,000 + gains
Norway	No maximum
Sweden	SEK 10 million
UK	GBP 3 million
USA	USD 25,000/d

Source: *Trident Alliance*

to change over the fleet may be a limiting factor. In long term HSFO usage will increase due to newbuild vessels (see the graphic; Global Bunker Demand in Metric Tones)

LNG / Methanol. LNG- or methanol-fuelled vessels should be cheaper than 0.5% sulfur bunker fuels, generate lower emissions and protect vessel owners from future changes in emission standards (carbon dioxide, NOx, particulate matter). The disadvantages of these technologies are the high upfront capex requirements (LNG is best suited for new builds), and the lack of high capacity supply location. From an environmental perspective, a key risk is the emission of unburnt methane in the combustion process (known as the "methane slip"), which can substantially limit the greenhouse gas reduction from using LNG. Recent studies suggest that this issue has been practically eliminated in the most recent LNG engines. However, a recent environmental impact study promoted by the European Commission continues to rank methane slip as a key issue "requiring further investigation". LNG is certainly an important long-term driver, but we won't see a widespread adoption of this technology in the shipping industry in the very near term. However it can be research topic especially for academicians in long term with source handicap.

Ada Ezgi Başer

Born and raised in Istanbul with Turkish and French roots with a long term interest in the maritime industry. This interest led her to persue and receive her Bachelor degree from the Department of Maritime Transportation and Management Engineering at Istanbul University.

After graduating, she worked on VLCC tankers on Swedish company where through hard work, perseverance and diligence she rose to the rank of chief officer. This led her to a career which was often challenging but always rewarding where she was fortunate enough to travel and work globally and helped to foster an interest other culturest and perspectives.

Her quest for a new challenge has led her to bunker industry which affords new opportunities to work and learn globally. Currently she is working for Danish owned company named as Dan-Bunkering at Dubai office since Feb/2019. Beside her native languages Turkish and French she speak also English and Spanish fluently which she feel are essential languages for the trading of bunkers, dealing with internal and eternal stakeholders and developing new business. Friends and family are very important for her and in her spare time she enjoy their company. She is also a professional rhythmic gymnast since the age of four and also enjoy snowboarding, running, swimming and travelling.

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TC-UV Reactors Evaluated as an Alternative Option in Treatment of Ballast Water

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Abstract

Over the last decade, UV disinfection technology has been widely employed in the disinfection of non-native species in wastewater and process water treatment. In this study, we assessed the feasibility of the adoption of a Taylor-Couette UV reactor in disinfection of unwanted species commonly found in ballast water. With this purpose, glycerol solutions were used in a Taylor Couette reactor with two different radius ratios. The observed flow structures and the critical transition values were simultaneously compared with each other and literature. Emergent flow structures in TC reactors provide considerable improvement in axial and radial mixing of particles and increasing the efficiency of the disinfection of E. coli. The obtained results show the possibility of utilizing the Taylor-Couette UV reactors as an alternative method in inactivation of non-native species in the ballast water.

Keywords: *Taylor Couette flow, Ballast water, UV disinfection.*

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1. Introduction

Maritime traffic worldwide has significantly increased with the globalized economy and the international trade system. This rapid development in maritime transport has resulted in an increased amount of released harmful pollutants into the marine environment, such as oily bilge water, garbage, sewage, ballast water and tank washings [1]. These pollutants endanger marine life and influence the coastal environment, and significantly affect human health. Among them, ballast water is one of the most dangerous threats to the marine environment. Tens of foreign species are discharged into the marine environment via ships each period, and these species can lead to significant changes to the structure of marine ecosystems and extensive coastal destruction. They are also considered to be a potential threat to human health [2,3].

In order to prevent introducing invasive species into the seas, a global protocol (Ballast Water Management Convention) for controlling and managing ballast water and sediments coming from ships has been adopted by IMO [4]. Under the rules of BWMC, the available techniques used in ballast water treatment can be listed as the systems of ultraviolet (UV) irradiation, electrolysis, ozonation, mechanical and chemical filtration. Each of these treatment options has its own advantages and disadvantages. For example, while the electrolytic disinfection and biocide processes are accepted as an effective treatment method, they lead to considerable corrosion losses from the ballast tanks and generation of undesirable by-products and effluents resulting from the chemical reactions. On the other hand, the UV disinfection process is a well-known chemical-free process that does not generate any harmful by-products and has many other advantages. This method is already used in inactivation of various microbial pathogens contained in the ballast water [5–7] as one of the most widely preferred disinfection methods (~48%) in the ballast water treatment technologies [8]. Previous studies on UV disinfection processes have mainly focused on minimizing and mitigating the introduction of invasive species via ballast water. Among them, Wu et al. (2011) compared the efficiency of UV and UV+ozone (O3) processes in disinfecting *E. coli* (indicator microorganism) in ballast water. Their results showed that the combined treatment of UV+ozone was significantly more effective in reducing indicator microorganisms than the UV unit used alone [9]. Monroy et al. (2018) investigated the disinfection efficiency of a treatment unit, including UV-C process and mechanical filter at different temperatures. It is reported that UV-C irradiation has a higher inactivation efficiency at low temperatures [10]. Lu et al. (2018) investigated the use of a high-gradient magnetic separation UV titanium-oxide photocatalysis system to inactivate *E. coli* in ballast water. Their results have indicated that the proposed disinfection technology can be effectively used to inactivate *E. coli* in ballast water [11]. Jung et al. (2012) studied the efficiency of medium-pressure ultraviolet (MPUV) treatment unit for reducing several indigenous marine species in ballast water. They reported that when a combination of the filtration and the MPUV irradiation was applied, inactivation percentages of the tested organisms were achieved to be above 99.99% [12].

The previous studies showed that the UV irradiation is still one of the most widely used methods in ballast water treatment. Therefore, future efforts are to focus on improving the efficiency and the performance of the UV irradiation techniques. Recent studies show that Taylor-Couette UV (TC-UV) reactors have been used effectively as an alternative disinfection method for various fluids [13–17] in different industries. For more than a century, Taylor-Couette flows have been studied in fluid mechanics at a fundamental level, e.g. in proving the no-slip boundary condition and the Navier-Stokes equations describing the Newtonian fluid flow. Taylor-Couette flows are already used in different industries. The efficiency of rotating filter separators used in separation and filtration of suspensions is much higher than those of other filtration methods, due to a much thinner cake formation on the filter under radial flow effects. Because the centrifugal instability in Taylor–Couette flows during supercritical transition increases the axial and radial dispersion via nonwavy and wavy toroidal vortices [18]. Taylor-Couette flows occur between independently rotating coaxial cylinders, and more than 26 different flow states may exist in Taylor-Couette flows between counter-rotating cylinders for a radius ratio of 0.88 [19]. Rudman (1998) carried dye tracer experiments and determined axial dispersion coefficients via DNS simulations, and showed that these mixing characteristics depend on the azimuthal wavelength and number in the wavy flow [20]. Whereas, low axial mixing in TVF increase high separation efficiency in case of liquid–liquid extraction applications. With increasing the rotational speed of the inner cylinder, the toroidal vortices carry azimuthal momentum radially within the annular gap. When the flow becomes WVF with wavy vortices, the fluid particles is transferred axially between the adjacent vortices. Therefore, WVF flow provides significant contributions to the mixing of particles [21]. In this regime, the vortex centers move axially and radially. Thus, the vortices formed in the TC-UV reactors may provide effective radial and axial mixing with higher values of heat and mass transfer coefficients.

Moreover, the thickness of the cake layers occurred between fluid and the UV source is reduced, providing prolonged UV exposure periods for the invasive species and uniform radiation levels [14,22,23]. Forney et al. (2008) studied the effect of boundary layer and wavy walls on the inactivation efficiency of *E. coli* using concentric cylinders. They indicated that higher axial velocities with longer cylinders are required for inactivating *E. coli* at the turbulent flow. And, the inactivation of microorganisms was increased with the wavy wall modifications in TC flows [21]. Ye et al. (2008) determined the optimum disinfection efficiency of microbes in various flow conditions. Their results show that inactivation in the laminar Taylor Couette flow was found to have significantly higher efficiency compared to the inactivation at laminar Poiseuille or turbulent flow. They also indicated that the flow structure is one of the most important indicators to determine disinfection efficiency [22]. Orlowska et al. (2014) tested the performance of a pilot-scale TC-UV reactor for inactivation of *E. coli* at various flow conditions. They show that inactivation of *E. coli* is entirely dependent on the Reynolds numbers, and the flow regimes occurred in the gap. The results have also demonstrated that the microbial inactivation efficiency was decreased at Couette–Poiseuille (CP) flow relative to that at turbulent vortices (TV) [23].

Previous studies investigating the disinfection of microbial species in TC-UV reactors are primarily in the food industry. It is known that the emergent flow structures in TC-UV reactors are significant in improving the inactivation process of microorganisms. The flow structures formed in the annular gap and their critical transition values are unexplored in terms of UV disinfection efficiency in the marine industry. This study aims to develop a comprehensive understanding of the emergent secondary flows in TC reactors for improving the efficiency levels of the ballast water treatment. In this regard, the effect of the radius ratio and the inner cylinder Reynolds number (Re_i) on the secondary fluid flows were investigated through various values of the rotational rate of the inner cylinder. The experiments were conducted to determine the critical Reynolds number at which the secondary bifurcation in a TC reactor occurs and their effect on the treatment efficiency.

2. Materials and Methods

The Taylor-Couette setup used for the experiments in this study consists of two concentric cylinders and shown schematically in Fig. 1. The geometrical specifications of the TC setup and its characteristic dimensionless parameters are listed in Table 1. In order to examine the effect of the radius ratio on flow bifurcation, two different cylinder diameters were used in this study. Both the inner and outer cylinders can be rotated independently in the range of 5–300 rpm in order to reach the desired Reynolds number values after transition and compare the flow patterns. The rotation speed of the cylinders slowly varied. The inner cylinder is made of aluminium, and its surface is uniformly coated with black acrylic paint. The outer cylinder is made of transparent plexiglass to

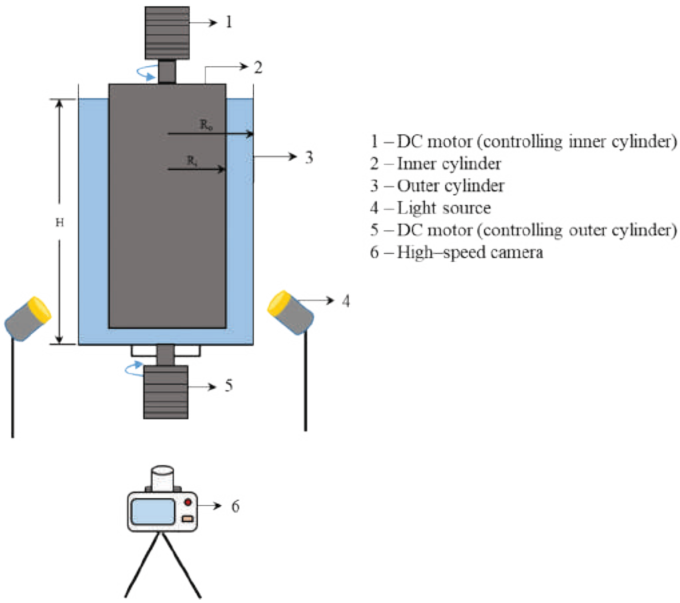

Figure 1. *Schematic View of the Experimental Setup*

Table 1. *Geometrical Specifications of the Cylinders and the Dimensionless Parameters*

Parameters	Abbreviation	Value used in the experiments
Outer cylinder radius [mm]	R_o	72 and 70
Inner cylinder radius [mm]	R_i	62.5 and 45
Active column height [mm]	H	400
Gap [mm]	d	9.5 and 25
Radius ratio	η	0.868 and 0.643
Aspect ratio	Γ	~42 and 16

obtain better visualization. The rotational rate of the inner cylinder is measured using an optical tachometer.

Two different concentrations of glycerol solutions were used as a working fluid. The rheological properties of the test fluids used in the experiments are presented in Table 2. Dynamic viscosity of the working fluids was determined using a rheometer by Anton Paar, MCR 302. The viscosity measurements were performed in a water bath controlled with a Peltier system and repeated at least three times for each solution. The precision in viscosity measurements was about ±0.5%. A reflective digital tachometer with an accuracy of ±0.05% was used to measure the rotational rate of the inner cylinder. The emergent flow patterns in the gap have been visualized using reflective flakes. These particles have unique properties that they align themselves with the direction of the flow, and their contrast reflection makes it possible to visualize the various flow structures. Flow visualizations were recorded at a rate of 200 fps by a high-speed CCD camera (Phantom Miro eX4) with 800×600 pixel resolution. The acquired images from the experiments were then enhanced via post-processing by adjusting the brightness and contrast.

Table 2. *Rheological Properties of the Glycerol Solutions Used in Experiments*

Solution	ρ [kg/m³]	μ [Ns/m²]
Glycerol 60 wt%	1148	0.0096
Glycerol 75 wt%	1187	0.028

For a Newtonian fluid flow between concentric cylinders, the Reynolds number, Re for a system with the inner cylinder rotating only is the inner Reynolds number, Re_i and defined as;

$$\mathrm{Re}_i = \frac{\rho\,\omega_i R_i d}{\mu} \tag{1}$$

where ρ is the fluid density, R_i is the inner cylinder radius, ω_i is the rotational speed of the inner cylinder, and μ is the fluid viscosity. In this system, the azimuthal flow is forced by rotating the inner cylinder at the desired rate. The critical conditions of the primary and secondary flow transitions are defined by the critical Reynolds number, Re_c.

In this study, the inactivation ratio was calculated for *E. coli* inactivation in ballast waters and follows the first-order kinetics, and given by

$$\frac{N}{N_0} = \exp(-k \times E) \tag{2}$$

In Eqn. 2, N is surviving population after exposure to UV influence (CFU/mL), N_0 is the initial concentration of *E. coli* (CFU/mL), k is first-order inactivation constant (cm^2/mJ), E is UV influence (mJ/cm^2).

The Lambert-Beer's law was used to determine the UV irradiance distribution in the annular gap. If the UV lamps are placed inside the inner cylinder, the UV irradiance distribution can be calculated using Eqn. 3 [24]. The general UV light irradiance (I) within the annular gap is obtained using Eqn. 4 [23].

$$I(r) = I_0 \frac{R_i}{r} \exp(-\alpha(r - R_i)) \tag{3}$$

$$I = \frac{I_0}{\alpha d}\left[1 - \exp(-\alpha d)\right] \tag{4}$$

where α is the absorbance coefficient (cm^{-1}), and I_0 is UV irradiance at the surface of the UV source. Then, the inactivation rate for a TC reactor can be defined as follows;

$$\ln\left(\frac{N}{N_0}\right) = -\frac{k I_0 \tau R_c}{\alpha d} \qquad R_c = \frac{2R_i}{R_o + R_i} \tag{5}$$

The absorption coefficient was taken as α=0.5 cm^{-1}, and UV doses were applied in the range of 5 to 25 mJ/cm^2.

3. Results and Discussion

In the present work, the critical transition values and the flow patterns for Newtonian fluids in a TC setup were investigated to assess the use of the proposed treatment method as an alternative method in ballast water treatment. The critical Reynolds number values at which the flow undergoes a transition from laminar Couette flow to Taylor vortex flow were determined experimentally by flow visualization and presented through the space-time plots in Fig. 2. In this figure, the evolution of the flow bifurcations can be clearly seen, and the flow patterns characterize the flow regimes. The boundaries between two counter-rotating Taylor vortices are stationary and this can be seen in these observations (Fig. 2). As the rotational rate of the inner cylinder is increased from the rest, the instabilities cause the flow to experience various flow regimes corresponding to several transitions depending on the azimuthal flow velocity and the radius ratio. The flow patterns and the critical Reynolds number values for Newtonian fluids were compared with the experimental results reported by Andereck et al. (1986) and Nemri et al. (2013). The results obtained in this study show good agreement with their results. In the case of a Newtonian fluid, with increasing the inner cylinder speed from the rest, Couette flow was primarily observed at the whole gap in the cylinder at the beginning, and then Circular Couette flow (CCF) with Ekman rolls near the top and bottom of the cylinders was developed at Re=120. As the Reynolds number is increased to a critical value, primary bifurcation, at which the flow is transitioned from CCF to Taylor vortex flow (TVF) appeared at Re=125. The flow patterns were found to be stable in the range of 125≤Re<153 at this regime. At higher speeds, the flow becomes unstable, and the secondary bifurcation of Wavy Vortex Flow (WVF) transition was observed at Re=153. As the flow state becomes Wavy vortex flow, the vortices deform axially and radially, and become azimuthally wavy. The fluid particles move chaotically and lose their circular motion in this flow state. Akonur and Lueptow (2003) carried out experiments on TC flows and showed that the wavy motion enhanced mixing for a rotating inner cylinder only. The occurrence of traveling waves in WVF enhances fluid exchange between adjacent vortices resulting in more efficient mixing in WVF than in TVF (Nemri et al., 2014). The degree of mixing within the vortices is proportional to the efficiency of separation and filtration. Akonur and Lueptow (2003) also stated that Taylor vortices transport azimuthal momentum radially and axially in Wavy vortex flow. The waviness comes from the jet-like azimuthal velocity profile [25]. The axial particle transport increases with increasing Reynolds number.

The secondary flows that occur after the onset of transition in TC flows have a significant impact on the efficiency of TC-UV reactors because secondary flows generate significantly more circulation and migration between the cylinders than laminar flows. It also affects the durability of UV lamps and light absorbance. Therefore, the accurate determination of the critical point to the transition and the control of the flow structures is important in understanding and then, increasing the TC-UV reactor performance in ballast water treatment.

It is shown in Fig. 3 that the number of emergent vortices and the wavelength of each vortex depends on the radius ratio. The flow structures are usually characterized by both the number of vortices and axial wavelength. For η=0.868, the axial wavelength and the number of vortices were found to be λ=20.35 mm (2.14d) and 42, respectively. Whereas in the large gap (η=0.643), 16 time-independent axisymmetric toroidal

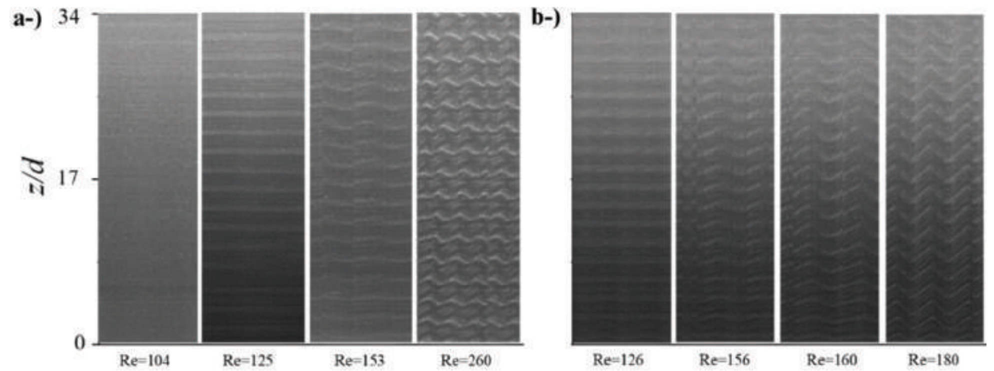

Figure 2. *Space–time Plots of the Various Flow Regimes for the Glycerol Solutions a-) 60% b-) 75%*

vortices by an axial wavelength of λ=50.51 mm (2.02d) were determined. The radius ratio affects the distribution of UV light within the TC reactor system, which is directly proportional to the exposure time. Therefore, the inactivation of *E.coli* is increased with increasing the exposure time and decreasing the gap between the cylinders. The mixing and transportation of microorganisms and suspended solids are expected to be enhanced at higher radius ratio setups compared to the wider gap systems.

Figure 3. *Formation of Taylor Vortices in TVF in Narrow and Wide Gaps*

The inactivation rate constant (k=0.43 cm^2 mJ^{-1}) for *E.coli* used in the present study was obtained from Martínez et al. (2014) [26]. The inactivation of *E. coli* using the TC-UV reactor was compared with that in a conventional UV (C.UV) reactor, and the results are presented in Fig. 4a. It can be seen that significant enhancement in *E. coli* inactivation efficiency is obtained in the TC-UV reactor compared to C.UV reactor. Results show that inactivation of *E. coli* in TC-UV reactor is increased by 36% when compared to C.UV reactor. This increase in efficiency is due to the vortex structures formed in the gap, promoting better mixing and longer contact times. The inactivation of *E. coli* is significantly increased with the Taylor vortices due to migration of microorganisms from the stationary outer wall towards into fast-moving region near the inner wall. The microorganisms and suspended solids will be displaced only within the vortex boundaries, which provide an increase in the exposure time of microorganisms. Moreover, Orlowska et al. (2014) indicated that the inactivation rate was increased by approximately 10-12% when the flow structure was transformed into other flow patterns. The measured inactivation rate values in Orlowska's study was used in the present study to determine the effect of the flow structures on the inactivation of *E. coli*. The inactivation rates of *E. coli* in TVF and WVF are shown in Fig. 4b. This figure clearly shows that the inactivation rate is increased as the flow structure is transitioned to WVF. Although the inactivation efficiency is lower in TVF, it is seen that it shows better results than the C.UV reactor. Axial and radial mixings are enhanced because of wavy flow, which leads to producing upward and downward vortex deformation and particle exchange. Moreover, the duration of exposure times of UV radiation increases and leading to a slight increase in the efficiency of inactivation of *E. coli*.

