Study on Application of Turbocharged Diesel Engine for the Air Lubrication System of Ship's Hull

船舶空気潤滑に供する主機過給システムに関する研究

by

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Abstract

Significant efforts are undertaken to improve the energy efficiency of shipping in response to the gradual tightening of regulations. At the same time, marine transportation of cargo grows continuously from year to year and awareness of environmental issues puts pressure on commercial vessels to become ever more efficient and environmentally friendly. Such conditions require that the efficiency of the prime mover and the propulsive efficiency of a ship be addressed simultaneously. At the same time, many innovative technologies to improve the efficiency have been already developing and have appeared in the market. The hull air lubrication method is one of such innovative energy-efficient technologies. The frictional drag of the hull is reduced significantly owing to the small air bubbles under the ship bottom. However, the air injection ensuring the sufficient air layer requires considerable pumping power. Thus, the net effect is a trade-off between the friction reduction achieved by air lubrication and the required pumping power. Meanwhile, modern propulsion engines are equipped with the high-efficiency turbochargers supplying air for fuel combustion. In most cases, the performance of the turbocharger at engine partial load is overestimated for the engines need, and thus surplus air can be used for the air lubrication system at the specific engine load. This paper analyses the way to integrate the advanced propulsion turbocharged Diesel engine with the air lubrication system (ALS) for achieving the ultimate efficiency of the propulsion plant.

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Abbreviations

ALS: air lubrication system
B_a: ship's hull breadth [m]
$C_{p.e}$: specific exhaust heat (at constant pressure) [J kg^{-1}K^{-1}]
$C_{p.a}$: specific air heat (at constant pressure) [J kg^{-1}K^{-1}]
G_{als}: air mass flow to ALS [kg s^{-1}]
G_s: air mass flow through the compressor [kg s^{-1}]
G_e: exhaust gas mass flow through the turbine [kg s^{-1}]
G_f: fuel mass flow [kg s^{-1}]
g: gravitation acceleration constants [m s^{-2}]
k_a: air gas specific heat ratio [$-$]
k_e: exhaust gas specific heat ratio [$-$]
P_a: ambient air pressure [Pa]
P_{in}: exhaust gas receiver pressure [Pa]
P_s: scavenging air receiver pressure [Pa]
R_{als}: resistance of hull due to ALS operation [N]
R_a: air gas constant [J kg^{-1}K^{-1}]
R_{exh}: exhaust gas constant [J kg^{-1}K^{-1}]
R_t: total resistance of the hull [N]
SFOC: specific fuel oil consumption $\left[\frac{\mathrm{g}}{\mathrm{kW\,h}}\right]$
TCH: turbocharged air compressor
T_a: ambient air temperature [K]
T_{in}: exhaust gas temperature (before turbine) [K]
T_{out}: exhaust gas temperature (after turbine) [K]
T_s: scavenging air receiver temperature [K]
t_a: air layer effective thickness [m]
V_s : ship speed [m s^{-1}]
W_c: work of the compressor [W]
W_T: work of the turbine [W]
η_{iC}: compressor isentropic efficiency [$-$]
η_{iT}: turbine isentropic efficiency [$-$]
η_{TCH}: overall efficiency of TCH [$-$]
ρ: density of water [kg m^{-3}]

1. Introduction

The intensifying transportation by sea of bulk cargo, goods and energy triggers profound concern of environmental issues. In response to this, in 2013 the International Maritime Organization (IMO) introduced the Energy Efficiency Design Index (EEDI) which restricts the CO2 emissions from ships and requires a final 30% reduction for a vessel built after 2025. Furthermore, in MEPC72 (April 2018), CO2 emissions per transport work target to reduce 40% by 2030 and 70% by 2050 compared with that of 2008 was settled. Besides, the initial IMO GHG strategy including a vision and target to reduce GHG at least by half by 2050 and 0 emission as soon as possible within this century was addressed as well. To meet these strict and revolutionary requirements, the engineering level of various countermeasures should be high and, hence the complexity of modern marine propulsion systems increase. The present stage of technological development provides many opportunities for improvement of the propulsion system efficiency. These include measures and devices for optimisation of the propulsion engine efficiency itself, as well as for optimisation of the propulsive effectiveness of a ship. Many solutions to improve the propulsion system have already been developed and have appeared in the market. Among others, the method of hull air lubrication is one of the innovative and promising energy-efficient technologies.