The choice of the gap in deciding TC-UV reactor design is a crucial aspect since it influences the disinfection efficiency in the overall process significantly. The velocity and the shear-rate distributions are altered considerably depending on the gap, and consequently, the overall disinfection efficiency is affected. From Fig. 4a it can be seen that the disinfection efficiency of *E.coli* is increased with increasing radius ratio. In the larger gap, the UV light intensity decreases across the gap and thus reducing the inactivation rate of *E. coli.*

Ballast water contains different kinds of harmful bacteria, sediments and suspended solids. Schematic representation of the transportation of these pollutants and the velocity distribution in C.UV and TC-UV reactors is shown in Fig.5. In C.UV reactors, the build-up of a fouling layer that affects the UV radiation efficiency is one of the most serious problems in this type of disinfection processes. The percentage of surviving *E. coli* is increased with decreasing UV radiation efficiency. Moreover, pollutant accumulation on the UV tube surfaces increases energy consumption with more

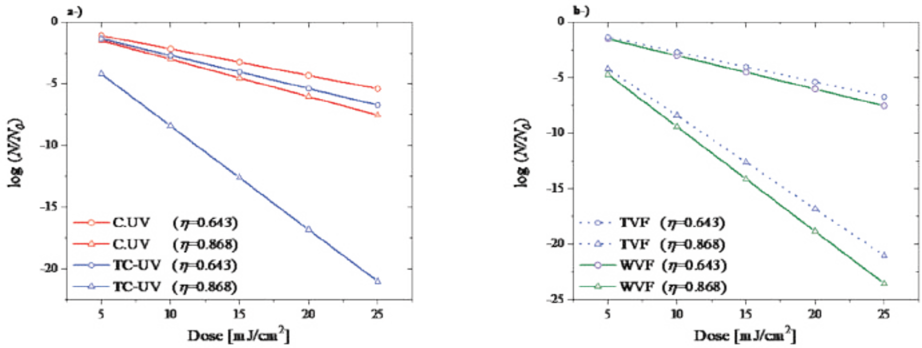

Figure 4. *Inactivation Rates of E. coli a-) in C.UV and TC-UV reactors, b-) at various flow structures in TC-UV*

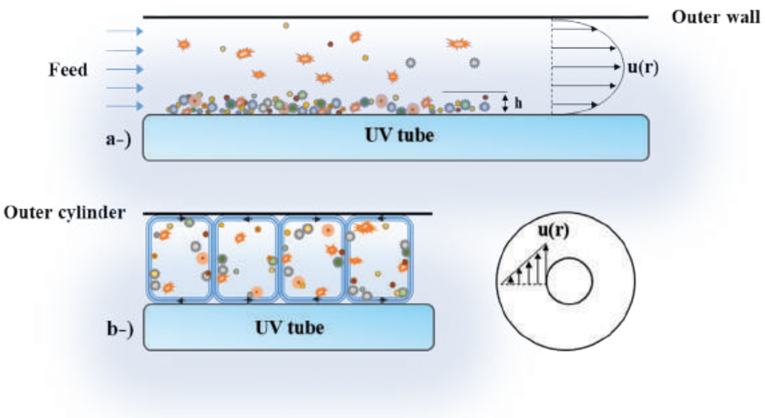

Figure 5. *Schematic Representation of the Transport of Suspended Sediments and Non-native Species in a-) C.UV and b-) TC-UV reactor*

frequent cleaning needs and reduces the lifespan of UV reactors. Whereas, the Taylor vortices emergent in the TC-UV reactor provides a self-cleaning of the tube surface of the inner cylinder. The rotation of the inner cylinder significantly enhances the mass transfer radially and azimuthally within the secondary flows in and between two adjacent vortices. Therefore, TC- UV reactor come into prominence as a ballast water treatment system with higher efficiency.

The influence of the co- and counter-rotating of the outer cylinder on the appearance of the flow structures and the critical Reynolds number was also investigated for a Newtonian fluid. It was observed that the critical values of the Reynolds number and the flow patterns change when the outer cylinder rotates at constant angular velocity. A variety of the flow bifurcations and patterns in the gap has been observed when the cylinders counter-rotate. Spiral vortex flow (SVF), ribbon (RIB) and interpenetrating laminar spiral flow (IPS) structures are observed and shown in space-time plots in Fig.6. Fig. 7 shows the flow regimes map obtained from the visualization experiments which helps understand the effect of the rotating speed and its direction on the flow patterns. From the perspective of the disinfection of harmful bacteria, each flow regime gives information about the flow characteristics, e.g. Couette flow (CCF), Taylor vortex flow (TVF), wavy vortex flow (WVF) and spiral

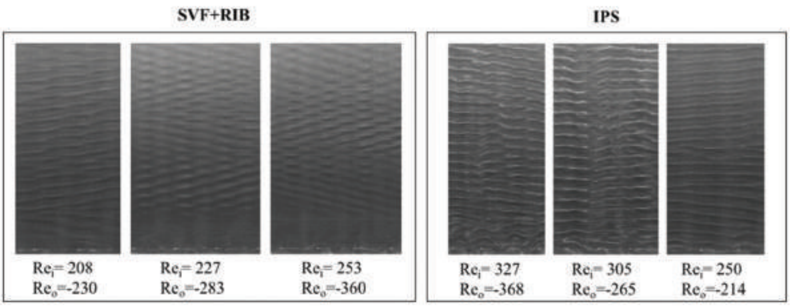

Figure 6. *Emergent Flow Structures in a TC Reactor with Counter-rotating Cylinders*

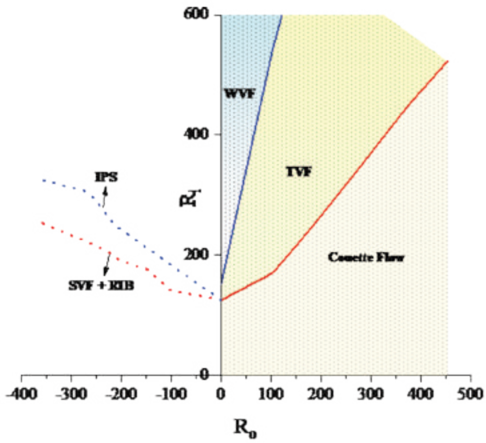

Figure 7. *Critical Transition Boundary Lines of the Various Flow Structures Observed in A Proposed TC-UV Reactor (η=0.868)*

flow. The disinfection efficiency of a TC-UV reactor is directly influenced by the flow pattern within the gap. For example, the occurrence of the WVF structures is associated with the deterioration of a vortex cell and the appearance of flow instabilities. Moreover, these flow patterns increase UV disinfection efficiency due to secondary flow behaviors. Therefore, knowing the flow structure in the gap makes of great practical importance, e.g. contributing to the increase in the inactivation efficiency of non-native species from ballast water.

4. Conclusion

In this study, the critical transition values for various flow patterns in terms of Reynolds number were obtained using glycerol solutions. The effect of radius ratio and the rotation direction of the inner and outer cylinders on the emergent flow patterns were experimentally characterized and compared. The most commonly used treatment process in ballast water treatment is the UV irradiation method. In this study, it is reported that TC-UV treatment unit achieved higher disinfection efficiency comparing to the conventional UV processes for which the results were obtained from the literature. The disinfection efficiency is strongly dependent on the characteristics of the flow structures in TC-UV reactors. Axial and radial mixings are enhanced in TVF and WVF regimes promoting continuous particle migration within the annular gap, i.e. the duration of exposure times of UV radiation increases. The inactivation of *E. coli* in TC-UV reactors with the appearance of the TVF structures is increased by 36% when compared to C.UV reactor. It is also shown that the disinfection efficiency of *E.coli* is increased with increasing radius ratio. The primary objective of this study was to determine the critical transition values of the flow structures which may occur in TC-UV reactors, and provide an excellent basis for further development and evaluation of an alternative UV treatment reactor for the inactivation of non-native species in ballast water. It is reported that TC-UV reactors are promising treatment units protecting the marine environment effectively and efficiently.

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A Study on Working and Living Conditions of Turkish Seafarers

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Abstract

In order to increase the number of well-qualified and well experienced seafarers on ships and their employment periods, as well as providing the desired safety at work, improving/promoting the working conditions on ships, is of utmost significance. The purpose of this study is to reveal to what extent working conditions for Turkish seafarers who work on commercial ships comply with the terms of MLC (Maritime Labour Convention). For this aim, a questionnaire, an instrument of quantitative research method, was issued and conducted through 296 seafarers working on the ships owned by Turkish shipowners. The results of the comparative analysis reveal that the working condition on Turkish-owned ships is moderately compliant with the terms of MLC.

Keywords: *Seafarer, Maritime Labour Convention, Working and Living Conditions, Human Resource Management.*

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1. Introduction

The number of researches carried out by labour unions and the relevant experts on determining the international working standards and protecting the rights of employees seems to be rather low in the 20th century. However, since the 1980s with the rise of the global workforce, there has been a need for determining the international working standards [1]. International companies have taken measures aiming to reduce the costs of the workforce, which have damaged the rights and the working conditions of workers. In order to eliminate such damages, the struggles of certain non-governmental organizations have brought about certain standards for working conditions, aiming to protect the rights of workers/employees [2]. Increasing the effectiveness and practicability of the international workforce and integrating it into the obstacles brought about by globalization is one of the most critical responsibilities of ILO (International Labour Organization). There has been a need for standardization in the transport and trading industries, the most widened and broadest ones within global sectors. Thus ILO has adopted the Maritime Labour Convention (MLC), having gathered the relevant standards together [3]. Seafaring has always been a profession with special legal protection in history. Due to the difficulty of the working environment and the power imbalance between ship-owners and seafarers, the necessity of protecting seafarers' rights and benefits were accepted as a reality [4]. Being on board of foreign flag ships and working in international conditions can cause exploitation of seafarers' rights by decisions for the benefit of ship-owners [5].

The harshness of the living and working conditions on board ship affects the mental and physical health of the seafarers and thus result in accidents and mishaps [6]. Seafarers are considered the most isolated groups due to their working environment. Because they work in the sea for months without contacting other than their colleagues, and they live on ships with working environments [7]. In addition to this, it is known that stress levels of employees that are bound to live and work in closed quarters for long periods of time tend to be higher than those who work in regular workplaces. In the maritime industry, living and working in the same closed space, lack of socializing possibilities, limited communication with family and friends, and feeling of entrapment have negative effects on productivity and health of employees [8]. The pursuit of competitive advantage in the maritime labour workforce results in shipowners trying to cut the costs, starting from the seafarers, which in turn, makes the working conditions worse. This fact pushes experienced and qualified seafarers out of the profession, and thus the uncertainty in the maritime labour workforce continues [9]. The increased use of technology on-board ships and the competitive environment in the marine industry are the reasons behind the employment of the lesser amount of personnel on ships, and these personnel are chosen among the cheaper workforce of developing countries. This situation births another problem, which is the abuse of seafarers, with little to no regard for their rights [10]. By taking these facts into consideration, it is required to make seafaring a profession that is reputable and preferable, by improving the working and living conditions and preventing the abuse of the workforce. This study aims to reveal whether the working and living conditions of seafarers working on Turkish flagged ships meet the conditions specified in MLC. The significance of this study is that it provides results that can be used to improve the status of the maritime profession and decrease the rate of qualified personnel leaving the profession, through the evaluation of the deficiencies in the working and living conditions of seafarers and also help identify factors that can cause accidents, in relation with this topic. Moreover, by full compliance to MLC, Turkish commercial fleet, would face no reputation loss in foreign ports' Port State Controls, thus gaining a commercial advantage.

MLC was issued by means of integrating all the issues in various conventions in favour of bettering (improving) the working conditions on board of ships, publishing and protecting the rights of workers as well as social welfare and freedom into a legalized frame of the maritime industry. MLC is a convention covering all such matters as recruiting and hiring (employing), the minimum age to be a considered in employment, business-employment contracts, wages, periods for working and resting, quitting, conditions for returning home, social life, victualling, social security and health-care for seafarers, and the liabilities (responsibilities) of shipowners for all these criteria [11].

2. Maritime Labour Convention

The purpose of the Maritime Labour Convention is to increase and sustain the working conditions and welfare of seafarers. The convention has adopted certain regulations aiming to raise the psychological welfare of seafarers in such matters as prompting the social facilities on ships and providing proper access to certain communication instruments like phone, internet, library, movies etc. Besides, the convention includes certain regulations favouring the improvements of the conditions such as accommodation, medical care, recreational facilities and social security. The regulations adopted also covers providing decent quality working and living conditions, eliminating exploitations, benefiting from proper medical support and enjoying the freedom of getting organized for various aims on ships. Shipping companies, therefore, are to be inspected on all points mentioned above, and they are to be documented accordingly [12]. Maritime Labour Convention (MLC) was formed by updating 68 previously produced conventions about protecting seafarers' rights. Section A in the convention contains rules and standards, while section B includes guides and recommendations for the application of those standards [13]. The previously produced 68 conventions, of which determine the maritime working standards, were needed to be updated in order to keep up with the changes in the maritime field. With growth and globalization, the maritime sector has become an organized structure that interconnects all stakeholders. Working with seafarers from different nationalities, and increasing stress and workload have negative consequences on seafarers' safety and health. Therefore, a renewed convention was needed [14].

The rights and liabilities of seafarers have predominantly taken place in the most international debates. On the other hand, shipping companies have insisted on trying to gain the highest possible profits in the severely increasing competition in the shipping/maritime industry by means of decreasing the cost of the workforce as to minimize the overall costs. In compliance with such attitude and aim, they have chosen to hire seafarers from countries (nations) that have no regulations favouring the rights of workers and have relatively low income per capita. This eventually lowered the overall prestige of seafarers and worsened their rights and working conditions [15]. Some of the difficulties on board that the seafarers have to face can be listed as insufficient nutrition, lower-wage from the values written on the contracts, no payments for wages and for overtime, lack of hygiene, lack of access to medical care, physical and mental violence, and sexual harassment [4]. In order to change and better this unfortunate situation, the companies trading through international waters are to comply with the terms of MLC and provide a certificate of compliance if they want to conduct their business steadily. Otherwise, as it was witnessed, those who act against the MLC terms might suffer from having to stop their activities at least temporarily for certain periods or lose their commercial reputation when encountering problems at the flag state and port state controls [15]. States that are party to the MLC make arrangements to accommodate the provisions of the convention to their national legislation. In this way, states have sanction on companies for the solution of problems related to the seafarers' rights [16]. To detect the problems related to seafarers, Port State Control and Flag State Control officers have to pay more attention to regulations of MLC. It is thought that there is no sufficient monitoring for working conditions regarding MLC regulations during regular inspections, and the detected items were not considered as necessary [17].

All states that aim to get a share from international maritime trade have to follow the regulations and make the preparations in terms of MLC 2006. By detailed inspection and evaluation, the states that are not the party of the convention are going to be forced to be a party [18]. Like other states, Turkey is also interested in being a part of the international maritime workforce. Thus, to be in the market, it has to show efforts via ships, seafarers, and employment offices complying with the MLC regulations. As the maritime profession has become a highly globalized profession in recent years [15], Turkey needs developments and applications, especially on private employment offices, to force them to comply with the MLC regulations.

Turkey comes on top of the list regarding the total number of seafarers working actively on board, but it cannot show the same success in the number of seafarers working on foreign-flagged ships. Therefore, the reconsideration of ship management and private employment offices in the context of MLC and certification has increasingly become more important. Efforts in this direction can help Turkey to get a more appropriate share in the international maritime workforce. The quantitative data in terms of seafarers in Turkey is given in Table 1.

3. Methodology

The purpose of this study is to reveal the working and living conditions on-board Turkish flagged ships from the seafarers' point of view and investigate if the seafarers' evaluations on the conditions differ depending upon experience, proficiency, ship type, tonnage, and gender. This study was designed as a descriptive study, which is one of the quantitative study designs. Descriptive studies are used to determine the views and characteristics of large groups [21]. Hence, the participants have responded to the questions, which were adopted by the researchers from the Report on Compliance with Maritime Labour Conventions.

The population of the study covered the Turkish seafarers employed on-board commercial ships with Turkish owners. The total number of seafarers working on commercial ships determined to be 101277 in August 2019, 29543 of whom are officers, and 71734 are ratings according to data from the Turkish Republic Ministry of Transport and Infrastructure. Those with crew certificates and employed at recreational boats and fishing boats are included in this number. While deciding the sample size, N (population value): 101277, t (theoretical dispersion): 1.96, p (likelihood of happening): 0.2, q (unlikelihood of happening): 0.8, d (accepted error ratio): 0.05 and n (sample size) 245 was

Table 1. *Number of Seafarers in Turkey*

OFFICERS			
Deck Officers		**Engineer Officers**	
Oceangoing Master	3852	Oceangoing Chief Engineer	2106
Oceangoing Chief Officer	2092	Oceangoing 2nd Engineer	1128
Oceangoing Watchkeeping Officer	3480	Oceangoing Watchkeeping Engineer	1991
Total Oceangoing Deck Officers	**9424**	**Total Oceangoing Engineer Officers**	**5225**
Master	816	Chief Engineer	980
Chief Officer	1097	2nd Engineer	728
Watchkeeping Officer	2804	Watchkeeping Engineer	2397
Limited Master	2717	Limited Chief Engineer	866
Limited Officer	1871	Limited Watchkeeping Engineer	618
Total Deck Officers	**18729**	**Total Engineer Officers**	**10814**
TOTAL OFFICERS: 29543			
RATINGS			
Deck Ratings		**Engine Ratings**	
Seaman	32294	Wiper	412
Able Seaman	19286	Oiler	11234
Bosun	4961	Motorman	2497
		Donkeyman	1050
Total Deck Ratings	**56541**	**Total Engine Rating**	**15193**
TOTAL RATING: 71734			
GALLEY			
Cook	5100	Steward-Cabin Boy	5744
TOTAL GALLEY: 10844			
ELECTRICAL			
Electrical Officer	645	Electrician	1496
TOTAL ELECTRICAL PERSONNEL: 2141			
FISHERS			
Fisherman	9147	Open Sea Fishing Boat Master	531
Fishing Boat Master	1075		
TOTAL FISHERS: 10753			
HEALTH CARE PERSONNEL			
Doctor	8	Nurse	6
Health Officer	9		
TOTAL HEALTH CARE PERSONNEL: 23			
YACHT MASTER			
Yacht Master (149 GT)	934	Yacht Master (2999GT)	10
Yacht Master (499 GT)	6377	Yacht Master (Unlimited)	783
TOTAL YACHT MASTER: 8104			

Source: *[20]*

determined. Thus, through a simple random sampling method, 296 participants were reached. The ages of the participants range from 22 to 62 (Table 2). Data collection took a long time as it is difficult to reach seafarers as their working periods differ and not on a regular schedule as it was the case for a traditional white-collar employee. Because it would be difficult for seafarers to respond to the questions objectively when the data are collected by masters, data collection has been carried out when the seafarers are not on active duty on a ship. The difficulty of accessing the internet and telephone at sea has also contributed to lengthening the period of data collection.

As a data collection tool, a questionnaire used in this study. The questionnaire comprises two parts. The first part aims to collect profile data about the participant e.g., age, gender, experience, ship type, and tonnage he/she is employed at. The backbone of the second part is the "Report on Compliance with Maritime Labour Conventions (2006) issued and adopted by ILO. This report made up of 179 items, consists of the four factors which are listed as follows, f1: contract, wages and working hours, f2: accommodation and provisions, f3: health care and safety, and f4: complaint procedures. 36 items out of this report, directly related to the working

Table 2. *Sample Characteristics*

Variable	Sub-Variable	f	%
Gender	Female	19	6,4
	Male	277	93,6
	Total	**296**	**100**
Experience	Up to 1 year	140	47,3
	1-5 years	38	12,8
	6-10 years	55	18,6
	11-15 years	24	8,1
	16-20 years	39	13,2
	Total	**296**	**100**
Proficiency	Master-Chief Engineer	37	12,5
	Officers	150	50,7
	Ratings	109	36,8
	Total	**296**	**100**
Type of Ship	Tanker Ship	97	32,8
	Dry Bulk Ship	122	41,2
	Ro-Ro Ship	22	7,4
	Container Ship	48	16,2
	Others	7	2,4
	Total	**296**	**100**
Gross Tonnage of Ships	0-3000	66	22,3
	3000-10000	82	27,7
	10000 and above	148	50,0
	Total	**296**	**100**

conditions for seafarers on ships, were chosen and included in the second part of the questionnaire (See Appendix 1). The participants were asked to respond to the 36 items through 5-point Agreement Likert scale (1-Strongly Disagree, 5- Strongly Agree).