Air lubrication can significantly reduce skin friction by the small air bubbles injected into the turbulent boundary layer developed along the bottom of a ship moving in water. The effectiveness of friction reduction by the air layer has been confirmed by numerous theoretical and experimental studies, including a full-scale experiment on a real ship[1), 2), 3)]. The experimental studies also showed the frictional resistance reduction ratio C_r directly proportional to the equivalent air layer thickness t_a[4)], expressed by:

$$C_r = \frac{R}{R_t} \propto t_a, \qquad t_a = \frac{G_{als}}{B_a V_s} \tag{1}$$

The pumping power, necessary for the air injection is proportional to the air mass flow rate G_{als}. Thus, for a ship with a large breadth B_a advancing with speed V_s, the net power-saving becomes a trade-off between the power required for air injection under the hull bottom and the frictional drag reduction achieved by the air lubrication[5)]. The standalone blowers are normally selected for air injection. However, due to necessary performance for the air lubrication system (large air flow rate at relatively small compression ratio), not all types of blowers are suitable for this purpose. Fig. 1 illustrates the characteristics of two blowers, namely roots and centrifugal, suitable for the ALS. As can be seen, in the typical operating region (estimated from the characteristics of a generic bulk carrier), the efficiency of air supply is below 70%. The x-axis shows specific speed of compressor function of air flow and compression ratio and y-axis shows efficiency.

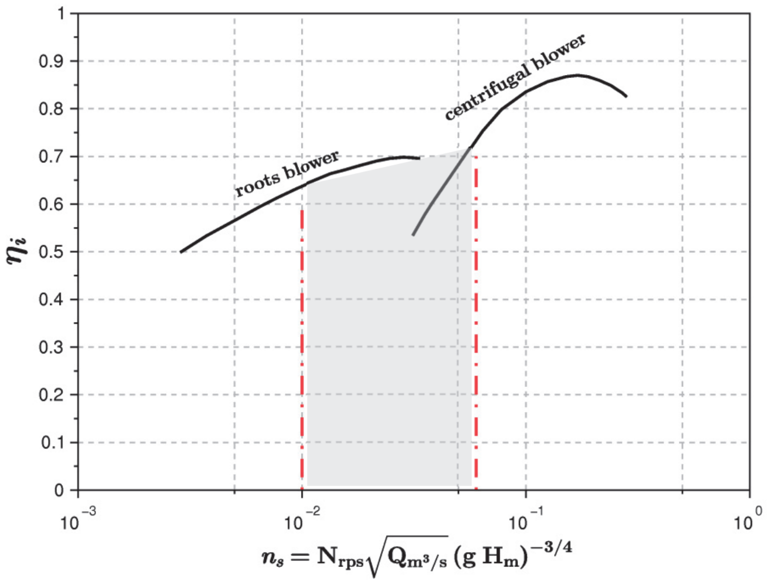


Fig. 1 Characteristics of blowers for ALS application

Meanwhile, the large ocean-going ships like bulk carriers or tankers use a high powered marine Diesel engine as a prime mover. Such an engine is equipped with a turbocharger (TCH) which utilises the energy of exhaust gas supplies pressurised air necessary for the cylinder scavenging and fuel combustion. The efforts in pursuing improved thermal efficiency of the engine and reduction of exhaust gas emissions led to the development of high-efficiency TCHs of which performance is overestimated for the engine needs at partial loads. As a result, the part of scavenging air can be bypassed, to some extent, and used for the air lubrication system increasing the overall efficiency of the ship operation at partial loads. The primary challenge of such a system relates to the fact that the air bleeding out of the scavenging system may deteriorate the combustion process of the engine; thus careful evaluation of the effect of scavenging air bleeding on engine performance is necessary especially at partial loads where the engine is normally used in service.

2. Utilization of Scavenging Air for ALS

2.1 Scavenging air bypass

When the propulsion engine operates at the steady-state condition, the power W_C required by the TCH's compressor to deliver air mass G_s to the engine is fully covered by the TCH's turbine power W_T. In turn, the air mass supplied by the compressor is used to burn the fuel mass G_f injected into the engine cylinder. The resulted exhaust gas mass G_e passing through the turbine, produce the required power. In this respect, the air mass bleeding ΔG_{bp} for the ALS (also known as scavenging air bypass) disturbs the power balance of the turbine-compressor. Therefore, it is necessary to examine the interaction of the TCH with scavenging air bypass and consider the measures avoiding the engine performance deterioration.