In terms of the validity of the data collection instrument, the view/evaluation of the academics from the maritime industry was utilized. As the items were adapted from a form previously issued, the validity from the point of the structure and scale was not questioned. After having received the expert (academic) views, a pilot scheme was conducted, and then the validity has been checked. The actual conduction of the questionnaire was carried out in September 2018 through August 2019.

SPSS 15 program was used for the data analysis. Descriptive statistical analysis was used for the evaluation of the working and living conditions, and the mean, standard deviation values were subject to the analysis. For the evaluations of the working and living conditions depending upon experience, proficiency, ship type, tonnage, the normality test (Kolmogorov-Smirnov) was used to determine the proper analysis method. In this test, the p value higher than 0.05 would mean normal distribution [22]. The test revealed that the data do not have a normal distribution. Therefore, in order to determine whether there exist meaningful differences among the averages, Kruskal-Wallis and Mann-Whitney U test, a nonparametric test, was used. While the Kruskal-Wallis test provides comparisons for 3 or more groups, the Mann-Whitney U test is used to measure/calculate the difference between two independent groups. The non-parametric Mann-Whitney U test was used due to the significant difference between the male and female participants for the evaluation of the working and living conditions depending upon gender.

4. Results

The reliability coefficient (Cronbach Alpha – α) values from the reliability analyses for the pilot study and the actual study is given in Table 3. According to Kalaycı (2010) [23], a value 0-0.4 means "the scale is not reliable," 0.4-0.6 means "low reliability," 0.6-0.8 means "reliable," and 0.8-1 means "high reliability." Therefore, the reliability coefficient regarding the data collection instrument of this study indicates that the scale used has high reliability.

Table 3. *Reliability Coefficients*

	Pilot Study (α)	Actual Study (α)
Whole scale	0,947	0,891
F1	0,819	0,770
F2	0,907	0,816
F3	0,936	0,849
F4	0,640	0,851

The mean and standard deviation values regarding the analysis for the evaluation of the working and living conditions are indicated in Table 4 and Table 5.

Table 4 reveals that seafarers are moderately satisfied with the working conditions available on ships (mean: 3.26). In terms of the factors, satisfaction level for "accommodation and provisions" is highest (mean:3.61), and the satisfaction level for "wages" is the lowest (mean:2.58).

Table 5 reveals that the items that have the highest and the lowest satisfaction levels are respectively "sufficient reliable fresh drinking water has been provided" (Item 16; mean 4.12) and "The working and resting periods have been recorded regularly and they are true" (Item 10; means: 1.78). The highest and the lowest satisfaction levels for the factors are as follows: Factor 1 "Seafarers receive their wages-payments as specified in the relevant contract" (Item 6; means: 4.02) and "The working and resting periods have

Table 4. *The Mean and Standard Deviation Values for Data Collection Instrument and the Factors*

		N	Mean	Standard Deviation
Working Conditions Survey of Seafarers		296	3,26	0,51260
Factor 1	Contract, Wages and Working Conditions	296	2,58	0,68170
Factor 2	Accommodation and Provisions	296	3,61	0,61106
Factor 3	Health Care and Safety	296	3,48	0,66409
Factor 4	Complaint Procedures	296	2,69	1,28195

Table 5. *The Mean and Standard Deviation Values for the Data Collection Instrument*

	Item	N	Mean	Standard Deviation		Item	N	Mean	Standard Deviation
F 1	06	296	4,02	0,9294		41	296	3,56	1,0875
	13	296	2,98	1,1715		22	296	3,52	1,1930
	07	296	2,96	1,2630		40	296	3,40	1,4968
	12	296	2,81	1,2479		39	296	3,19	1,2334
	09	296	2,42	1,1672		25	296	2,51	1,3404
	11	296	2,23	1,2688	F 3	35	296	3,81	0,9157
	14	296	2,18	1,0916		29	296	3,73	1,0354
	08	296	1,82	1,0853		33	296	3,72	0,9936
	10	296	1,78	1,0787		28	296	3,69	0,9978
F 2	16	296	4,12	0,9701		31	296	3,60	0,8997
	18	296	3,86	0,9616		32	296	3,60	0,9072
	19	296	3,86	0,9156		36	296	3,52	1,1639
	20	296	3,86	0,9303		34	296	3,50	1,0732
	15	296	3,81	1,0231		30	296	3,15	1,2103
	24	296	3,79	1,0979		27	296	3,14	1,1703
	21	296	3,76	1,0615		26	296	2,79	1,1542
	23	296	3,71	1,2093	F 4	38	296	2,84	1,4530
	17	296	3,63	1,0658		37	296	2,54	1,2902

been recorded regularly and they are true" (Item 10; means: 1.78). Factor 2: "sufficient reliable fresh drinking water has been provided" (Item 16; mean 4.12) and "there are insects and other similar creatures in the galley" (Item 25: mean: 2.51). Factor 3: "there have been educational activities, and instruction regarding safety, health care and accident prevention" (Item 35, means: 3.81) and "Seafarers' health is well cared, and easy access to good enough medical care including tooth care is available" (Item 26, mean: 2.79). Factor 4: The levels of satisfaction for the 2 items were found closer to each other and the mean.

The Kolmogorov-Smirnov normality test reveals that the data do not show a normal distribution for the variables; experience, proficiency, ship type, and tonnage (Table 6).

The normality test reveals that for each variable, some groups do not indicate a normal distribution ($p<0.05$). As the data do not show any normality, in order to see whether there are meaningful differences between the groups, the non-parametric Kruskal-Wallis test was applied (Table 7).

The result of this test reveals that experience and proficiency do not bring about any differences in the evaluation of working conditions ($p=0.929>0.05$; $p=0.300>0.05$) whereas the type and the tonnage of the ships do bring about certain differences ($p=0.006<0.05$; $p=0.00<0.05$).

Table 6. *The Results of the Normality Test on Working Conditions for Seafarers*

Kolmogorov- Smirnov Test		Statistics	N	p
Experience	Up to 1 year	0,061	140	0,200
	1-5 years	0,077	38	0,200
	6-10 years	0,176	55	0,000
	11-15 years	0,081	24	0,200
	16-20 years	0,136	39	0,067
Proficiency	Master-Chief Engineer	0,078	37	0,200
	Officers	0,050	150	0,200
	Ratings	0,119	109	0,001
Ship Type	Tanker Ship	0,082	97	0,114
	Dry Bulk Ship	0,099	122	0,005
	Ro-Ro Ship	0,088	22	0,200
	Container Ship	0,155	48	0,006
	Others	0,205	7	0,200
Gross Tonnage	0-3000	0,151	66	0,001
	3000-10000	0,102	82	0,035
	10000 and above	0,059	148	0,200

Table 7. *The Results of the Kruskal-Wallis Test Regarding the Working Conditions for Seafarers*

		N	Rank Average	Sd	X2	p
Experience	Up to 1 year	140	148,94	4	0,871	0,929
	1-5 years	38	146,91			
	6-10 years	55	153,94			
	11-15 years	24	152,81			
	16-20 years	39	138,14			
Proficiency	Master-Chief Engineer	37	160,70	2	2,406	0,300
	Officers	150	152,39			
	Ratings	109	139,00			
Ship Type	Tanker Ship	97	171,50	4	14,465	0,006
	Dry Bulk Ship	122	129,07			
	Ro-Ro Ship	22	134,00			
	Container Ship	48	156,42			
	Others	7	159,79			
Gross Tonnage	0-3000	66	113,03	2	16,819	0,000
	3000-10000	82	147,37			
	10000 and above	148	164,94			

In order to see whether there are meaningful differences between the gender and gross tonnage groups, the Mann-Whitney U test was used (Table 8,9,10).

Table 8 reveals that there are meaningful differences between the working conditions on tankers and those on dry bulkers (p=0,000 <0,05). The analysis of means reveals that the differentiation is in favour of tankers. The analyses on the other ship types, however, reveal that there are no meaningful differences between tankers and ro-ro's; tankers and container ships; dry bulkers and the others; ro-ro's and container ships; ro-ro's and the others; and container ships and the other variables (p>0,05).

Table 9 reveals that there is a meaningful difference between the gross tonnages of 0-3000 and 3000-10000 grt regarding the working conditions (p=0,008 <0,05). The analysis of the means reveals that this difference is in favour of 3000-10000 grt. Likewise, there seems to be a meaningful difference between 0-3000 and 10000 and above grt (p=0,000 <0,05), and this difference is in favour of the 10000 grt. Besides, the analysis reveals that there exists a no meaningful difference between 3000-10000 and 10000 above grt (p>0,05).

Table 10 reveals that there appears no meaningful difference in the evaluation for the working conditions on ships based on gender (p>0,05).

Table 8. *The Results of U Test Based on the Ship Types*

Ship Types	n	Rank Average	Total Rank	U	p
Tanker	97	127,19	12337,5	4249,5	,000
Dry Bulk	122	96,33	11752,5		
Tanker	97	62,88	6099,5	787,5	,056
Ro-Ro	22	47,30	1040,5		
Tanker	97	75,64	7337,0	2072,0	,282
Container	48	67,67	3248,0		
Tanker	97	52,79	5120,5	311,5	,716
Other Types	7	48,50	339,50		
Dry Bulk	122	72,02	8787,0	1284,0	,747
Ro-Ro	22	75,14	1653,0		
Dry Bulk	122	80,95	9875,5	2372,5	,54
Container	48	97,07	4659,5		
Dry Bulk	122	64,26	7840,0	337,0	,349
Other Types	7	77,86	545,0		
Ro-Ro	22	31,70	697,5	444,5	,291
Container	48	37,24	1787,5		
Ro-Ro	22	14,36	316,0	63,0	,500
Other Types	7	17,00	119,0		
Container	48	27,94	1341,0	165,0	,951
Other Types	7	28,43	199,0		

Table 9. The Results of U Test Based on the Mean Gross Tonnage

Gross Tonnage	n	Rank Average	Total Rank	U	p
0-3000	66	64,17	4235,0	2024,0	**,008**
3000-10000	82	88,22	6791,0		
0-3000	66	82,36	5436,0	3225,0	**,000**
10000 above	148	118,71	17569,0		
3000-10000	82	106,05	8696,5	5293,5	,109
10000 above	148	120,73	17868,5		

Table 10. The Results of U-Test in Term of Gender

Gender	n	Rank Average	Total Rank	U	p
Female	19	147,08	2794,5	2604,5	,940
Male	277	148,60	41161,5		

5. Discussion

The results show that the level of satisfaction regarding wages and work hours is under average (mean). The overall application regarding payment reveals that the wages/salaries are paid as per the relevant contracts based on the national wage averages. Besides, the differences brought about by the changes in the currency rates are said to be not reflected in the wages. The complaints also include such points as non-compliance to the MLC-based working hours at sea and at ports, shortages in the required number of personnel, and non-payment for overtime working. According to previous studies, issues such as rest and work hours of seafarers and wage-related issues that are caused by exchange rate changes seem to have increased [24] Besides, showing the extraordinary nature of the work on ships as an excuse, claiming that the work has to go on non-stop, certain shifts are created. Still, no payment is made for such essential/unavoidable overtime. On the other hand, it must be kept in mind that a fair organization and well-planned working and resting hours is of great importance in terms of both the health of the crew as well as the safety of the ship.

The results also reveal that the personnel working on Turkish flagged ships are quite satisfied with the comfort of the accommodation and the provisions. This satisfaction covers the quality and quantity of the drinking water supplied, the amount, variety, nutritional value, and hygienic conditions of the food provided. Besides, it is almost commonly agreed that the drinking water and the food are regularly inspected, well conserved, and the providers are well-educated. Furthermore, it is stated that while preparing and offering food, religious, and cultural differences are taken into consideration. Moreover, the cabins, showering facilities, and clean restrooms are said to be satisfactory. The only problem regarding these is the existence of insects, which must be prevented.

Another point satisfying the personnel employed on Turkish flagged ships is health care and safety. It is commonly stated that there are certain procedures on board of ships regarding the safety and health of the personnel as well as preventing any likely accidents, and personnel are regularly trained in compliance with these procedures. The working sites are said to be neat and clean; risk analyses are said to be made in due time, and the national and international rules are complied with. Regarding health care, it is said that there are infirmaries, pharmacy warehouses, and health care equipment available on the ships. However, the moderate satisfaction with regard to the health care to be applied at ports for any health problems encountered while at work indicates that this particular need is met sometimes but not all the time. Besides, the participants seem to be dissatisfied with the attitudes of the employers about tooth care. According to a previous study, it is seen that there is an improvement in satisfaction rates on this subject [24].

The results also reveal that the level of satisfaction with the complaint procedures is under the mean. It is said that the seafarers have no right to come with complaints, and even if they dare to do so, there is no complaint procedure that works fairly, effectively, and rapidly. In other studies, it was found that there was similar dissatisfaction with the complaint procedures [24].

Another point of dissatisfaction seems to be about the working conditions on small tonnage ships. The type of ships fully complying with the terms of MLC is said to be tankers, which is attributed to the regular and serious inspections.

The results of analyses also reveal that there are no meaningful differences in the attitudes of the participants towards the working conditions on the ship based on experience and proficiency. Besides, no significant differences appear to be brought about by gender, which is debatable as the number of female participants is very low.

6. Conclusion

The study reveals that Turkish seafarers employed on Turkish flagged ships are moderately satisfied with the working conditions on board. This implies that there is a need for improvement in the circumstances. Improving the conditions is necessary to increase the level of satisfaction, and is believed to positively affect the periods of staying at sea working on ships. This study intends to determine the weaknesses and strengths of the relevant struggle, considering the scope of the Maritime Labour Convention.

The rights of seafarers are to be protected by means of issuing employment contracts favouring the seafarers, in terms of overtime payments, working hours, reflecting the gains caused by any changes in the currency rate to the wages, and providing decent rights permitting all to join the relevant unions, which was ignored and overlooked for Turkish seafarers.

Another critical point to be considered is the shortage of the number of crew on board ships. Despite the recent advances in technology, which wrongly implies that fewer employees would be needed, the working hours for the Turkish seafarers on Turkish flagged ships are exceeding the adopted standards, which is a matter that needs to be considered and corrected. Furthermore, the health care facilities on ships are regularly inspected and standardized. In case of any need to be met from outside, however, the complaint procedures are said to be followed insufficiently and ineffectively. Such particular health care needs must not be overlooked and must be met regardless of the high cost. Moreover, regardless of the size, type, and region, all ships must be decently inspected and must comply with the terms of MLC. Last but not least, other than within the companies and ships, certain other mechanisms must be established so as to protect and preserve the rights of seafarers employed on ships.

Future qualitative studies involving observations on-board ships and in-depth interviews with crew members, aiming to determine the actual working and living conditions on-board, in terms of all MLC items, would be useful to help to improve the overall conditions, as well as the health and safety of the seafarers.

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Appendix 1. *Data Collection Tool Items*

Factor	Item Nr.	Item
F1 Contract, wages and working hours	**06**	Seafarers receive their wages-payments as specified in the relevant contract
	07	The wages are consistent with the national wages
	08	The hours of work recorded in the wage account correspond with the overtime records and/or hours of work and rest
	09	Exchange rates and service charges meet national regulations
	10	The working and resting periods have been recorded regularly and they are true
	11	A table set out the schedule of service at sea and port and these arrangements conform to the applicable minimum hours of rest or maximum hours of work
	12	There is no restriction to shore leave imposed by the shipowner/master without adequate reason
	13	Seafarers' repatriation entitlements to national requirements for repatriation including coverage for costs and choice of destinations
	14	The ship has sufficient seafarers onboard to meet concerns about safety, security and seafarer fatigue considering the particular nature and conditions of the ship's voyages
F2 Accommodation and provisions	**15**	The food and drinking water served on the ship of appropriate quantity, nutritional value and quantity, in accord with national provisions, to cover the requirements of the ship and takes into account the differing cultural and religious backgrounds of seafarers working and living on board
	16	sufficient reliable fresh drinking water has been provided
	17	Seafarers who are responsible for food preparation trained and the ship's cooks are qualified
	18	Frequent and documented inspections of food and catering facilities including food storage areas are carried out by the master or an officer
	19	The organization and equipment in the catering department permit the provision of adequate, varied and nutritious meals prepared and served in hygienic conditions
	20	Adequate facilities are provided for the cleaning, disinfecting and storage of utensils and equipment
	21	There are a sufficient number of temperature-controlled food storage and handling rooms for the number of persons on board and the duration of the voyage
	22	The food is being correctly stored with respect to stock rotation, segregation and spillages
	23	The variety of the food is provided satisfactory taking into account any religious requirements and cultural practices of the seafarers on board
	24	Drinking water is safe and is the quality regularly monitored
	25	There are insects and other similar creatures in the galley
	39	The cabins for seafarers have adequate space for living
	40	Each cabin contains a bathroom and toilet inside
	41	The responsible officer carries out routine hygiene controls on

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Appendix 1. *Data Collection Tool Items (Cont')*

Factor	Item Nr.	Item
F3 Health care and safety	**26**	Seafarers' health is well cared, and easy access to good enough medical care including tooth care is available
	27	The shipowner is responsible for costs with respect to sickness and injury to seafarers during employment or arising from their employment
	28	The medicine chest, medical equipment and medical guide is in compliance with national legislation
	29	The onboard hospital and medical care facilities meet national requirements for the ship
	30	Seafarers are permitted by the shipowner to visit a qualified medical doctor or dentist in port (where practicable) without delay
	31	Seafarers are provided with occupational health and safety protection and accident prevention in accordance with national requirements
	32	The living, working and training environment onboard ship safe and hygienic
	33	There are procedures in place and followed for reporting and recording and investigating unsafe conditions and onboard occupational accidents
	34	A proper risk assessment has been carried out for onboard occupational safety and health management
	35	There have been educational activities and instruction regarding safety, health care and accident prevention
	36	The seafarers are covered by flag State social security protection
F4 Compliant procedures	**37**	The ship has onboard procedures for the fair, effective and expeditious handling of seafarer complaints
	38	Seafarers have a right to complain directly to the master and appropriate external authorities

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Analyzing the Effect of Fuel Injection Timing and Injection Duration on Performance and Emissions in Diesel Engines

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Abstract

Fossil-based fuels have been decreasing all over the world and the energy requirements of power generation systems are increasing. Diesel engines are one of the most common and efficient power generation systems. However, national and international organizations impose various restrictions to reduce emissions from diesel engines. Reducing emissions and improving performance in diesel engines are one of the most common areas of work. Improvement of performance and emission parameters is possible with changes in alternative fuels, engine geometry and fuel injection systems.

In this study, the effects of different injection timing and injection duration on diesel engine performance and exhaust gas emissions have been investigated with computational fluid dynamics (CFD) method. The numerical study has been carried out on a 4-stroke, single cylinder test engine and the results have been compared with the experimental results obtained from the literature. As a result of the study, combustion chamber speed profiles, fuel mass change, temperature, pressure, chemical heat release rate has been determined for the standard operating conditions. Parametric study has been performed for different injection timing and injection duration of engine. For each case, performance and emissions parameters have been determined. Analysis results has compared, and the most suitable injection parameters has been introduced.

Keywords: *Diesel Engine, Computational Fluid Dynamics (CFD), Injection Timing, Combustion.*

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1. Introduction

Diesel engines are widely used because of high reliability and highly efficient energy conversion. The use of fossil fuels in diesel engines has also led to the creation of undesirable harmful emissions. These undesirable harmful emissions have caused acid rain, global warming and many environmental problems [1–3]. Many countries and international organizations have made mandatory restrictions to reduce emissions such as Carbon Monoxide (CO), Carbon Dioxide (CO_2), Nitrogen Oxides (NO_x), Hydrocarbon (HC) and Particular Matter (PM) from diesel engines [4–6]. In the scope of MARPOL Annex 6, especially in marine diesel engines, restrictions have been applied by International Maritime Organization (IMO) to reduce emissions caused by greenhouse gas effects.

Restrictions on NO_x emissions have been determined as 17, 14.4 and 3.4 grams per kWh on ship diesel engines on January 1, 2000, 2011 and 2016, respectively. In diesel engines, NO_x emissions can be reduced with engine operating parameters, engine design parameters or after treatment systems. Engine operating parameters cause a decrease in emissions as well as performance. The injection timing is an operation parameter that directly affects engine performance and emissions. Injection timing varies based on the fuel specification, inlet air pressure and temperature, compression ratio, injection systems, engine speed and combustion chamber design [7]. Many studies have been carried out demonstrating the effect of the fuel injection timing on the diesel engine. Hagos et al. [8] have experimentally investigated the effects of start of injection timing (SOI) on the performance, combustion and emissions on the SI engine fueled with a hydrogen-rich synthesis gas. Fan et al. [9] have examined the effects of injection timing and nozzle angle on various blends formation and combustion performance in 3D model. The study has been conducted for 25 different cases. Wang et al. [10] have numerically analyzed the effect of ignition position and fuel injection timing on the engine performance and combustion in a direct-injection natural gas engine. Pham et al. [11] have examined both experimentally and numerically the effects of variable fish oil-biodiesel blends on the common-rail diesel engine performance and emission characteristics at different injection timing and injection pressure. How et al. [12] have studied the effects of injection timing and split injection strategies on emission and combustion characteristics. This study deals with parametrically that relation with variable start of injection timing and multiple injection schema for B20 and B50 biodiesel blends. Wamankar et al. [13] have analyzed the effect of injection timing on a DI diesel engine with synthetic fuel blends. It has been observed that the early injection timing has increased the cylinder pressure and engine performance. Ashok et al. [14], Gong et al. [15], Natarajan et al. [16] and Deep et al. [17] have investigated the effects of injection timing, injecting pressure and alternative fuel blends on diesel engine.

This study numerically examines the effects of injection timing and injection duration on the diesel engine performance, emission and combustion characteristics through computational fluid dynamics (CFD). In the previous studies, generally while the parameters such as alternative fuels, injection angle and injection pressure have been examined, in this study injection duration and injection timing have been investigated as a combination. Computations of fluid mechanics in internal combustion engines put a strain on including parameters such as spray dynamics, chemical reactions and turbulence [18]. CFD method, which is widely used in modeling of heat-flow problems in recently, is an alternative to experimental studies in terms of time and cost [19]. Accurate emissions and engine performance characteristic can be predicted through appropriate chemical reduction mechanisms in combustion processes. Numerical results obtained by this study has been compared with the experimental data from the literature.

2. Materials and Methods

2.1. Numerical Investigation

In this study, a single cylinder, 4 stroke diesel engine is modeled in 3D to obtain chemical and physical properties. With 3D-CFD model, all the processes that occur during combustion have been examined [20]. The numerical model has been developed by means of commercial software Ansys-FORTE [21]. The numerical study has been performed for the operating conditions of the diesel engine in Table 1 at a rotation speed of 2200 rpm and a torque of 16 Nm [22]. The aim of the numerical analysis is to enable the investigation of diesel engine performance and emissions parameter in different injection durations and injection timing conditions.

Chemical reactions and thermodynamic properties should be defined to determine combustion products and performance characteristics in diesel engines [23]. N-tetradecane reduction mechanism developed by the University of Wisconsin Engine Research Center (ERC) has been used. The reduction mechanism consists of 35 species and 76 reactions [24]. The diesel fuel has been selected as tetradecane ($C_{14}H_{30}$) to analyses the fuel atomization, vaporization and the mixing fuel with air. It is very important analyze that the combustion process in the diesel engines is controlled by the fuel spray dynamics. Choosing the right spray model allows you to model the combustion process correctly. Kelvin-Helmholtz Rayleigh-Taylor (KH-RT) and gas-jet model spray breakup models have been used for the analysis [25]. In internal combustion engines, air is compressed in the combustion chamber and has high turbulence. The k-ε Re-Normalization Group (RNG) turbulence model using Reynolds Averaged Navier-Stokes equations (RANS) has been used in the analysis [25]. 3D Mesh structure has been carried out engine combustion chamber as domain. The computational model described in Figure 1 with a 90-degree sector mesh consists of nozzle, cylinder head, liner and piston parts.

The numerical analysis must have mesh independency to improve the accuracy of the CFD simulations. The mesh independent solutions are entirely dependent on the mesh selected to resolve the fluid flow and the turbulence model that is chosen to illustrate the physics of the problem. For this reason, the correct mesh structure must be applied the to demonstrate reliability of the analysis. In this study, 117840, 202095 and 320500 element numbers have been analyzed.

Table 1. *Basic Engine Parameters*

Parameter	Units	Value
Basic Engine Model	-	Antor 6LD400
Number of Cylinders	-	1
Bore × Stroke	mm	86 x 68
Compression Ratio	-	18
Displacement	mm^3	395
Combustion Chamber Type	-	Mexican Hat
Diesel Fuel Injection Type	-	Direct Injection
Maximum Power	kW	5.4 (3000 rpm)

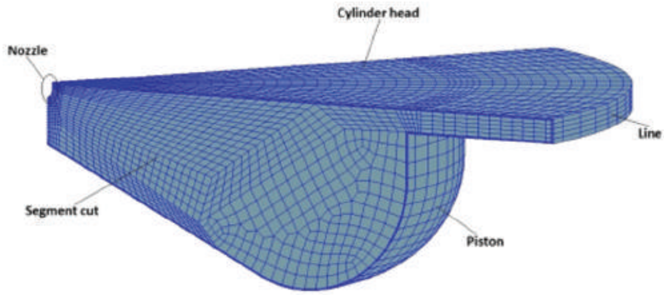

Figure 1. *Computational Domain*

The cylinder pressure for three different mesh number is shown in Figure 2. The results have demonstrated that the analysis is independent from computational grid.

In addition, Table 2 has shown that the boundary conditions and injection parameters of diesel engine. As nozzle diameter and cone angle has affect combustion performance, these parameters have been determined according to experimental test engine. The solutions of elementary gas-phase chemical kinetics have been enabled by chemkin solver which is used as combustion model. Combustion model has allowed identification thermodynamics properties, equation of state and chemical and chemical production rates [27].

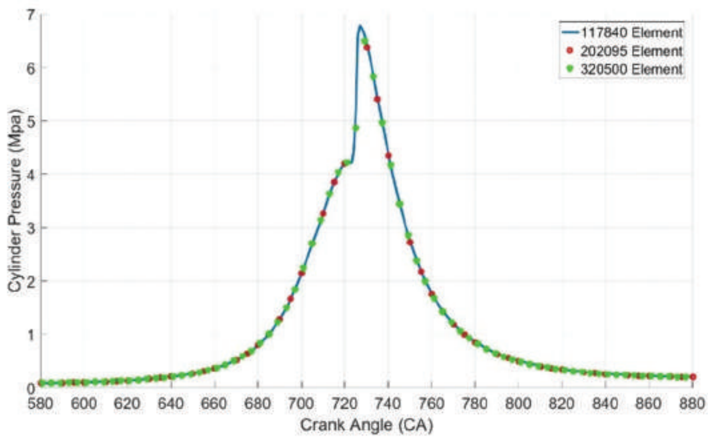

Figure 2. *Mesh Independence Test*

Table 2. *Boundary Condition*

Parameter	Units	Value
Inflow Droplet Temperature	K	368
Mean Cone Angle	-	20°
Nozzle Diameter	mm	0.24
Inlet Temperature	K	293.15
Inlet Pressure	bar	0.8
Combustion Model	-	Chemkin

The computational model is designed based on the opening and closing times of the intake and exhaust valves. The analysis includes compression and combustion processes between 565 crank angles (IVC) and 880 crank angles (EVO) [28]. Dimensionless representation of the intake, exhaust and piston movement has been shown as in Figure 3.

The numerical analysis of the diesel engine is usually carried out in the case where both the intake and exhaust valves are closed. For an engine calculation using a sector mesh, the work will be calculated for the compression stroke and the expansion stroke (from –180° ATDC to 180° ATDC). In such a case, the calculation is typically carried out from intake valve closure (IVC) to exhaust valve opening (EVO) [21]. The P-V curve between IVC and EVO is integrated directly using the following equation.

$$W_{from\ 540\ ATDC\ to\ IVC} = P_{IVC} \ x \ (V_{IVC} - V_{BDC}) \quad (1)$$

$$W_{from\ EVO\ to\ 900\ ATDC} = 0.5 \ x \ (P_{IVC} - P_{EVO}) \ x \ (V_{BDC} - V_{EVO}) \quad (2)$$

where, P_{IVC} the combustion chamber pressure when intake valve closed, P_{EVC} the combustion chamber pressure when exhaust valve open, V_{IVC} the combustion chamber volume when intake valve closed, V_{BDC} the combustion chamber volume when bottom dead center and V_{EVO} the combustion chamber volume when exhaust valve closed. Therefore, for the partial combustion chamber model, the total work and power expression is as follows.

$$W = W_{from\ 540\ ATDC\ to\ IVC} + W_{from\ IVC\ to\ EVO} + W_{from\ EVO\ to\ 900\ ATDC} \quad (3)$$

$$P = WxN/(60xn_{rev}) \quad (4)$$

where, N is engine speed (revolution/min), n_{rev} is number of revolutions per engine cycle [21].

2.1. Governing Equations

A gas-phase flow motion is governed using the Navier-Stokes equations. The continuity equation is based on conservation of mass. The rate of change in the volume of the arbitrarily selected unit control volume in the combustion chamber is equal to the total mass flow at the control volume limits. Following equations over all species yields the continuity equation for the whole gas flow [29].

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho U_j)}{\partial x_j} = \grave{S}_k \quad (5)$$

where, ρ, U and $\grave{S}_k$ are fluid density, velocity and source terms due to fuel injection respectively.

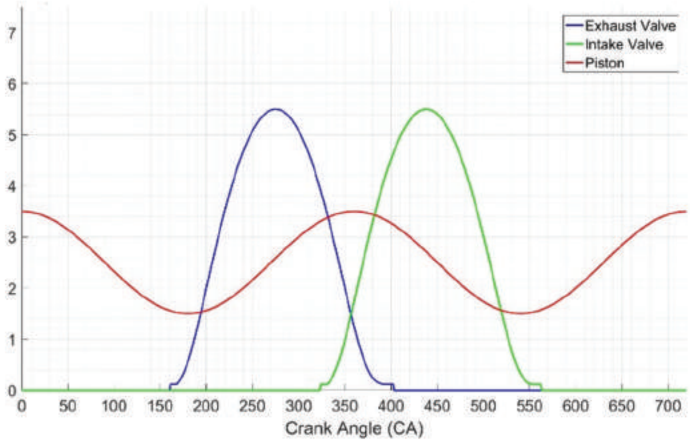

Figure 3. *Intake Valve, Exhaust Valve and Piston Movement Profile*

The momentum or Navier-Stokes equation for combustion chamber control volume is

$$\frac{\partial(\rho U_i)}{\partial t}+\frac{\partial(\rho U_i U_j)}{\partial x_j}=-\frac{\partial p}{\partial x_i}+\frac{\partial \tau_{ij}}{\partial x_j}+F_i^s+F_i^b \quad (6)$$

where p, τ and F_i^s and F_i^b is combustion chamber pressure, viscous stress tensor, spray induced source term and the body force which is equal to ρg.

The energy equation for control volume thermodynamics properties can be expressed as follows.

$$\frac{\partial(\rho e)}{\partial t}+\frac{\partial(\rho e U_j)}{\partial x_j}=-P\frac{\partial(\rho U_j)}{\partial x_j}+\frac{\partial \rho j_j}{\partial x_j}+Q^s+Q^c \quad (7)$$

where e, J_j, Q^s and Q^c are sensible energy, the heat flux arised from heat conduction and enthalpy diffusion and the source terms which derived from injection, respectively.

3. Results and Discussions

Under the specified boundary conditions, the effects of injection timing and injection duration on engine performance and emissions have been determined. Numerical analysis should be verified by experimental setup or experimental data which has been received from the literature. So, the results obtained by numerical analysis have been compared with experimental data.

3.1. Model Validation

In this section, numerical model has been compared with experimental model discussed with literature. Comparisons have been made at 2200 rpm speed and 16 Nm torque. The cylinder pressure obtained from the numerical analysis has been confirmed by the experimental results. Experimental analysis results used to verify the numerical analysis have been obtained from the Ph.D. Thesis [22]. This study has investigated the effects of partial premixed fuel charge effects on the emissions and performance parameters of Antor 6LD400 diesel engine. Numerical and experimental data are demonstrated in Figure 4. Experimental data obtained from the experimental results have been created by using statistical and filtering methods within ± 0.6% accuracy.

Cylinder pressures obtained from experimental and numerical data during combustion and the engine performance parameters for the boundary conditions are shown in Table 3.

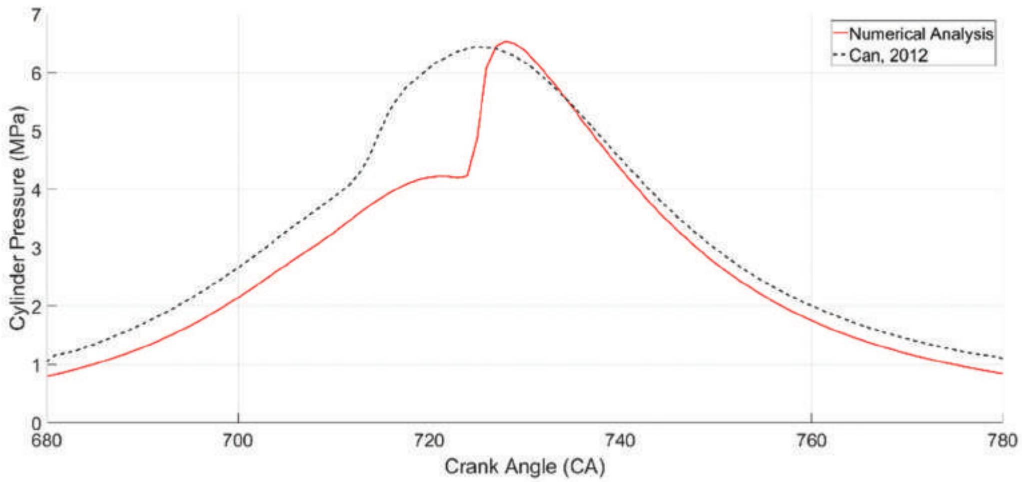

Figure 4. *Experiment and Numerical Results Comparisons in terms of the In-Cylinder Pressure*

***Table 3.** Motor Performance Parameters for Injection Timing*

Parameter	Units	Numerical Results	Experimental Results (Can,2012)
Power	kW	3.65067	3.6858
Torque	N.m	15.8472	16
Specific Fuel Cons.	g/kWh	247.68	225
NO_X	ppm	539	545
CO	% Volume	0.292	0.312

The power, torque, specific fuel consumption, NO_x and CO emission characteristics which has been calculated through numerical analysis were compared with the experimental study as in above table. According to the comparison results, it is observed that the maximum deviation is 8.9% with specific fuel consumption. comparisons have been done with the results of the combustion analysis for 2200 rpm, 16 N.m, 24° CA injection timing under operation conditions.

3.2. Combustion Characteristics

At first, numerical analysis was carried out for different injection timings and injection durations of fuel. In the study, temperature, fuel concentration and performance parameters were determined for different injection timings and injection durations. Combustion chamber temperature, pressure, chemical heat release rate and unburned hydrocarbon amount were determined. These parameters have expressed combustion characteristics. In Figure 5, combustion performance parameters have been demonstrated.

Chemical heat release rate, combustion chamber pressure, combustion chamber temperature, and unburned hydrocarbons are shown to vary with the crank angle (CA) for different injection timing for 20° CA injection duration. Reliable estimation of the combustion process depends on correct determination of performance parameters such as ignition delay, flame, temperature and pressure [30]. Injection timing directly

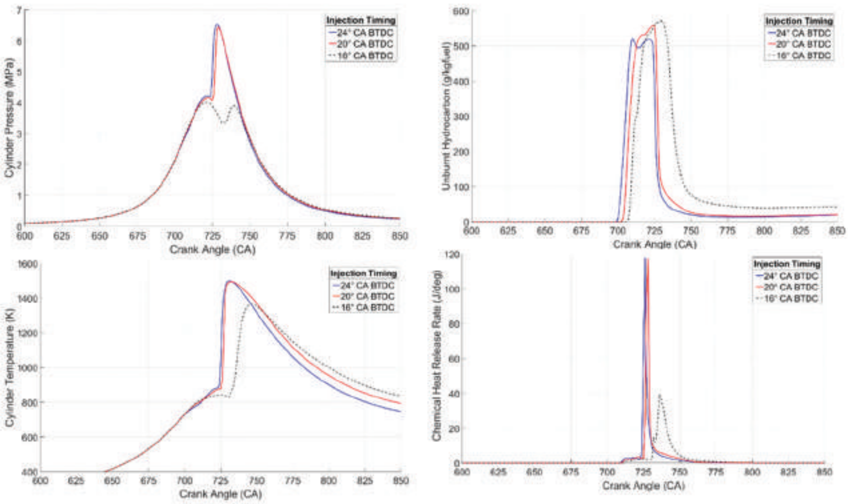

***Figure 5.** Motor Performance Parameter for 20° CA Injection Duration*

affects the ignition delay of fuel. Optimum injection timing improves air-fuel mixture quality. Analysis results have indicated that the maximum combustion performance has designated for 20° CA BTDC injection timing. It can be observed that the cylinder pressure has been significantly affected by injection timing. Maximum cylinder pressure has risen with early injection timing. As a matter of fact, the compression temperature and pressure will be higher near the TDC. Therefore, this should be considered in determining the time of fuel injection. Table 4 has demonstrated the motor performance parameter results that has been realized in the same fuel amount and properties.

According to results of various performance characteristics shown in Table 4, the engine power has been determined to be the highest for the 20° BTDC injection timing and the lowest for the 16° BTDC injection timing. The combustion efficiency in diesel engines is based on the ratio of the amount of energy chemically released to the maximum amount of fuel that can be supplied. For 16° CA BTDC injection timing, it was determined that the performance parameters are decreased due to the lean and inefficient combustion of the fuel in the combustion chamber. Fuel-air mixing is a substantial for diesel engine performance parameters. Air fuel does not mix sufficiently with injection timing delay. Insufficient mixture causes unburned hydrocarbons in the exhaust gas. The decrease in combustion efficiency negatively affects the temperature and the amount of the heat release.

Some of the fuel taken into the cylinder is stored by hydrocarbon formation sources during the normal spreading process of the flame. Therefore, they do not participate in the burning event. Some of these unburned hydrocarbons are oxidized in the cylinder in the next combustion process. Some of the hydrocarbons that are not oxidized but remain in the cylinder leave the cylinder. The unburnt hydrocarbons remaining in cylinder mix with fuel-air blends. Remaining unburnt hydrocarbon amount causes a decrease in engine performance. So, to determine mass fraction of hydrocarbons in cylinder and to select suitable injection timing is important for diesel engine performance parameters. In diesel engine performance parameter changes during combustion processes. The fluctuation has transformed into steady state behavior in progress of time. According to in Figure 6, the amount of unburned hydrocarbon remained constant after about 800° CA. Combustion chamber fuel mass fraction been obtained from the numerical analysis at 800° CA which is shown in Figure 6. For the same injection duration of the fuel, it has been observed that the unburned mass fuel fraction has been at most 16° CA injection timing and the least for the 20° CA injection timing.