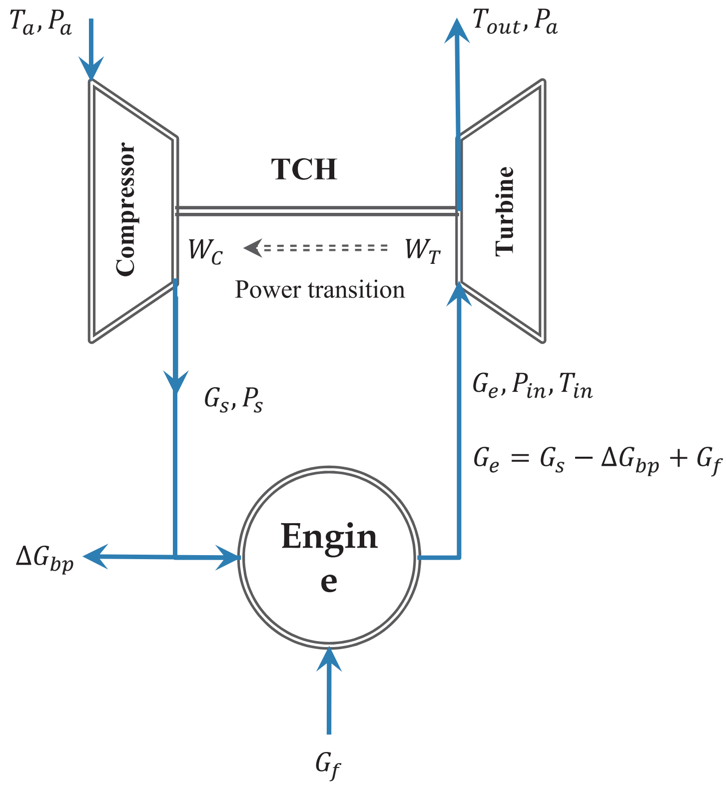


Fig. 2 Schematic of TCH-Engine interaction

2.2 Analysis interaction of TCH with scavenging air bypass

To reveal the effect of scavenging air bypass on the TCH, joint balance of the necessary turbine power and gas mass flow through compressor has to be considered. Figure 2 illustrates a schematic of the TCH-Engine interaction.

The power developed by the turbine due to isentropic work of the gas expansion can be evaluated with the following equation:

$$W_T = C_{p.e} T_{in} G_e \eta_{iT} \left[1 - \left(\frac{P_a}{P_{in}} \right)^{\frac{k_e - 1}{k_e}} \right] \tag{2}$$

The power required to compress the gas in the compressor can be calculated from the equation below:

$$W_c = \frac{C_{p.a} T_a G_s}{\eta_{ic}} \left[\left(\frac{P_s}{P_a} \right)^{\frac{k_a - 1}{k_a}} - 1 \right] \tag{3}$$

Since the transition of gas from input to output of the turbine is considered isentropic, it can be written that:

$$\frac{T_{out}}{T_{in}} = \left(\frac{P_a}{P_{in}} \right)^{\frac{k_e - 1}{k_e}} \tag{4}$$

Making use of the Eqs.2, 3 and 4, the power balance between compressor and turbine yields following expression for the overall TCH efficiency:

$$\eta_{TCH} = \frac{C_{p.a}}{C_{p.e}} \frac{T_a}{T_{in} - T_{out}} \frac{G_s}{G_s - \Delta G_{bp} + G_f} \left[\left(\frac{P_s}{P_a} \right)^{\frac{k_a - 1}{k_a}} - 1 \right] = f\left(\Delta G_{bp}, P_s\right) \tag{5}$$

Furthermore, for the sake of the analysis, the nonlinear Eq.5 was subjected to linearisation by applying a method of small increments[6]. Following this method, the nonlinear function is first decomposed into a linear combination of constituent variables by applying the logarithm, and then, the partial differentiation is performed to separate variables and constants; finally, introducing coefficients of influence and substituting relative increments for differentials, the transformation yields:

$$\delta\eta_{TCH} = K_1 \delta\left(\Delta G_{bp}\right) + K_2 \delta P_s \tag{6}$$

Where δ denotes a relative change of the corresponding variable and K_1, K_2 are the influence coefficients with the corresponding expressions:

$$K_1 = \frac{G_s}{G_s + G_f} \approx 0.96, \qquad K_2 = \frac{0.286 \left(\frac{P_s}{P_a} \right)^{0.286}}{\left(\frac{P_s}{P_a} \right)^{0.286} - 1} \approx 0.97 \ @ \ \frac{P_s}{P_a}{=}3.4 \tag{7}$$