3.3. Emissions Characteristics

The NO_x and CO emissions are shown in Figure 7. Considering temperature and pressure in Figure 5, it appears that emissions parameters are affected

Table 4. *Motor Performance Parameters for Injection Timing*

Parameter	Units	24° BTDC	20° BTDC	16° BTDC
Power	kW	3.65	3.89	3.52
IMEP	MPa	0.50	0.54	0.49
Lower Heat Value	MJ/kg	44.52	44.52	44.52
Total Chemical Heat Release	J	423.7	454.8	421.3
Combustion Efficiency	-	0.69	0.746	0.691

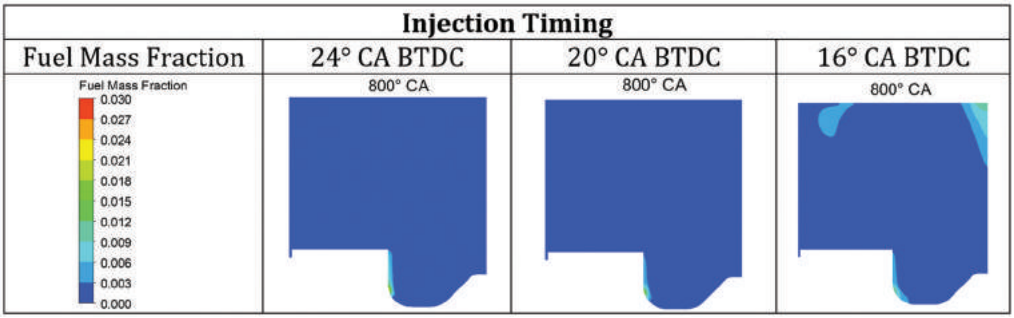

Figure 6. *Fuel Mass Fraction in 800° CA for 20 CA Injection Duration*

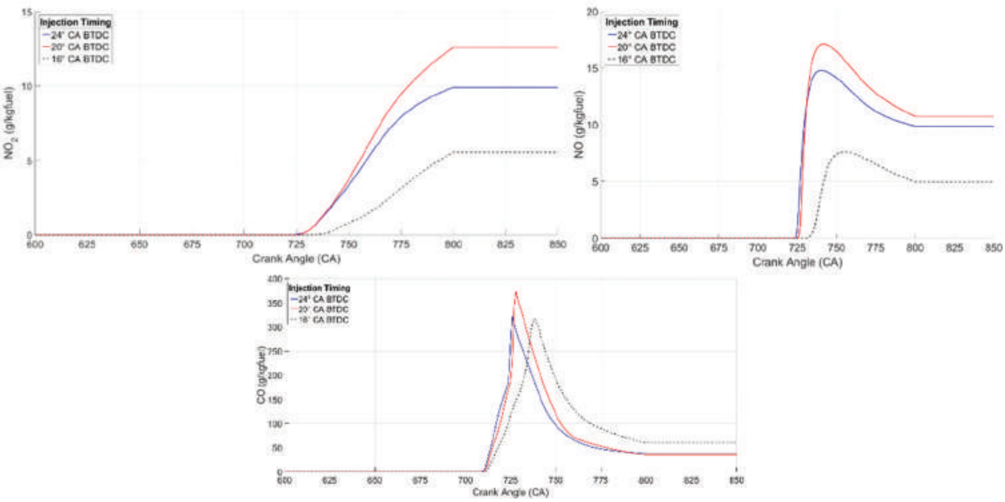

Figure 7. *NO_x and CO Emissions for 20 CA Injection Duration*

combustion temperature and pressure during operation conditions. Although NO_x emissions comprise of high combustion temperature, CO emissions arise from poor engine performance based on low temperature.

It is seen that CO emissions has increased with decreased combustion efficiency. CO emissions has occurred primarily when fuel has not burnt completely. This was due to longer ignition delay and poor mixture formation. However, it is clearly noticeable that if injection timing selected in early CA, cylinder CO emissions would decrease [31]. According to Figure 8, the in case of combustion chamber temperature rises, NO_x emissions increases, and CO and unburned hydrocarbons decreases. Temperature and NO_x emissions indicated in the figure at 800° CA. This crank value is the final phase of the combustion process and the chemical components have reached equilibrium. The emission characteristics of diesel engines depend on combustion temperature and pressure. Most of NO_x emissions are formed from NO. As shown in Figure 8, NO_x emissions have been observed to increase in parallel with the temperature. NO_2 emissions has consist of NO emissions at approximately 750°-800° CA interval. In this case it can be explained with thermal NO which is formed by the combination of

N_2 and O_2 atoms at high temperatures. With the decrease in the combustion chamber temperature, NO emissions decrease and turn into NO_2. With the temperature combustion, although NO_x formation has been raised, CO emissions have been decreased due to partly non premixed and incomplete combustion. The increase in CO is due to the reduction of combustion efficiency and the unburned hydrocarbons. In Figure 9, the relation between CO and temperature has been shown. It has been observed that the CO mass fraction is less than it is in the early injection timing. As a result of, injection timing has affected NO_x and CO emissions. For the early injection timing, CO emissions has been determined as the minimum while NOx is maximum.

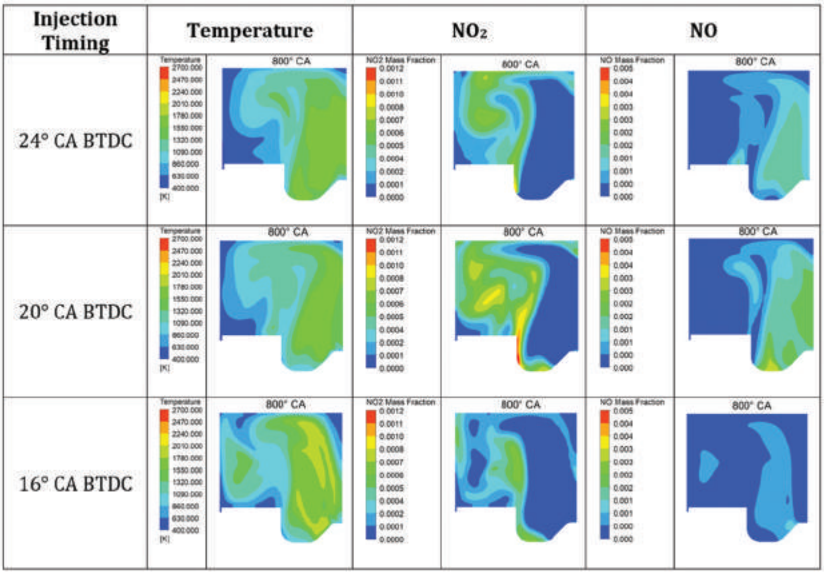

Figure 8. *Combustion Chamber Temperature, NO_2 and NO Emissions*

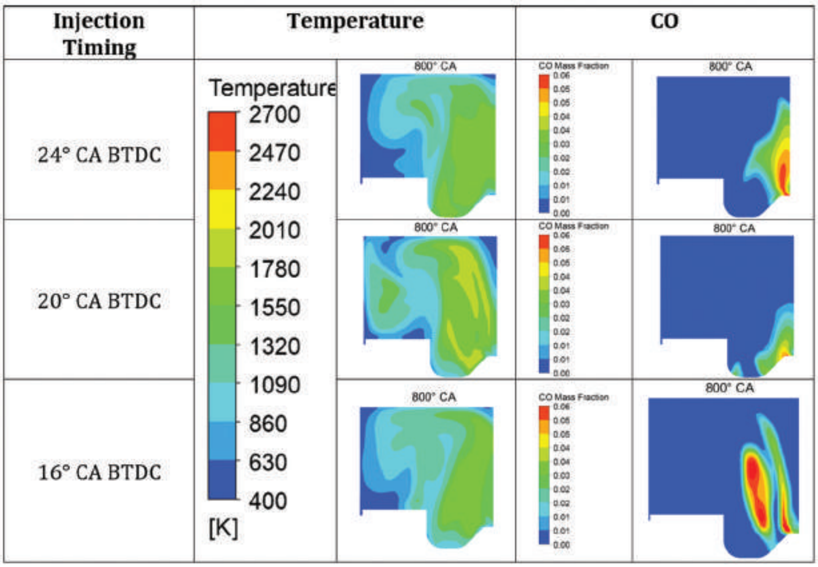

Figure 9. *Combustion Chamber Temperature and CO Emissions*

3.4. The Effect of Injection Duration on the Emission and Performance

Another issue investigated in this study is the effect of injection duration on engine performance and emissions. Different injection duration has been examined for different injection timing. The boundary conditions for different injection duration are given in Table 5. Nine different parameters have been evaluated for three different injection duration.

For each injection timing, three different injection duration have been analyzed at constant boundary conditions. Exhaust gas emissions and performance parameters have been calculated under the same boundary. In order to ensure efficient combustion of diesel engine, the injection timing and injection duration must be optimally adjusted. Injection duration which should be selected considering the injection timing is significant for combustion and performance parameters. Since the injection timing directly affects the ignition delay of the fuel, selecting both injection timing and injection duration properly will prevent loss of efficiency. Spraying the same amount of fuel for different boundary conditions affects fuel injection pressure. With increasing injection duration, injection pressure is decreased inside the cylinder. with increasing injection pressure, maximum value of pressure is increased inside the cylinder. Increasing of spraying pressure raises the fuel speed and air mixture formation in delay phase of combustion. This provides more mixture for pre-mixing phase. Therefore, if injection duration is very high, engine performance parameters adversely affected.

For different injection durations and injection timing, combustion chamber temperature is given with nine varied contour plots in Figure 10. The maximum cylinder temperature has been determined for 20° CA BTDC injection timing and 20° CA injection duration. Because the engine performance parameters are affected by combustion temperature and pressure. Minimum combustion temperature has been obtained for 16° CA BTDC injection timing and 25° CA injection duration compared to other injection parameters. Table 6 shows that motor performance parameters depend on injection duration. According to Table, maximum engine power and IMEP is determined for 20° CA injection duration. The combustion results show that the combustion chamber temperature value is clearly parallel to the engine performance parameters. In addition, NO_X emissions have been determined to be minimum for 25° CA injection duration. It is clearly seen that NO_x emissions rise with rising combustion chamber temperature and CO decreases.

Table 5. *Boundary Condition for Different Injection Duration*

Boundary Condition	Units	Boundary Values		
Injection Timing	-	24° CA BTDC	20° CA BTDC	16° CA BTDC
Number of Nozzles	-	4	4	4
Spray Direction	-	14°	14°	14°
Injection Temperature	K	368	368	368
Mean Cone Angle	-	20	20	20
Turbulence Model	-	k-ε RNG	k-ε RNG	k-ε RNG
Injection Duration	-	15° CA 20° CA 25° CA	15° CA 20° CA 25° CA	15° CA 20° CA 25° CA

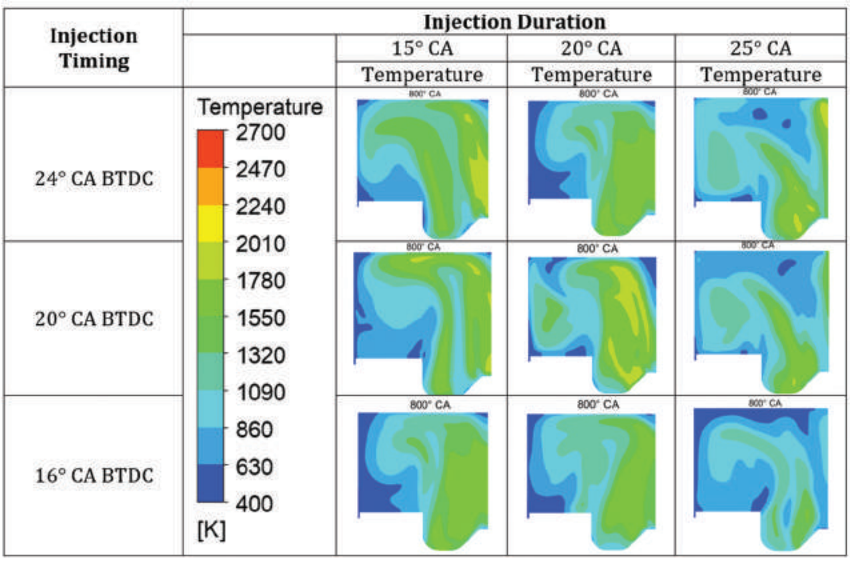

Figure 10. *Combustion Chamber Temperature for Different Injection Duration*

Table 6. *Performance and Emissions Parameter for 24° CA BTDC Injection Timing*

Performance Parameter	Units	Performance Values		
Injection Duration	-	15° CA	20° CA	25° CA
Power	kW	3.18	3.65	3.44
IMEP	MPa	0.44	0.5	0.47
CO Emissions	ppm	1178	1135	1446
NO_x Emissions	ppm	515	539	481

The performance and emission parameter are shown in Table 7 for 20° CA BTDC injection timing. The numerical analysis results show that maximum NOx emissions, IMEP and engine power have been obtained for 20° CA injection duration.

Table 8. demonstrate the performance and emissions parameters for the 16° CA BTDC injection timing. Emissions and performance parameters differ from other injection timing characteristics. Maximum performance parameters and NO_x emissions has been found for the 15° CA injection duration. In addition, for the 16° CA BTDC injection timing, performance and emissions parameter have been determined as most close to each other.

Table 7. *Performance and Emissions Parameter for 20° CA BTDC Injection Timing*

Performance Parameter	Units	Performance Values		
Injection Duration	-	15° CA	20° CA	25° CA
Power	kW	3.42	3.89	3.50
IMEP	MPa	0.47	0.54	0.48
CO Emissions	ppm	1468	1237	2063
NO_x Emissions	ppm	474	624	422

Table 8. *Performance and Emissions Parameter for 16° CA BTDC Injection Timing*

Performance Parameter	Units	Performance Values		
Injection Duration	-	15° CA	20° CA	25° CA
Power	kW	3.49	3.42	3.43
IMEP	MPa	0.48	0.46	0.47
CO Emissions	ppm	1325	2108	1939
NO_x Emissions	ppm	399	283	313

4. Conclusion

In this study, the effects of a single cylinder, four stroke diesel engine injection parameters on engine performance and emissions have been investigated numerically. The engine performance and emissions were compared for injection timings of 24° CA BTDC, 20° CA BTDC and 16° CA BTDC. It has been determined that the power is the maximum value for the 20° CA BTDC injection timing. When the amount of exhaust gas emission is considered, it is observed that CO amount is at least, and NO_x amount is highest due to the highest combustion efficiency of 20° CA BTDC injection timing.

Additionally, the effect of injection duration on diesel engine combustion and emissions have been investigated. The effect of 15° CA, 20° CA and 25° CA injection durations have been investigated for different injection timing. As a result of the study, it was observed that the highest power and combustion efficiency value was obtained with the 20° CA BTDC injection timing and 20° CA injection duration.

In this study, it was determined that combustion efficiency and exhaust gas emissions depend on injection timing. In order to achieve high combustion efficiency, injection timing must depend on optimal crank angle. It was observed that combustion temperature and pressure affect the engine performance and emissions parameters. Increasing cylinder temperature increases NO_x emissions while reducing CO emissions. Injection timing and injection duration should be selected at suitable crank angle. If the injection timing coincides with earlier or later crank angle timing, engine performance and emission parameters are affected negatively.

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Investigation of the Effect of Leading-Edge Tubercles on Wingsail Performance

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Abstract

In this study, effects of leading edge tubercles on a 2013 America's Cup boat wingsail are investigated by viscous Computational Fluid Dynamics (CFD). Adding tubercles on the leading edge of the sail is inspired by humpback whales, which are fast and maneuverable animals along baleen whales thanks to their distinctive flippers. It has been seen from the examined studies that tubercles on the leading edge of the wings delay stall and provide better lift/drag ratio in high angle of attacks (AoA) compared to the plain wing, which might be beneficial for wingsails.

A 2013 America's Cup boat wingsail geometry is developed for measuring the effects of tubercles on its performance. Sinusoidal tubercles are placed on leading edge with different wave lengths and amplitudes varying as a function of chord length. Post-stall performance of the wingsail has been improved whereas onset of stall has been observed to be identical to that of the base wingsail.

Keywords: *Biomimicry, Bio-inspiration, Tubercle, Wingsail, CFD.*

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1. Introduction

Sailing yacht races and events play significant role on developing technology for the faster sailing yachts. America's Cup (AC) is one of oldest and most well-known regatta's in the world. As in Formula 1 races, where technology later adapted to production cars, technologies developed for regatta yachts are eventually being adapted to other sailing vessels and boats.

Wingsails are one of the technologies that attracted attention of sailing community after such races. They became more popular after 34th America's Cup boat AC 72, which goes extremely fast on hydrofoils and powered by large wing sails.

Biomimicry has been an interesting phenomenon for engineers for a long time, especially in the field of aero and hydrodynamics. This paper presents a review of previous studies involving foils with bio-inspired leading edges. In the rest of the study, leading edge tubercles, inspired from humpback whales are applied to a wing sail designed to compete in the America's Cup on an AC72 catamaran. The effect of these tubercles on the aerodynamic performance of the wing sail has been investigated. Viscous Computational Fluid Dynamics (CFD) method has been used for the investigations following a grid sensitivity study and a validation case based on wind tunnel experiments of 2-d foil sections with leading edge tubercles.

2. Wingsail Design and Bio-Inspired Wings

Although airfoils and wing shapes have been extensively examined and utilized by aeronautics industry; wing sails have only been of interest to some enthusiasts and racing boat designers in yachting industry. Nevertheless, first wing sails have been used since 1980's and they became more popular after fast going boats of 2013 America's Cup regatta.

One of the main advantages of wing sails over soft sails is that they can generate much better pressure distribution around sail and create more lift (L) and less drag (D) with same sail area.

There are some major important subjects that need to be considered carefully while designing a wing sail. First one is, since solid wing sails cannot adjust their camber such as soft sails in both tacks; two or more element wing sails are being utilized in boats. Since the gap between flap and main sail cannot be closed perfectly, analysis regarding the extent of the slot must be carried out carefully while designing a wing sail. Another major design element for wing sails is reducing induced drag (C_{DI}) as much as possible to increase overall performance. As seen from the Equation (1) induced D is proportional to L^2 and will eventually limit the available thrust in upwind sailing [1].

$$C_{DI} = \frac{{C_L}^2 A_S}{\pi b^2} \qquad (1)$$

where:
As: Sail area,
b: Span of sail.

As hydrodynamic performance and maneuvering capability of humpback whales gathered attention of researchers, morphological studies and wind tunnel tests have been based on flippers of these whales.

From the studies of Fish and Battle [2], it is seen that humpback whales utilize high aspect ratio wing like flippers which have similar sections with NACA 634-021 symmetrical airfoil. It seems from the research that tubercle distribution is stochastic, but size is gradually getting smaller while going to tip of the flipper. Symmetrical cross sections and elliptical planform of the flipper create favorable L distribution along the span and minimize induced drag. Research shows that undulations on the leading edge minimize profile drag by lowering pressure gradient due to the flow around tubercles. Therefore, reduction of this pressure gradient postpones the flow separation and allows flipper to continue generating L by minimizing energy lost in the wake.

Miklosovic et al [3] constructed a wind tunnel test based on NACA 0020 airfoil section to compare L and D of a flipper with and without leading edge undulations. They tested models with Reynolds Number (Re) around 10^6 at Mach Number 2.0 in different angle of attacks ranging from -20 to +20. They observed that stall angle increased from 12 to 16.30 and maximum lift coefficient (C_L) increased 6% in flipper with leading edge tubercles.

Wind tunnel experiments, CFD studies and panel method analysis are utilized by various researchers to examine finite and infinite aspect ratio wings with leading edge tubercles. Performance difference is examined and physics of flow phenomena in different situations are tried to be determined by these researches.

3D panel method is utilized by Watts and Fish [4] to investigate forces acting on a wing. NACA 634-021 airfoil is used in analysis and method code for analysis is based on first order vortex method by Hess, Katz and Plotkin. Since panel method constructs inviscid simulations, high Re numbers regimes are more suitable for this method as indicated by authors. It has been observed from the analysis that undulations on leading edge increased lift around 5% and reduced drag around 11% at an angle of attack of 10 degrees. Main theory from research for performance increase is that undulations delay and reduce flow separations by shifting pressure gradient in top surface without effecting mean pressure.

Johari et al [5] constructed a series of wind tunnel tests with finite wings that have sinusoidal leading-edge undulations. Undulations on wings had different wavelength (λ) and amplitudes (A) as a function of chord length(c). Wave lengths were specified as 0.25c and 0.50c while amplitudes were 0.025c, 0.05c and 0.12c. Similar results are achieved with Miklosovic's experiment while there are slight differences in pre-stall regime. Drag coefficient (C_D) of the modified wings increased more in Johari's experiments while similar stall delay and post-stall L/D ratio increase occurred in both cases. Similar result is also stated by Hansen et al [6] that tubercles on leading edge reduce L/D ratio at Re below 300000. Six of the tested airfoils with leading edge tubercles continued to provide L where baseline foil stalls.

Effects of change in amplitude and wavelength of tubercles are also studied by Johari et al. [5] and it has been indicated that while wavelength has a light effect on the performance, amplitude effects behavior of the foil significantly. According to Atkins [7], this result can be possibly explained by the vortices generated by tubercles resulting in the exchange of momentum at the boundary layer and re-energizing flow to attach to the foil and postpone stall.

Lohry et al [8] studied tubercles on NACA 0020 airfoils by using RANS solver developed at Princeton University. According to Lohry, both low Re and unusual geometry of airfoils render RANS simulation results highly responsive to turbulence models used. In their study it has been concluded that best results which are close to wind tunnel tests are achieved with Menter SST k-ω turbulence model. It has been indicated that performance of undulations relies on Re, thickness and planform shaping [8].

Hansen [9] executed several experimental and computational studies on NACA 65-021 and NACA 0021 airfoils to analyze the influence of leading-edge tubercles on wing performance and the physical phenomena behind the effects.

Tests done with different Re showed that performance increase is dependent on Re and high Re are more suitable for performance increase with leading edge undulations. Similar tests were conducted with finite and infinite spans and seen that results are free from 3D effects and tubercles do not affect tip vortices. In the studies with both airfoils, maximum L/D ratio is achieved with smallest tubercles in terms of both wavelength and amplitude. But it has been stated that there is an optimum λ/A ratio since reduction of wavelength after certain limit compared to amplitude is reduced the efficiency of the wing.

Initial studies done by Watts and Fish [4] indicated that leading edge tubercles increased wing performance by prohibiting tip vortices. However, studies executed by Hansen [9] and Johari et al [5] showed that lift and drag characteristics of a wing with leading edge undulations are independent from wingspan and 3D effects. Therefore, tip stall theory is eliminated according to the latest studies. It has been observed from the recent studies that while wavelength of the tubercle had small effect on the lift and drag characteristics, amplitude played much significant role on performance change. As indicated previously, this phenomenon can be explained by such flow behavior that vortices generated by tubercles exchange momentum in viscous layer and delay stall by delaying flow separation similar to the vortex generators [7].

The literature review on the studies regarding the utilization of tubercles indicate that performance improvements may be possible in the post-stall regime and a general insight into the flow phenomenon associated with tubercle utilization has been obtained. However, studies are based on finite and infinite aspect ratio standard foil profiles and a peculiar study on the utilization of tubercles on wing sails and its effects on the performance of the wing sail has not been observed. This study aims to investigate the effect of leading-edge tubercles on wing sail performance by viscous CFD simulations. Systematic variations of the tubercle geometry attached to the leading edge of a wing sail will be made and variations on the aerodynamic performance of the wing sail will be investigated.

3. Computational Analysis

A systematic computational study for investigating the undulations on wing sail has been executed. Unsteady Reynolds Averaged Navier-Stokes Equations (U-RANS) solver of commercial CFD code Star-CCM+ has been utilized. A time step value of 0.001s has been used in the analyses.

3.1. Methodology

As a start, mesh convergence study is executed to determine minimum number of cells required to achieve a converged result without increasing the computational cost. Then turbulence models are examined and Menter SST k-ω model is used in simulations since it gives better results in separated flows and gives consisted results when compared to data extracted from experimental works. Standard Menter Shear Stress Transport k-ω is a turbulence model comprised of two equations that solves additionally turbulent kinetic energy (k) and specific dissipation rate (ω) transport equations [10]. This model associates both k-ω and k-ε turbulence models to increase accuracy of results on inverted pressure gradients. Therefore, by combining two models, Menter SST k-ω gives accurate results in cases such as flow around airfoil in both small and high angle of attacks.

Prior to analysis of wing sails, validation of Star-CCM+ software and U-RANS numerical models is executed. Wind tunnel section and foil placement similar to experiments done by Tezel et al [11] has been constructed in Star-CCM+. Results of the CFD analyses are then compared to C_L and C_D measured by Tezel. NACA 0012 airfoils are tested in the mentioned paper from -3 to +33 degrees of angle of attacks by 3-degree increments. 3-part tubercle with 30 mm wavelength and 8mm amplitude (λ30A8) is selected for comparison with base model. Flow speed is taken 33 m/s in both CFD and experiment while corresponding Re is 3.19x 10^5.

Effect of mesh cell count on C_L and C_D are examined as a first stage of validation study to achieve reliable converged results that are independent from cell numbers in the domain. Base NACA 0012 model is investigated in 12^0 angle of attack with mesh sizes shown in the Table 1. Results have started to converge after base cell size of 1.25 cm although there are slight differences in C_D. Maximum cell size chosen as 1cm and refined mesh size around wing and in wake area is taken 0.5 cm as seen on Figure 1 to achieve accurate results. Further refinement is done on the leading edge of aerofoil to define smooth leading edge as decent as possible. Figure 2 shows refined leading edge with cell size of 0.1 cm.

Table 1. *Grid Independence Study at 12^0 Angle of Attack*

Max Size	Cell Size	Cell Count	CL	CD
2.5 cm	1.25 cm	46629	0.4571	0.1308
1.5 cm	0.75 cm	122459	0.6432	0.0908
1.25 cm	0.625 cm	181913	0.6474	0.0832
1 cm	0.5 cm	306278	0.6482	0.0826
0.75 cm	0.375 cm	610824	0.6463	0.0791

Boundary layer thickness (δ) and dimensionless wall distance (y^+) are also important parameters while simulating a viscous flow. Boundary layer thickness in turbulent flow is calculated 5mm by Equation (2) found on Schlichting [12]. Boundary layer is modeled with prism layer mesher and total 12 prism layers are used

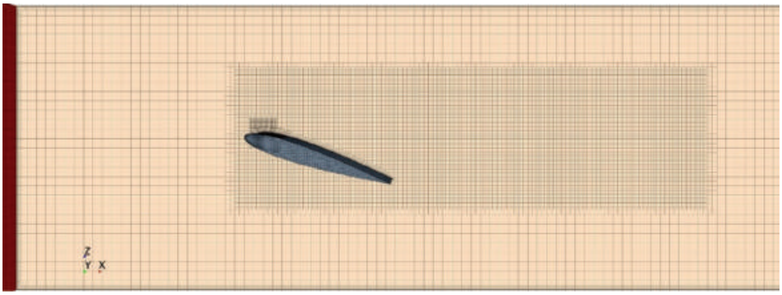

Figure 1. *Meshing of Domain and Volume Refinement*

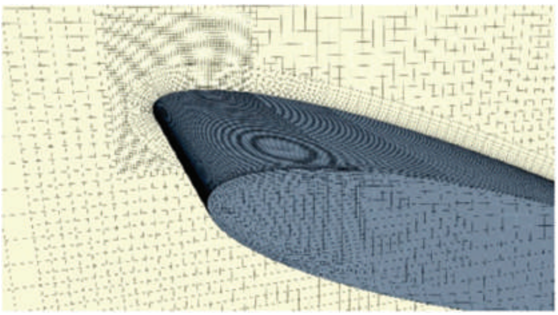

Figure 2. *Mesh Refinement on Leading Edge*

with stretching factor of 1.3. Therefore, y^+ is calculated as approximately 10 according to (Equation 3) also found on Schlichting [12].

$$\delta \approx 0.37x/Re_x^{1/5} \quad (2)$$

$$y^+ \equiv (u^* y)/\upsilon \quad (3)$$

Menter's SST k-ω turbulence model is used in analyses since literature review pointed that in almost all previous studies, best results close to experiments are achieved with this turbulence model.

Figure 3-5 demonstrate the comparison between base NACA 0012 and modified λ30A8 airfoils in both CFD and experiment. CFD results tend to over predict C_D in high angle of attack for base NACA 0012 wing however, general behavior of flow and airfoil is consistent with experimental results. Interestingly, CFD predicted C_D for λ30A8 wing close to experiment while over predicting C_L this time. However, in both case L/D ratio is consistent with experimental data.

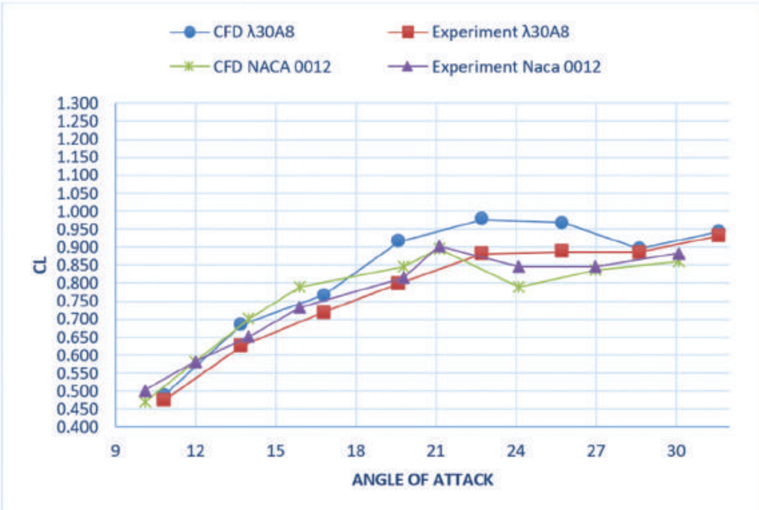

Figure 3. *Comparison of C_L Between Experiments and CFD Analyses*

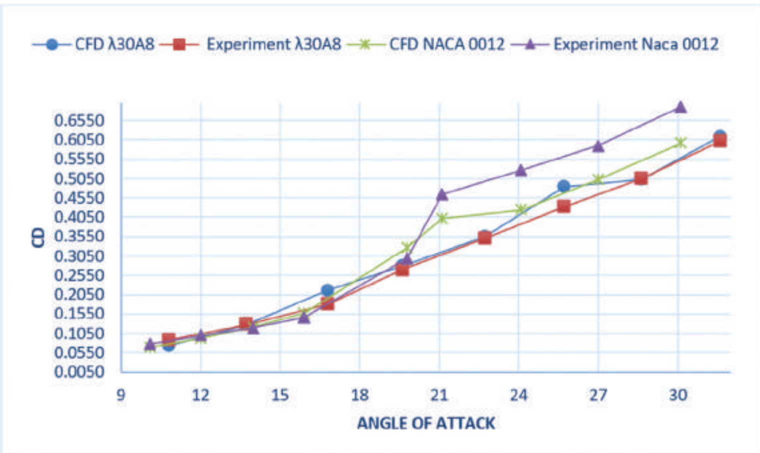

Figure 4. *Comparison of C_D Between Experiments and CFD Analyses*

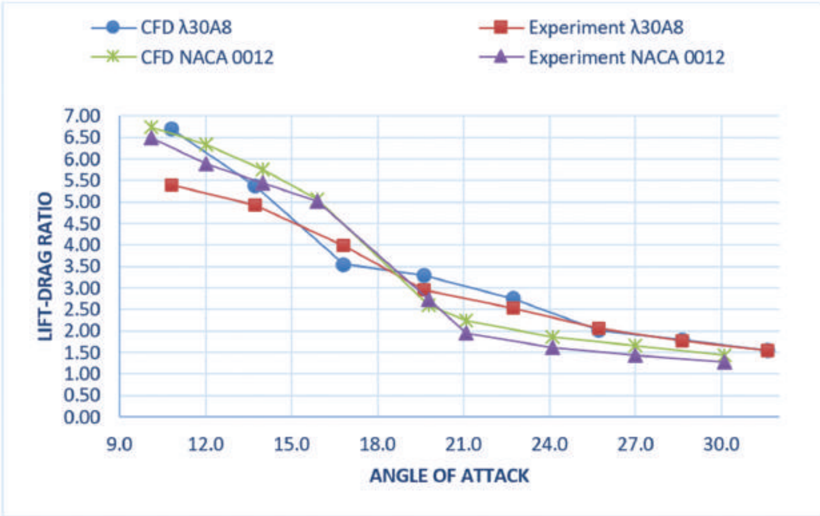

Figure 5. *Comparison of Lift to Drag Ratio Between Experiments and CFD Analyses*

3.2. Wing Sail Analyses

Geometry of the wing sail to be investigated in this study is designed according to the 2013 America's Cup rule. In the rule book, wingspan is divided into 12 segments and maximum-minimum chord lengths are restricted between certain values [13]. Also, total sail area of wing including main element and flaps needs to be between 255 and 260 square meters. Rule permits teams to design and experiment on their own profile selection and number of flaps. For the Emirates Team New Zealand, Collie et al [14] investigated effects of element number on performance and concluded that increase in element count also increases downwind performance while having negligible effects on upwind performance. Nevertheless, all teams adopted two element wing sail with one main element and one flap due to several reasons; main one is after 2 elements, increase in performance gradually becomes smaller while controlling the boat becomes practically too challenging for the crew.

As mentioned previously, slot width between main element and flap plays important role on the multi element wing sail performance. Chapin et al [15] indicate that this gap dimension alters the wake and boundary layer interaction, causing an unsteady coupling between wing elements. Also, in the same study 2D URANS analysis had been executed on 1/20 scale AC72 wing sail section and performance of wing decreased with increasing slot width which is a function of chord length [15]. Viola et al [16] constructed similar analysis in their paper and determined optimum gap dimensions.

Final wing sail design for this study has been obtained from Kemali [17] and can be seen on Figure 6. NACA 0025 and NACA 0009 airfoil sections are selected for main element and flap respectively according to Blakely et al [18]. Total sail area of the sail is 257 square meters and rotation angle of flap is fixed to 20^0 for all analyses. Gap dimensions are selected as 0.02c and 0.015c for x and y directions respectively.

As a first step for the wing sail analysis, sinusoidal tubercles are placed on a plain wing sail, then wavelength and amplitude of undulations systematically changed to construct test matrix for the study. Figure 7 shows totally 6 different wing sails with

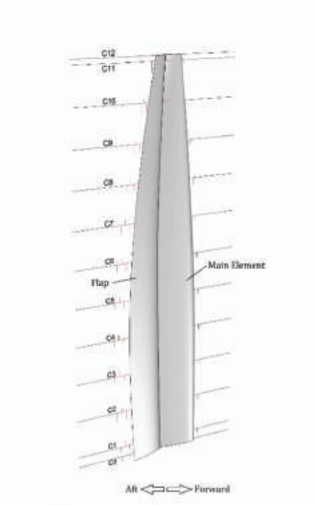

Figure 6. *Final Geometry of Plain Wing Sail for Analysis [17]*

different tubercle dimensions. Wavelength and amplitude of tubercles changed as a function of bottom chord length of the final wing sail. Final test matrix can be seen on Table 2.

All analyses are executed at 1/10 scale since available computer power does not permit full scale calculations due to substantial increase in mesh number to correctly model boundary layer with trimmer mesh and prism layer mesher in Star CCM+. In full scale, boat speed is considered as 12 knots which is approximately taken as 6 m/s. In 1/10 scale speed is calculated 60 m/s with Re similarity. In this configuration Re is $1.5x10^6$ and boundary layer thickness δ is approximately 8mm. Dimensionless wall distance y+ in wing sail analyses is adjusted as 10, same as in validation study.

Second step in wing sail analyses is comparing the base plain wing sail with modified wing sails. For the performance comparison, C_L and C_D as well as L/D ratio are investigated. As a beginning, plain wing sail's lift coefficient, drag coefficient and lift to drag ratio is measured in CFD with different angle of attacks ranging

Table 2. *Test Matrix for Wing Sail Analysis with Tubercles*

Test No	m.	λ (c)	m	A (c)	Name
1	0.12	0.3	0.006	0.015	L30A15
2	0.12	0.3	0.017	0.045	L30A45
3	0.15	0.4	0.006	0.015	L40A15
4	0.15	0.4	0.017	0.045	L40A45
5	0.19	0.5	0.006	0.015	L50A15
6	0.19	0.5	0.017	0.045	L50A45

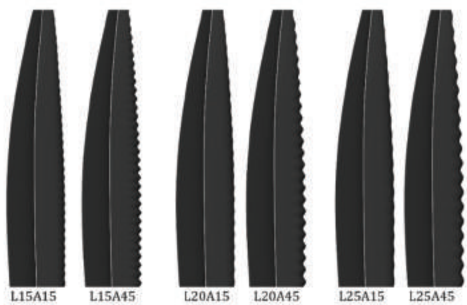

Figure 7. *Developed Wing Sail Geometries with Tubercles on Leading Edge [17]*

from 14 to 32 degrees. It has been observed that stall angle is approximately 26 degrees. Therefore, modified wing sails with tubercles are tested in CFD at angle of attacks 23 and 30 degrees to see performance change in pre-stall and post-stall regimes. Best results are achieved with largest wavelength and smallest amplitude tubercles in test matrix. Comparison of coefficients between different wing sails can be seen on Table 3.

As a final step, this best performing wing sail with tubercles is compared with plain wing sail in all angles of attack between 14 to 32 degrees with incremental step of 2 degrees. Therefore, characteristics of both wing sails can be compared more thoroughly in all regions of apparent wind angle of attacks.

Comparative results of wing sails with and without tubercles are given in Figure 8-10 respectively. In Figure 8, lift coefficients of the base sail and best performing wing sail with tubercle is presented. It is seen that the tubercles do not influence the lift generation tendency in the pre-stall regime. The stall angles are approximately identical. The gain in lift generation is achieved in the post-stall regime; the wing sail with the tubercle creates more lift force. In other words, the reduction in lift force is lesser for the wing sail with the tubercle.

Figure 9 shows the drag coefficients of both sails. It is seen that a marginal increase in drag coefficient is observed in the post stall regime due to the extra lift generation. This results an increased efficiency (L/D ratio) in the post-stall regime as depicted in Figure 10.

Table 3. *Comparison of Coefficients Between Wing Sails at 23 and 30 Degrees of AoA*

	Straight	L30A15	L30A45	L40A15	L40A45	L50A15	L50A45
AoA	CL	CL	CL	CL	CL	CL	CL
23	1.465	1.478	1.472	1.468	1.465	1.456	1.455
30	0.940	1.142	1.145	1.146	1.141	1.170	1.182
AoA	CD	CD	CD	CD	CD	CD	CD
23	0.157	0.153	0.155	0.154	0.154	0.155	0.155
30	0.321	0.365	0.322	0.383	0.378	0.315	0.326
AoA	L/D	L/D	L/D	L/D	L/D	L/D	L/D
23	9.331	9.660	9.497	9.532	9.513	9.394	9.387
30	2.928	3.129	3.556	2.992	3.019	3.714	3.627

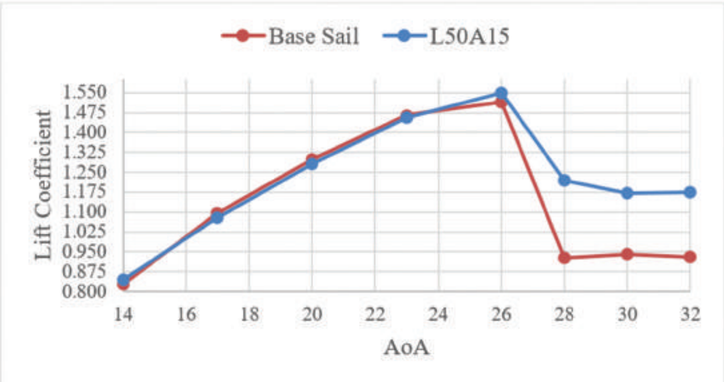

Figure 8. *C_L Comparison*

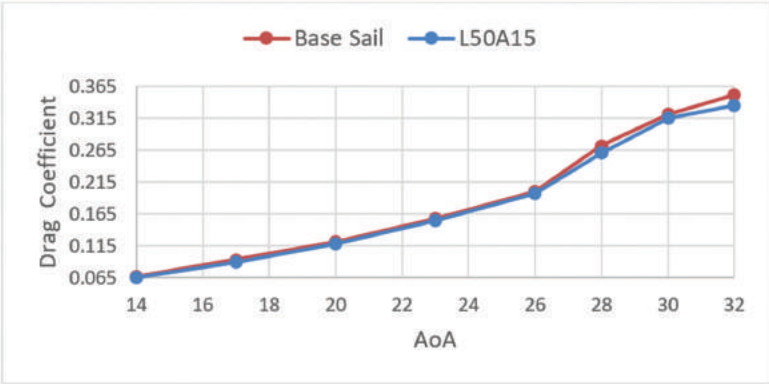

Figure 9. *C_D Comparison*

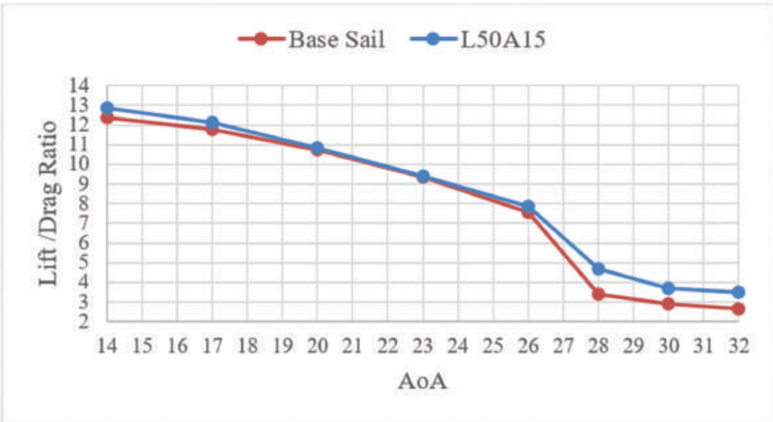

Figure 10. *Lift/drag Ratio Comparison*

4. Conclusions

Tubercle geometry on the leading edge increased wing sail performance as expected after post-stall regimes by increasing lift/drag (L/D) ratio compared to plain wing sail. Stall angle remained same with modified wing sail with tubercles while increasing L/D ratio after stall angles and having negligible negative effect in pre-stall regime. In small angles of attack performance almost remained same between two wing sails.

To increase performance of AC72 boat which mostly sails in upwind condition, improving speed made good (the vector component of the velocity towards the direction of the wind) has a significant importance. Delaying stall angle and improving performance in post-stall regime contributes to this performance increase of speed made good. Therefore, better wing sail with optimized leading-edge tubercles is expected to enable AC72 boat to complete racecourse in shorter time than other competitors with plain wing sails due to its better performance in these regions. The wing sail with tubercles, utilized in this study has slightly better performance at stall angle of attack and significantly better performance in post-stall regime.