From the Eq. 6 it is readily seen that in order to keep the power balance in view of scavenging air bypass (ΔG_{bp}), either the TCH overall efficiency should be increased ($\delta\eta_{TCH}$) or the scavenging air pressure drop (δP_s) be allowed. Concerning the first choice, advancements in the turbochargers development have enabled the performance-optimised design[7] of turbochargers showing improvement in overall efficiency by approximately 2%. Furthermore, various solutions have been introduced increasing the turbine output, in particular, the Variable Turbine Inlet (VTI)[7] which provides another 2% increase in TCH efficiency. Thus, using Eq. 6 with parameters introduced in Eq.7, the relative increase of TCH overall efficiency by 6% makes it possible to bypass approximately 6% of total scavenging air flow. If, in addition, scavenging air pressure drop is allowed, the total 10% bypass of scavenging air is possible.

The described system, namely scavenging air bypass coupled with ALS, was successfully tested on a vessel owned by NYK and named Soyo[8] confirming net fuel efficiency 4%~8% depending on loading conditions.

2.3 Effect of scavenging air bypass on engine performance, experiment

Nonetheless, scavenging air bleeding, harmless to the engine, is possible only in the narrow operational range. This is explained by the fact that the engine and TCH are matched to keep the proper ratio of injected fuel and air charge at all loads. If the performance of TCH deteriorates, the performance of the engine may also degrade due to lack of air for combustion. In order to investigate the effect of scavenging air bypass on engine performance, the series of full-scale experiments were performed on a two-stroke low-speed Diesel engine of 4S50ME-T type, installed at Mitsui Engineering and Shipbuilding Co. Ltd. (MES) Tamano works.

The test engine was equipped with a scavenging air bypass system as shown in Fig.3. The bypass system is comprised of control valves; flow, pressure and temperature sensors as well as a control system and directly connected to the engine's air manifold after charging air cooler. The test engine specification is listed in Table 1. Here it should be noted that the experiments were done on the standard engine with the standard TCH to clarify the effect of air bleeding only. The range of engine loads varied from 50% to 85%. The results of experiments are depicted in Fig. 4.

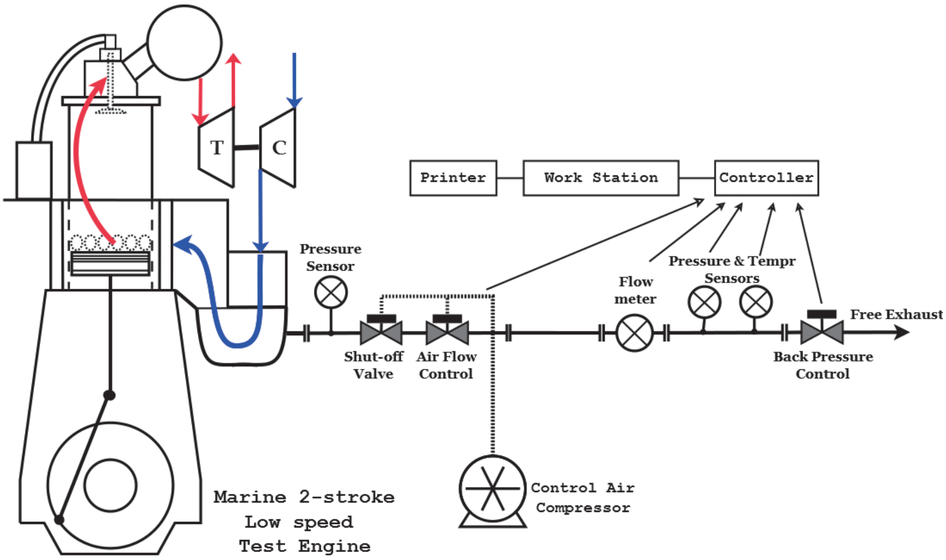


Table 1. Two-stroke low speed engine particulars

Mitsui-MAN 4S50ME-T9.2		
No of Cylinders	--	4
Bore/Stroke	mm/mm	500/2214
Power/Speed	kW/rpm	7120/117
Scavenging air pressure	barA	4.4
Scavenging air flow	Nm^3/h	40932