Since determining optimum tubercle dimension for best performance increase without affecting pre-stall behavior of wing is an optimization problem, excessive amount of analyses is required to achieve detailed and meaningful outcomes. One way of overcoming this situation is using artificial neural networks and machine learning. By this method, a specific written computer code can learn performance change and generate consistent results after certain amount of analyses, since it can learn behavior and response of wing changing tubercle dimensions.

Another future study can be done on a Velocity Prediction Program (VPP) and assessing time gains of AC72 boat with tubercle geometry wing sails more especially in upwind sailing.

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An Exploratory Study on the Perceptions of Stakeholders in LNG Bunkering Supply Chain

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Abstract

IMO 2020 regulations force maritime industry to look for alternative fuels for compliance. LNG is a promising option as a fuel considering today's emission control regulations and for measures to be adopted in the future. However, supply chain development for small-scale LNG is not at the expected level. The study examines the development of LNG bunkering supply chain based on different perspectives of stakeholders. The research explores the challenges regarding LNG bunkering development and aims to provide suggestions to overcome these challenges. Semi-structured interviews were conducted through purpose sampling including various representatives of LNG bunkering supply chain. The study identifies barriers in LNG bunkering development, categorizes some key approaches and links challenges from the view point of relevant stakeholders for improvement in supply chain. The research findings indicate that collaboration of stakeholders is the main driver for LNG bunkering development, public opinion, standardisation and transparency are the other outstanding factors to improve LNG bunkering supply chain.

Keywords: *LNG Bunkering, LNG as Ship Fuel, Emission Control, Small/Mid Scale LNG Supply Chain.*

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1. Introduction

International Maritime Organization (IMO) GHG (Greenhouse Gas) study indicates that CO_2 emissions from the shipping industry could grow by 50% to 250%, depending on economic development and energy demand[1]. In addition to the effect of climate change, shipping-based emissions such as particulate matter (PM), nitrogen oxides (NO_x), sulphur oxides (SO_x), unburned hydrocarbons (UHC) can lessen the ozone layer, produces acid rain and GHG effect. The burning process of the main and auxiliary engines produce substantial amounts of air pollutants such as sulfur oxides (SO_x), nitrogen oxides (NO_x), carbon dioxide (CO_2), volatile organic compounds (VOC), carbon monoxide (CO), black carbon (BC) and particulate organic matter (PM)[2], as well as transitional and alkali earth metals (V, Ni, Ca, Fe) and their soluble or insoluble chemical forms (sulphides, sulphates, and carbides)[3]. IMO GHG study estimates that shipping is responsible for 12% of global SO_x emissions and 13% of global NO_x emissions[1]. As the international regulatory body of shipping, IMO adopted the first air pollution prevention regulations by Marpol Annex VI, and regulations came into force in May 2005. Sulphur emission restriction compliance is subject to the owners and operators of the fuel-use strategy. Fuel prices, environmental impacts, and payback time of investments are the factors for choosing emission mitigation measures[4]. There are three main sulphur emission reduction strategies for Emission Control Area (ECA) compliance: low sulphur distillates, scrubbers, and liquefied natural gas (LNG)[5]. The three viable alternatives have different aspects for decision making, such as the price of the fuels, trading area, regulations, remaining lifetime of the vessel, time at sea, and port[6]. Low Sulphur distillates require low capital expenditure, but the unit price is higher than the alternatives. IMO Tier III compliance needs additional investment. Scrubber and HSFO alternatives require retrofitting for the scrubber. Vessel's stability or constraints could be an issue for installation. On the other hand, LNG has a significant positive effect on air pollution as it provides complete removal of SO_x and PM, reduction of NO_x up to 85% and reduced CO_2 emission at least 20%[7]. However, there are several challenges, such as lack of infrastructure and operational standards, that prevent faster developments. Though LNG ship fuel is to be used by LNG driven vessels -that is under shipowner discretion; LNG fuel supply is controlled by other stakeholders of the shipping -ports, terminals, suppliers, etc.

This study aims to contribute to LNG bunkering development as a business case that needs to be investigated through different perspectives of supply chain stakeholders. Shipowners, port authorities, technology providers, and suppliers have various concerns for overall supply chain development.

The structure of the study is followed by section two, which explores related literature, section three describes the research method and data collection; section four analysing data and presenting the findings. Section five discusses empirical findings, their relations, and LNG bunkering development, and the study ends with concluding remarks and suggestions for future research.

2. Literature Review

LNG bunkering supply chain problem is a relatively new subject in literature. LNG fuel option for shipping has been discussed with different perspectives in literature. The port operation side is also investigated by various research. However, the entire network design of the LNG bunkering supply chain with different stakeholders' perspective is somewhat limited.

LNG bunkering operation brings ship and port dynamics side by side. The same perspective is observed within the literature review. Some studies propose LNG bunkering handling terminal or jetty design alternatives [8–10], some others operational efficiency of ships [11]. Another important factor has been seen as the safely handling of LNG for bunkering, safety zones, simultaneous operations, collision risk, gas leakage, onboard safety systems, and hazardous consequences are discussed[12–16]. Regulatory discussions are relatively less than other perspectives [17–20]. Economic framework and demand are widely discussed, along with comparative analyses of the other alternative fuels evaluating through different methods and variables[21–29]. Some articles bring more broad approaches to LNG bunkering. Wang and Notteboom[30] carry out a systematic review of the present reports, papers, articles, presentations, and it provides a holistic approach to the challenges of LNG fuel propulsion. Another study of Wang and Notteboom [31] explores the LNG bunkering development with a port perspective; however, the study is limited with only North Europe ports within the ECA area. Only a few articles in literature investigates the supply chain viewpoint of LNG bunkering. Aymelek et al. [32]'s research covers up challenges of LNG bunkering and proposes a network model with a system approach for deep-sea liner shipping. Jafarzade et al. [33]'s system engineering approach explores technical aspects of LNG fuelled systems and significantly contributes to the decision making process while taking into account operation, safety, and economic perspective. However, the study is limited to fishing vessels and the Norway case. Calderon et al. [34] explores the LNG bunkering development by port perspective and investigate safety standards, logistics, and financial aspects, based on secondary data obtained through port websites, reports, and IHS database. Gucma et al.[35] propose a model of the LNG distribution concept based on the location-routing problem (LRP). The research on the small-scale LNG supply chain is somewhat limited, and they focus on the optimisation of LNG distribution [36–39]. Jokinen et.al. propose a model for regional small-scale supply chain utilization in Finland based on fuel procurement cost by mathematical modelling[36]. A small-scale LNG supply chain has been explored by Bittante et al. at tactical and strategic aspects in which the distribution problem has been solved with mixed-integer linear programming. The optimum size of satellite terminals, convenient ports, optimal fleet deployment, including ships and trucks, were determined[38]. Bittante et al., in another research, propose a model for Caribbean small -scale LNG distribution based on fleet size and mix vehicle problem with mathematical modelling methodology at the strategic level while taking into account uncertainty in demand[39]. A recent study by Wan et al.[40] proposes a model to evaluate LNG fuelled vessels based on Norway, China, and USA data. The authors used SWOT analysis, AHP, and evidential reasoning approach (ER) in order to deal with qualitative and quantitative features of the problem.

There are two dimensions in the literature; the points dealt with on the one side explore the ship side: engines, emission control measures, sustainability, and economic feasibility, another side investigates port developments, feasibility as LNG bunkering. The other studies can be grouped as safety standards, operational, and technical challenges for LNG bunkering development. The general two-sided approach in the literature is reflected in real life as the 'chicken-egg' problem. These arguments could be categorized as Safety, Operational Challenges, Technical

Challenges, Regulatory Framework, Commercial Factors, and Sustainability. The shipping industry is in a truly international context, and taking a further step is not an easy decision. Therefore, understanding barriers in LNG bunkering development, a holistic approach that merges different perspectives, covering not only various stakeholders but also different regions across the world, is needed. There are limited number of studies focusing on the factors affecting LNG bunkering development. However, no specific research has been found in the literature regarding the factors affecting LNG bunkering supply chain development based on expert views. This study provides a comprehensive and detailed qualitative analysis while taking into account the views of the related stakeholders.

Based on the relevant literature, two research questions have been formulated in this research in order to address LNG bunkering development with a holistic approach: RQ1-What are the main factors affecting LNG bunkering development, RQ2-How do different stakeholders contribute to LNG bunkering supply chain development. RQ1 is critical to identify the present challenges in front of LNG bunkering, which is not at an expected level in the shipping industry. RQ2 is formulated to address how to cope with challenges and which stakeholders are linked.

3. Methodology

The literature covering LNG bunkering, LNG Supply Chain, Small/Mid Scale LNG has been reviewed in order to see the LNG bunkering supply chain development. Six main themes were derived from the literature review: Safety, Operation Challenges, Technical Challenges, Regulatory Framework, Commercial Factors, and Sustainability perspectives as inputs of the supply chain. The interviews help researchers to collect valid and reliable data that are relevant to the research questions. There are different typologies in the literature to categorize interviews; commonly, interviews are classified as structured, semi-structured, and in-depth (unstructured)[41]. While structured interviews are designed to identify general patterns in descriptive studies, unstructured interviews help to explore new insights. On the other hand, in the semi-structured interviews, the researcher has lists of themes and questions that may vary for different respondents. Some questions may differ according to the flow of the interview or could be focused on specific points according to the context and provides flexibility for the researcher to explore the new phenomena. This approach in semi-structured interviews allows researchers to conduct an exploratory and explanatory study. Therefore, as this study aims to explore a relatively new concept in the industry, a semi-structured interview method was employed.

The researchers prepare a list of themes and questions to be covered; however, this could be varied from interview to interview. Additional questions could be asked according to the flow of the interview in order to explore the research questions and the objectives. The exploratory study is particularly used to understand the problem and provides insight into the phenomenon. It creates casual relationships between variables and explains the relations [41]. Therefore, open-ended questions were preferred in order to reveal and understand the 'what' and 'how' but also exploring the 'why' for LNG bunkering development as it allows us to make exploratory and explanatory research.

The interviews were planned to be conducted through the leading experts in the industry during the LNG bunkering summit 2019 in Amsterdam. Company profiles, organizations, company reports, or other publications related to LNG bunkering along with company representatives' profiles were investigated in order to be prepared for a possible interview opportunity, demonstrate credibility and to encourage the interviewees for more detailed data. The purposive sampling strategy was used with a maximum variation approach as a sampling method in order to reach the research objectives, which requires different perspectives in the supply chain as it was categorised as suppliers, shippers, regulatory bodies, and technical service providers [42]. Samples were selected deliberately in accordance with the research objectives. The size of the samples was restricted in line with theoretical saturation, i.e. untill data collection generates no new insight. The themes of the interview were given to the participants in advance to promote validity and reliability as the participant was allowed to be prepared or gather related information before the interview.

Before each interview, some terms such as the aim/scope of the research, the researchers' background were explained to establish credibility. At the end of the interviews, a brief summary was made in order to test the researcher's understanding. The interviewee was able to evaluate the researcher's understanding and correct it if deemed necessary. The coding of the interviews was compared with an expert who carried out coding separately using Maxqda18 and evaluated based on statistical data. The participants were selected on purpose to represent different stakeholders, titles, and companies in order to assure transferability. In order to achieve confirmability, the researcher made clear his own background and position in advance against potential bias. The coding and theme creating processes were clarified and the findings were linked to the conclusion. The research was conducted with ethical principles through which the participants' consent was gained; their views were represented as accurately as possible, the names and company details were kept confidential so as to assure the integrity of the research.

A mobile phone interview application was used for recording, and notes were taken during the interviews. The participants were informed regarding voice recording in advance and some of them declined to speak over the recorder. In these cases, only notes were taken. Some of the interviews were declined as well, due to the length of the meeting or due to some technical reasons. Finally, twenty interviews were clarified, which included six suppliers, five shipowners, five technical service providers, and four interviews represent regulatory bodies from ports, flag, and classification society. All participants are already in the LNG bunkering business as different stakeholders and experts in this field with titles of one Chairman, one Vice President, one Chief Operating Officer, one Chief Financial Officer, six Directors, nine Managers, and one Senior Safety Advisor. All participants represent companies that are already in LNG bunkering business.

Shipowners representatives run container fleet, ferryboats, LNG vessels, and tankers. The participant covered under the regulatory body, represent one of the leading ports in shipping. Truck to ship and ship to ship operations are currently conducted, and simultaneous operations have just started. The port develops regulatory content and sets standards in order to perform safe and effective LNG bunkering operations. The second port respondent represents one of the busiest ports in Europe for Ro/Ro shipping, container, and LNG handling. The port also provides ship to ship LNG bunkering facility. Classification society representative already has LNG fuelled vessels under their service. Suppliers are either major oil representatives taking part in every stage of the supply chain, or conventional bunker supplier recently who invested in LNG bunkering, or LNG suppliers who recently started to provide marine fuel. Technical service providers represent engine manufacturers, safety equipment manufacturers for gas systems and infrastructure developers for gas supplies. LNG bunkering operations are very limited across the word, and it's still only possible at specific locations. The dedicated LNG bunkering summit provided the opportunity to reach out to senior-level experts in this newly developing field.

Face-to-face interviews, skype interview, notes taken during interviews were transcribed. To analyse this primary data obtained from the interviews, Maxqda 18.1.1 Software was used. The qualitative data were coded on software. The study was conducted in four stages: 1-Open Coding, 2- Creating categories, 3- Generating themes, 4-Comparing the themes, analysing and integrating [43].

4. Analysis

Maxqda descriptive statistics were evaluated in order to gain insight into LNG bunkering. The distribution of codes and parent codes were analysed. The respondents were grouped into four categories: Shippers, suppliers, technical service providers, and regulatory bodies. The codes were explored based on different stakeholders' views.

During the first round of coding, the transcripts were read through and coded with the open coded approach with no limitations or segmentations. In the second round, transcripts were coded based on the interpretation of the raw data. In the third round, higher-level codes and lower-level codes were defined. After the third round, the codes were refined, and the most highlighted codes were determined. The location/Operational region was determined as the highest frequency in data -emphases in nineteen documents. The top ten frequent codes were listed in Table 1. Demand, LNG bunkering price, LNG price were found as other significant factors. Infrastructure was mentioned in 14 different interviews and followed by oil prices, market conditions, and crew training factors.

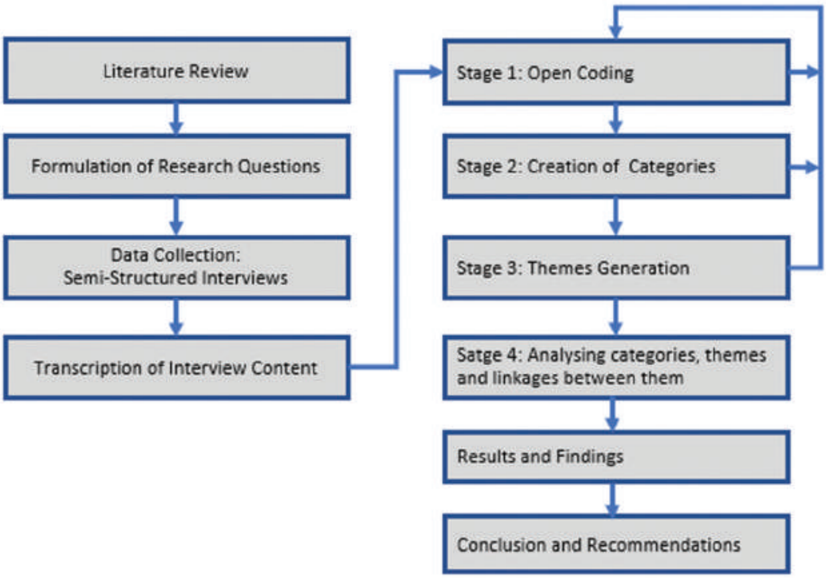

***Figure 1.** Flowchart of the Research Method*

Table 1. Distribution of Codes based on Frequency

Code	Frequency	Documents
Location/Operation Region	5,79	19
Commercial Factors\Demand	4,52	12
Commercial Factors\LNG Bunkering price	4,34	15
Commercial Factors\LNG Price	3,98	13
Infrastructure	3,80	14
Safety	3,80	13
Commercial Factors\Oil Prices	3,62	12
Collaboration	3,62	10
Commercial Factors \Market	3,44	12
Safety\Crew Training	3,44	11

In the second stage, the codes were customized, and the categories were created. Parent codes and sub-codes were shaped in hierarchical order. In the third stage, twelve main themes were generated. Commercial factors represent the most emphasized factors that have 34% frequency and mentioned in all documents. Other theme frequencies are between 1.65 and 9.9%. Safety consideration took second place, with 9.9% narrowly in front of the environmental considerations (8.55%). Related codes were gathered under the regulatory framework, technical factors, and infrastructure. Themes were created as Location/Operation Region, Operation factors, Collaboration, Fleet Type, and Supply Chain. Some factors, which are considered important but not frequently mentioned in data sets, were grouped under 'Others.' These include transparency, work management, strategy, public opinion, etc. Parent code distribution is summarized in Table 2.

As the study aims to explore different stakeholders' insight into LNG bunkering, the respondents were grouped as Suppliers, Shipowners, Technical Service

Table 2. Distribution of Parent Codes based on Frequency

Main Code	Coded segments	Coded segments as %	Documents
Commercial Factors	228	34,18	20
Safety	66	9,90	16
Sustainability/Environmental	57	8,55	15
Regulatory Framework	51	7,65	16
Technical Factors	49	7,35	11
Infrastructure	40	6,00	14
Location/Operation Region	37	5,55	19
Collaboration	37	5,55	10
Fleet type	34	5,10	10
Operational Factors	34	5,10	14
Supply Chain	23	3,45	7
Others	11	1,65	5

Providers/Consultants, and Regulatory bodies -Classification Society, Flag, Port respondents. There were 6 suppliers, 5 shipowners, 5 technical service providers, and 4 regulatory bodies. Commercial factors are the main challenges for all stakeholders. While commercial factors are narrowly leading factors for technical service providers (22%), it represents the far biggest challenge for the shipowner perspective (44%). Infrastructure issues were indicated as the second most significant challenge for the ship owners. On the other hand, the regulatory body perspective considers safety issues as the second important challenge (20.3%). Suppliers frequently mentioned cooperation issues in second place after commercial factors. Technical service providers' perspective is broader than other groups that frequencies are more equally distributed among themes, and not surprisingly, technical factors took second place after commercial factors. The distribution of parent codes based on the stakeholder group is listed in Table 3.

At the fourth stage, theoretical links between categories were investigated in order to analyse, underpin the themes, and explain the relations between them. The data were refined through asking questions, the findings were compared, analysed, integrated, and the results were presented in a realistic scheme in order to address research questions and objectives.

5. Discussion

The study explores LNG bunkering development through different stakeholders' perspectives: suppliers, shipowners, technology developers, and regulatory bodies. As main difficulties are represented as lack of infrastructure and prices, there are other factors are affecting directly or indirectly; so the overall supply chain development is interlinked. Main themes -environmental, safety, operational, technical, regulatory framework, and commercial challenges were critically discussed in order to bring a holistic approach to overall supply chain design.

5.1. Environmental Considerations

LNG has a positive impact on air quality as sulphur content and PM are almost zero. Short sea shipping and cabotage shipping require more attention as local

Table 3. *Distribution of Parent Codes based on Stakeholders*

Main Codes	Supplier	Shipowner	Technical SP	Regulatory Body	Sum
Commercial Factors	37,8%	44,7%	22,8%	33,3%	34,0%
Safety	7,8%	5,8%	5,1%	20,3%	9,4%
Sustainability/Environmental	6,7%	10,7%	8,9%	6,5%	8,0%
Regulatory Framework	7,3%	1,9%	8,9%	12,2%	7,8%
Technical Factors	5,2%	1,0%	20,3%	2,4%	8,0%
Infrastructure	2,1%	14,6%	3,8%	4,9%	5,4%
Location/Operation Region	6,2%	8,7%	3,8%	4,9%	5,7%
Collaboration	10,4%	1,0%	7,6%	1,6%	6,1%
Fleet type	3,6%	1,0%	6,3%	6,5%	4,5%
Operational Factors	2,6%	8,7%	8,9%	4,1%	5,7%
Supply Chain	7,8%	1,22%	1,9%	2,4%	3,6%
Others	2,6%	1,9%	1,9%	0,8%	1,9%
Total	6(30,0%)	5(25,0%)	5(25,0%)	4(20,0%)	20(100,0%)

communities are directly affected. However, one respondent argues that environmental considerations are still neglected as in business context, only economic factors are being discussed without taking into account where we live and how the next generation is to be affected by present air quality. IMO 2020 regulations could be a positive contributor to LNG bunkering development. Stricker regulations have a positive impact on LNG bunkering, however; if major oil/ gas companies are not involved in LNG fuel, it will not be future fuel of shipping. Methane slip is still a drawback for LNG as it has thirty times more impact on global warming compared to CO_2. However, technology improvement is promising. Low distillates and scrubbers are other viable options for shipowners for strict regulations compliance. Shipowners could decide to do nothing and follow low distillates option. In this case, the availability and price of the low distillates could be a question mark as refineries could have difficulties to satisfy the increase in demand. Another option is to install scrubber and take advantage of cheaper HSFO. The scrubber option has two alternatives as closed- loop and open-loop. Closed-loop scrubber installed ships need to deliver their waste to shore periodically. Waste reception facilities, their availability, price of handling, and reluctant port authorities could be an obstacle for ships. On the other hand, open-loop scrubbers drain the washing waters into the sea -rather than air. Some ports across the world already banned open-loop scrubbers within their port limit. As these options look more convenient investment decisions, it is going to be difficult to sustain those solutions. Alternative fuels are still infant compare to LNG either due to global availability, technological competency, or regulatory standards. All parties agree that LNG is a viable option for the environmental sustainability of shipping. While shipowners' calculation is based on economic variables, technology providers emphasized technological improvement in the methane slip issue, being a transition fuel for future carbon-neutral fuels. Life cycle assessment of LNG as fuel, taking into account the entire supply chain, is arguable as different approaches bring different results.