Fig. 3 Scavenging air bypass system test bench

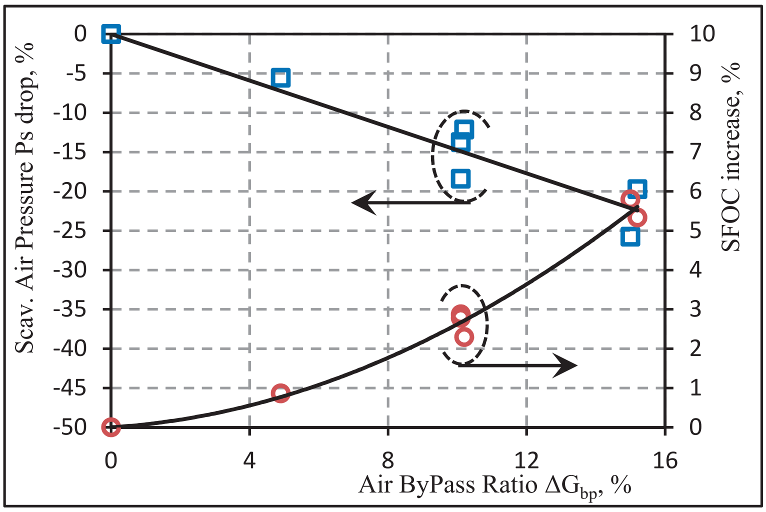


Fig. 4 Effect of scavenging air bypass on the engine performance

The primary effect of air bleeding becomes apparent in air manifold pressure drop; it also follows directly from the Eq. 6 if overall TCH efficiency assumed unchanged. Following the pressure drop, specific fuel oil consumption (SFOC) increases due to lack of air for combustion. The experiments confirmed that large air bleeding rate significantly deteriorates engine performance. This is because air bleeding can be considered like an additional load for the compressor and at the same time power input from the turbine side remains unchanged. As explained the power balance can be partially restored by a more efficient turbine or by using the VTI system, but the operating range of such systems is limited.

Moreover, operational measure, such as slow steaming, inevitably lowers engine load to reduce the ship's energy consumption, and this fact limits the utilisation of the engine as a source of air. This is because at low loads the excess exhaust gas energy reduces significantly, due to lower TCH efficiency, and is not enough to keep the desired scavenging pressure when the air is bypassed for use in ALS. In order to ensure the load-wise air supply from the engine to ALS, improving the TCH design only is not enough

3. Turbocharger Assist System for Application with ALS

3.1 System description

As mentioned above, environmental issues concern has triggered the development of various energy-saving technologies. The result of such efforts developed into an application of waste heat recovery systems to the modern TCH's. The two systems have been injected into the market: an electrically assisted turbocharger[7)] (hybrid TCH) and a turbo hydraulic system[9)] (THS). These provide power take-off of the surplus turbocharger energy. These assist systems, if use in reverse as a power take-in, would potentially extend the operation of scavenging air bypass for use in combination with the ALS. The power take-in capabilities of the TCH assist system in conjunction with the scavenging air bypass were checked experimentally on the test engine provided by MES. The TCH's compressor was equipped with an assist system of THS type also developed by MES[9)].

THS is a system of the closed hydraulic circuit, which is composed of a hydraulic pump and hydraulic motors. The fixed volume hydraulic motors assembled with a reduction gear are attached directly to the compressor's silencer. The THS was initially developed as a waste heat recovery system to convert the surplus TCH's turbine energy into the engine crankshaft power. For the purpose of the experiment, it was modified to operate in reverse direction. The hydraulic power, required to assist the compressor, is taken off from the crankshaft by the fixed volume hydraulic pump. A separate hydraulic unit controls the system and the hydraulic energy flow.

Since the system has never been considered to work in the reverse direction, a preliminary analysis would have been necessary.

3.2 Required assist power estimation

The additional air bleeding in addition to the engine need, adds loading to the compressor while the power input from the turbine stays constant. In this respect in order to restore the power balance of the TCH and thus avoid engine performance deterioration, additional energy should be added to the turbine equivalently to the air bleeding rate.

The required assist power can be estimated through the analysis of the compressor specific power described by Eq. 3 applying the method of small increments. Following the method, the transformation yields:

$$W_c = \frac{C_{p.a} T_a G_s}{\eta_{ic}} \left[\left(\frac{P_s}{P_a} \right)^{\frac{k_a - 1}{k_a}} - 1 \right], \qquad \therefore \delta(\Delta G_{bp}) \equiv \delta G_s \tag{8}$$

$$\Downarrow$$

$$\delta W_c = \delta(\Delta G_{bp}) - \delta\eta_{iC} + K_2\, \delta P_s$$

For the standard compressor, the isentropic efficiency η_{iC} changes with either airflow change or pressure ratio change, thus contributing to the assist power demand. Based on the processed data of several centrifugal compressor maps, the following relation is proposed:

$$\delta\eta_{iC} = \frac{1}{3}\delta P_s - \frac{1}{2}\delta G_s \tag{9}$$

The estimate of compressor isentropic efficiency, provided by Eq.9 agrees reasonably well with the experimental data, as detailed in Fig. 5.