5.2. Safety Considerations

All stakeholders are concerned about conducting LNG bunkering operations safely. Crew training is the most important part strongly emphasized by different respondents. Safety concerns usually come up with a regulatory framework and safety standards stressed by regulatory bodies. Shipowners focus more on the availability of the qualified crew and higher industrial standards' economic impact on LNG marine fuel. LNG is not a new issue for shipping as already being transported by ships for years and has excellent safety records. The industry has safety standards to handle it as cargo. Special precautions need to be taken to handle it out of LNG carriers. Crew training is a very crucial step to handle LNG as a marine fuel. Crew dealing with bunkering should be qualified with a fundamental understanding of the product. Safety awareness of the crew is highly related to the type of the vessel they work on. Therefore, training of the crew is a primary concern, especially other than the tanker segment. The training process could need a long time as there are not many places where you can get LNG bunkering training. The key risk is a gas release that could lead to ignition or asphyxiation. The liquid release is also important, which causes fractures on steel. Exposure of cryogenic liquid is going to be resulting in life threating skin burns. Water curtain, personal protective equipment are basic precautions against any liquid release. The location where LNG bunker operation is to be conducted must be safe and to be avoided from nautical risk areas. Approach area, fendering, mooring, and passing vessels through channels are the factors affecting the safety of the operations. Restricted zones should be set for safety reasons. Flow rate and pressure are the two key indicators to determine the safety zone. Quantitative and qualitative risk assessments should be carried out to see if the risk is acceptable. Location choice is critical in reducing the risks to a reasonable limit. Providing simulator training and hands-on training are critical for crew improvement.

5.3. Operational Considerations

LNG bunkering operation has difficulties. Different respondents argue that these are mostly related to lack of experience and globally standardized process, which will be sorted over time. The compatibility of the vessel could be fixed as industrial practices for different sizes of the flanges, and the distance between manifolds can be overcome with flexible hoses. Both facilities exchange information and come up with an appropriate transfer system. However, one respondent argues that the size of the bunker barge could cause some compatibility concerns at loading terminals, as small barge will not fit LNG receiving terminals and some modifications are required. LNG bunker barges are typically designed as Type C tanks, which have no issues with sloshing, and it provides flexibility to load slack cargo according to the client's request. On the other hand, it has been pointed out by one respondent that the capacity and size of the receiving vessel will be a criteria for the supplier in order to reduce the unit cost, fully loading the barge, and then distribute it as much as possible before returning for new loading. Delivered LNG bunker calculation is being made by mass flow meters in Ship-to-Ship transfers. Truck to Ship transfers could be calculated based on the number of trucks. Characteristics of the LNG is different based on the sources. Therefore, BDN (Bunker Delivery Note) should include the quantity transferred as volume, mass, and energy. Which figure will be taken into account is subject to a contract between the receiver and the supplier. Simultaneous operation is another critical stage for LNG bunkering as it allows us to perform cargo or passenger operation at the same time. Larger vessels require a longer time for bunkering, and simultaneous operation resolves time concerns over LNG bunkering. One of the serious obstacles in front of the shipowners could be sorted.

5.4. Technical Considerations

The shipping industry has had experience over LNG handling on a bigger scale for years; however, small or mid-scale handling is relatively new, and some technical problems still exist, or standardized solutions have not been provided yet.

Methane slip at the engine is still one of the biggest drawbacks of the LNG as a marine fuel. Technology providers are very ambitious to minimize it. In addition to the engine, it was highlighted that long hose connections without proper insulation cause leakage and evaporation, which eventually leads to global warming that the industry ignores. The vessels working in long haul need sufficient bunker tank capacity to complete the round trip. The bigger fuel tank means relatively less cargo space. The boil of gas (BOG) problem was pointed out by several respondents. Reliquefication plant or sub-cooling systems are the solutions to the industry so far. Burning of the BOG in auxiliary engines is another alternative to handle the issue. BOG management is the responsibility of each individual vessel, and it has been incorporated into the design of the LNG fuel system onboard the vessel, and the LNG cargo system onboard the LNG bunkering vessel. Quality and methane number of LNG affects the performance of the engine. As LNG is provided from different sources with different quality, it's a question mark for the vessels which need to supply bunker across the world. So standardization in methane number is required for the performance of the vessels' engine. Standardization is achieved in a temperature of the LNG as -158C° in industry. Temperature difference of the LNG also slows down bunkering operation that leads in time concern. Technical obstacles affect the shipowner's investment decision, as it leads to high capital expenditure. Technology providers are optimistic about developments and technical standards. However, the industry still needs to be standardized, and some technical factors are to make LNG marine fuel a more acceptable option globally.

5.5. Regulatory Framework

Handling LNG is already well set by the highest industry standards and regulations. An extended part of the handling LNG involves the bunkering purpose, which is covered by some guidance and best practices prepared by SGMF, EMSA, IMO, SIGTTO, or OCIMF. However, it was observed during the interviews that different stakeholders have different views in terms of implementation, coverage, or practices of the regulatory framework.

Supplier respondents were satisfied with the regulatory coverage of LNG bunkering. However, the other groups were critical in the overall implementation. IGF Code has been developed based on safe handling, environmental considerations in mind; however, it is argued that IMO does not take into account standardization. The implications differ from country to country, even port to port. The process is implemented in various ways, and it makes the process complicated for the ships. Local regulations are different, and they require a different process even within NW Europe. It was highlighted by a respondent that standards have been transferred from conventional LNG handling to LNG bunkering, and it might be too high and difficult to implement at a small scale. However, small revisions and updates on IGF could be sufficient to cover the industrial needs. The technical service provider argues that even if the regulatory framework is in place, there are different opinions between classification societies, and it's hard to keep balance if working with different societies of classification. Their experiences in LNG bunkering are at different levels, and it is reflected on site. Standards are made by experts, not by regulatory bodies. Therefore, IACS should propose canons to facilitate similar implementations in the industry. Ship-owners have a more optimistic view that as operations are conducted, the industry will set its own standards on the way.

5.6. Commercial Considerations

Inevitably commercial factors are far important criteria for any stakeholders. Energy demand, pricing, contracts, supply and demand along with market structure and available funds were discussed through different perspectives.

Commercial viability of LNG fuelled ship investment is critical for ship owners. They have to calculate financial sources, private equity, indirect finance via shipyards or green funds. European Commission or governments subsidize significant amount of the project, 'green' funds are available for investments, however, it requires some work to introduce it to 'shipping' and how to match with 'green'. LNG bunkering investment decision is not an easy process as it comes up with sum of uncertainties. Supplier side points out that there are not so many vessels available in order to serve at regularly basis LNG to customers so they can organize logistics in advance. Shipowner side argues that the main challenge is supply as they can not reach out

LNG fuel as they want. However, regulatory body and technical service providers see the challenge mostly: lack of demand as supply chain for LNG is already available in many places. However, the market does not really exist yet, in progress, bunkering facilities are still on developing stage.

The market is growing very slowly, and it's a costly decision, it depends on how you operate and where you are going to operate. Normally, volume of the market is the key point to decide, however, it was overridden by big oil majors' decision -irrespective volume of the market and they invested in bunker barge. As LNG bunkering market has not been matured yet, the market development depends on where your client is, and you must see potential demand in order not to pursue your client when supply chain is oversized for a single client. Economies of scale is critical at this stage that suppliers will concentrate bunkering stations at these locations. However, small scale LNG logistics cold be very expensive compared to conventional LNG logistics as it requires high CAPEX with unsatisfied demand.

Scalability is important to initiate LNG bunkering supply, relative less investment can afford small amount of LNG by trucks until the market gets matured. The first need is to see the market, and then market will set supplying limits to set the price. One important factor for market development is price. Shipowner side argues that there are very few LNG suppliers in the market without competition, which leads to high LNG fuel prices and it makes the business case for LNG not viable. Availability and the cost related logistics chain is an obstacle. Apart from logistics added cost of LNG, competition with oil price is critical as well. The gap between MGO and LNG will affect shipowners' decisions. Moreover, LNG has different prices in different regions. Pricing in Europe is relatively stable and fluctuating less than that in far east market where gas price absolutely linked in the contract to the oil prices or where gas price oppositely is linked to the oil price in the USA. Conventional fuels have standard products and limited specifications, then it's easy to price this product. However, in LNG, reference quality does not exist, therefore pricing LNG based on specification is not easy.

Another difficulty is there is not much transparency in the industry, and stakeholders do not have knowledge of LNG bunker prices. It's something that needs to be negotiated by shipowners still another challenge for LNG contracts. Supplier side seeks long term contracts to set infrastructure according to demand. On the other hand, shipowners want to see spot market and don't want to commit to long term contracts as they need flexibility and may change their trade patterns. Therefore, contracts should be short -spot deal agreements. Longer term contracts may provide more price security for both LNG suppliers and the LNG consumers, but take away the opportunity for ship owners/charterers to profit from a drop in LNG prices. As global market is changing, with an impact on price, contracts and LNG bunkering pricing, IMO 2020 regulations and new LNG bunkering infrastructures are expected to have positive impact. However, uncertainties are inevitable in a relatively new business case, and sharing the risk is a critical stage to start up new concept.

5.7. Infrastructure, Operational Region and Fleet Type

Lack of infrastructure is an outstanding challenge in front of LNG fuel. Availability and affordability are not established in the industry where owners/operators can be relieved. For the shipowner, the challenges are securing a reliable source of LNG in all ports that the vessel will call. Traditional bunkering hubs where main shipping trade pass through are the key locations for LNG fuel development as large vessels lift substantial amount of bunker and generate demand. Specific vessel types and trade could be important factors. Container vessels, car carriers or cruise vessels need very large volume of fuel, and usually their port of call list is prepared in advance and they are represented as good customers. The vessels which are on tramp trade still need to see more supply security. Baltic Sea and NW Europe already have infrastructure, busy shipping routes, environmental pressure and subsidies from EU to comply with emission mitigation targets. If there is a cluster of several LNG users or potential users with sufficient LNG demand in around specific location, the investment in an LNG bunker barge will be viable as we have seen in Baltic region or NW Europe. LNG bunkering barge means that large volume of supply and along with less bunkering time.

5.8. LNG Bunkering Supply Chain Development

Challenges in LNG bunkering development were discussed and analysed through different perspectives. Outstanding concerns were defined, and how they are interlinked was highlighted. As the research objective questioned how to develop the LNG bunkering supply chain, challenges that stakeholders faced were identified, and the key factors were proposed to link different parties and bring solutions to these observations.

Collaboration is the core element for LNG marine fuel development. It is a relatively new business case that different stakeholders need to work together. Traditional LNG suppliers are not bunker suppliers. The same implies to another side of the chicken-egg paradox; traditional shipowners are not LNG marine fuel customers. As it is still observed in the industry today- the link between suppliers and shipowners is missing. Both sides are not willing to take the risk for this high CAPEX investment. A strategic approach in terms of creating clusters in certain regions could link all stakeholders and facility infrastructure development, secure a certain level of demand and competitive prices. Public interest and opinion bring green fund initiatives as well as government subsidies. A network between stakeholders should be set to create a business case and feasibility for new investments. Agreement between parties, a joint venture for bunker barge, or partnership for technology development is necessary.

Transparency is required to cope with uncertainties in pricing. One of the biggest commercial challenges for LNG marine fuel development is 'price'. The price gap between MDO and LNG is an important criterion for investment decisions. However, despite the relatively stable LNG prices, shipowners are still hesitant to take firm decisions, as the LNG bunker price is still speculative and expensive on a small scale. LNG price is listed in TTF, Henry Hub, JKM, or NBP.

These are references to LNG marine fuel. However, logistics cost has not been set, and the profit margin of the supplier is not clear. It's interlinked between suppliers and shipowners. It needs to be negotiated between supplier and receiver sides, and the market needs to see more transparency. The price of LNG fuel is not clear, and it is questionable for ship-owners that they need to do their calculations based on the final price of LNG fuel that needs transparency. Flexibility is required to persuade shipowners into business as they avoid long-term commitments and take the opportunity of the market during up and downs times. Another reason is flexibility in the trading area. It is the case not only for tramp shipping, but also for some container vessels that may change their lines according to the market conditions or manage their fleet without considering bunkering infrastructure or fuel availability.

Safety culture is critical for LNG marine fuel implementations and starts with training. Training needs were emphasised by all stakeholders. One of the crucial points is qualified crew to handle LNG. Even though shipowners make decisions to shift to LNG fuel today, there are not qualified crew to handle or institution to give proper training. Not only bunkering operations, hose connections, safety precautions, but also engine staff who need to know how to operate dual-fuelled engines are necessary to be adequately trained for this purpose. Shipowners and regulatory bodies are primarily responsible for crew training. Setting safety culture with training and on-board implementations are important to keep LNG's clear safety record and to prevent any resistance that could arise from the public.

Standardisation is still a crucial issue for LNG marine fuel development in some places. There are industrial standards and guidelines in place; however, implementations are not standardized. Technical standards of classification societies are different, and still handling by expertise is on duty's decision in many places. Each port or country sets its own rules, and even within Europe, complying with these standards is not easy. Unlike conventional bunkers, LNG marine fuel itself is not standardised with specifications in terms of quality. It makes it difficult to set prices commercially and comes up with technical problems on the engine side. Therefore, technical service providers and regulatory bodies need to work together to improve standards clearly to make LNG fuel a more reliable option. Otherwise, the industry in the course of time will set its own standards in different regions, and LNG will not be a viable option for shipowners who trade worldwide at a large scale.

The rationale behind using LNG marine fuel concerns environmental considerations, air pollution, and global warming. IMO's new regulations are coming into force to achieve global CO_2

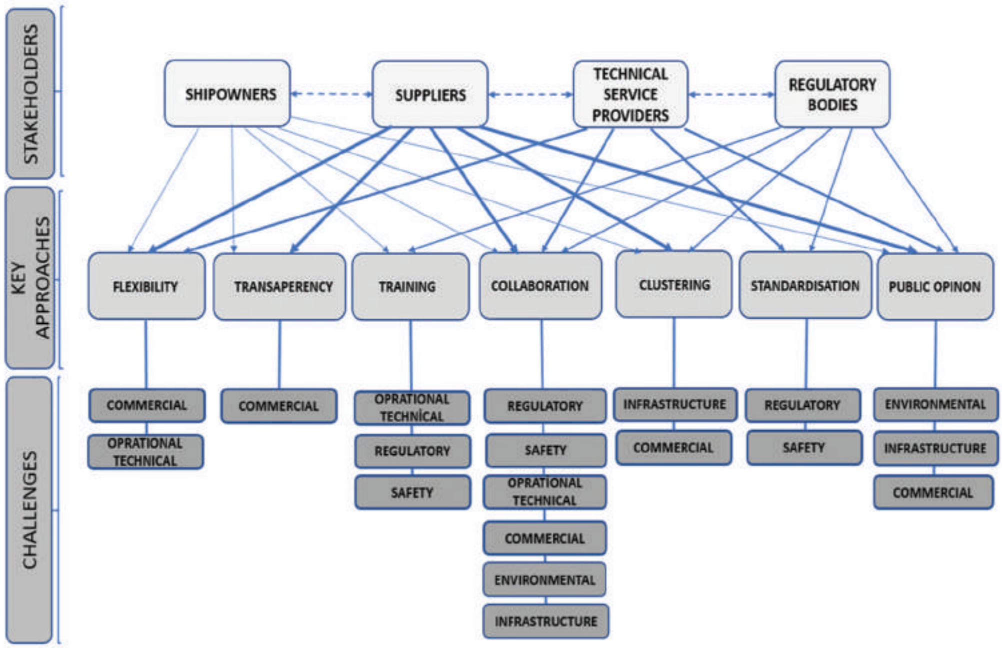

Figure 2. *Key Approaches to Overcome the Challenges and Stakeholders' Relation*

emission mitigation targets and to reduce air pollution that causes dramatic health problems. Therefore, while discussing alternative fuels or LNG marine fuel, 'public interest' needs to be in the centre rather than just 'economy'. Public opinion on green awareness is vital for environmental sustainability. Shipowners, suppliers, technical service providers, or regulatory bodies all have the responsibility to collaborate and achieve emission targets. Pollution causing health problems as well as public interest and public opinion should be a strong driver for this.

Figure 2 summarises the findings of the research. The fundamental approaches, which are critical in overcoming subject challenges, have been interlinked to related stakeholders, and it is conceptualised as a model.

6. Conclusion

The study brings together the views of different stakeholders for LNG bunkering supply chain development, which comprises determining the challenges and proposing key approaches for LNG bunkering supply chain improvement. The outcome of the research reveals the main factors affecting LNG bunkering development and provides suggestions for how different stakeholders overcome the present challenges as a business case based on expert views and the related literature. Interviewees represent different continents such as America, Europe and the Far East, which are critical to gain holistic insight for LNG bunkering, as LNG has different dynamics at different continents in terms of supply, demand and pricing. LNG bunkering operations are very limited across the world and reaching expertise knowledge, and on-site experience is an important contribution of the research. The key approaches, which are revealed after the analysis, could be practical guidance to cope with the present difficulties for suppliers, shipowners and the other industrial actors who are already in LNG bunkering business or for those willing to enter. The study could also be benefited by policymakers as it identifies the weak points in the regulatory framework and provides suggestions on how to improve them. The research is one of the few papers in this field in terms of methodology and the content. The study contributes to knowledge through semi-structured interviews which provide insight from experts and reflects different stakeholders' views in a holistic approach. It provides a base for future research in academia in this field.

IMO 2020 regulations force the industry to look for compliance strategies. LNG as a ship fuel has great advantages in terms of compliance with the new regulations and availability across the world compared to the other alternative fuels. On the other hand, there are some drawbacks that the industry needs to tackle. These are grouped under environmental, safety, operational, technical, regulatory framework and commercial considerations. LNG bunkering is relatively new for the shipping industry, but LNG as cargo has a history with very clean safety record. LNG industry applies the highest industrial standards, and it is reflected in the entire supply chain. Small/mid-scale LNG is not only an extended part of the LNG supply chain as it involves different stakeholders. Therefore, transferring this experience into small scale needs some adjustments in the operational, commercial or regulatory framework.

The research findings indicate that different stakeholders have different concerns according to their points of view: suppliers are not confident about demand, shipowners' biggest challenge is the lack of infrastructure, poor technical standardisation is a barrier for technical service providers, and regulatory bodies still need to work on improvement for worldwide implementations and take crew training as an important issue. Integrating different views in a holistic approach reveals that there are other factors affecting LNG bunkering development. Shipowners out of gas transportation are not familiar with LNG as fuel and suppliers have no experience in LNG bunker delivery. The link between two stakeholders is missing, and it leads to some other challenges as highlighted above. The collaboration of stakeholders is a must to fight against the concerns, and it comes along with transparency, flexibility, and standardisation. Public interest is a strong argument to support initiatives. Developing clusters in some regions along with public opinion in green awareness brings green funds and substantial subsidies from authorities, which is what the industry needs to cover high investment costs.

The research has some limitations to be emphasized: Total twenty Interviews were evaluated, and all of them were conducted during and after the LNG bunkering summit. LNG bunkering is a relatively new subject in bunkering; therefore, historical data is very limited, and operational experience still is to be matured. Further researches should be done in facilitating LNG bunkering at port and risk assessment. How to optimise small/mid-scale LNG supply chain at the operational, tactical and strategic level, could be another research direction in order to contribute to the shipping industry as well as mitigating air pollution and global warming.

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