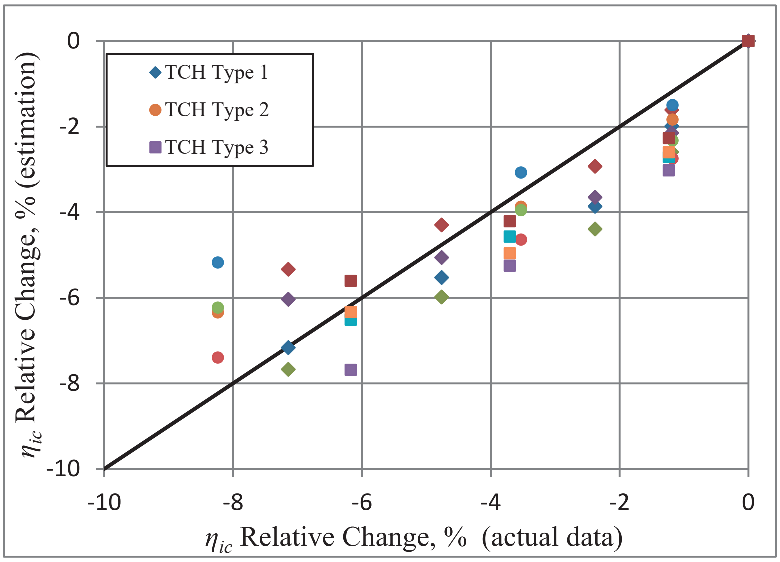


Fig. 5 Compressor efficiency relative deviation; estimated and experimental

As was found from the experiments with scavenging air bypass, it is precisely air pressure drop that explains the deterioration of the engine performance. Thus, the last term in the Eq. 8, notably scavenging air pressure deviation, can be considered as a controllable variable. From the analysis of Eq. 8 it becomes evident that depending on the way of control: astatic $\delta P_s = 0$ or droop $\delta P_s = -\kappa\, \delta(\Delta G_{bp})$, the assist power demand may differ significantly. This is because of the influence coefficient K_2, defined in Eq. 7, which is higher than 1.0 in the operating range of pressure ratios at partial engine loads.

Finally, the characteristics of assist power demand as a function of compressor flow increment for astatic and droop control of compressor pressure are illustrated in Fig. 6.

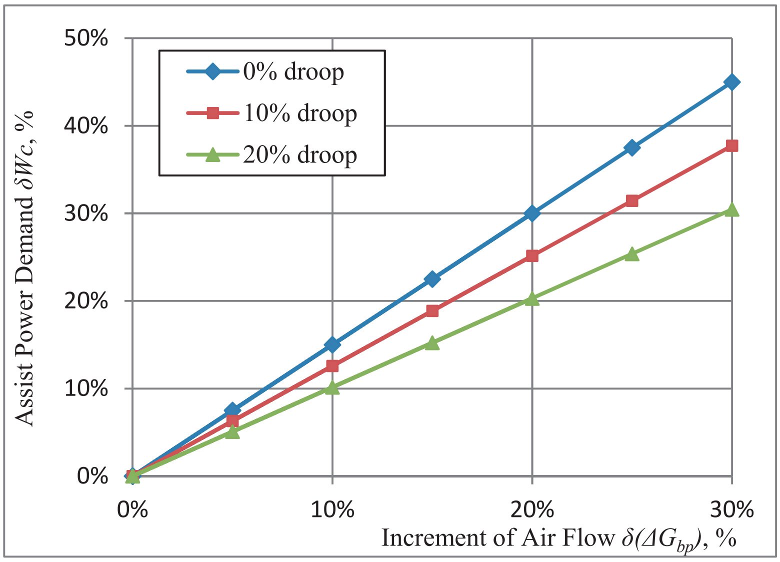


Fig. 6 Compressor assist power demand

3.3 Assist system experiment

The test engine was equipped similarly to the previous test with scavenging air bypass but supplemented with THS system as shown in Fig. 7. The test engine specification is listed in Table 1. The range of engine loads varied from 40% to 60%.

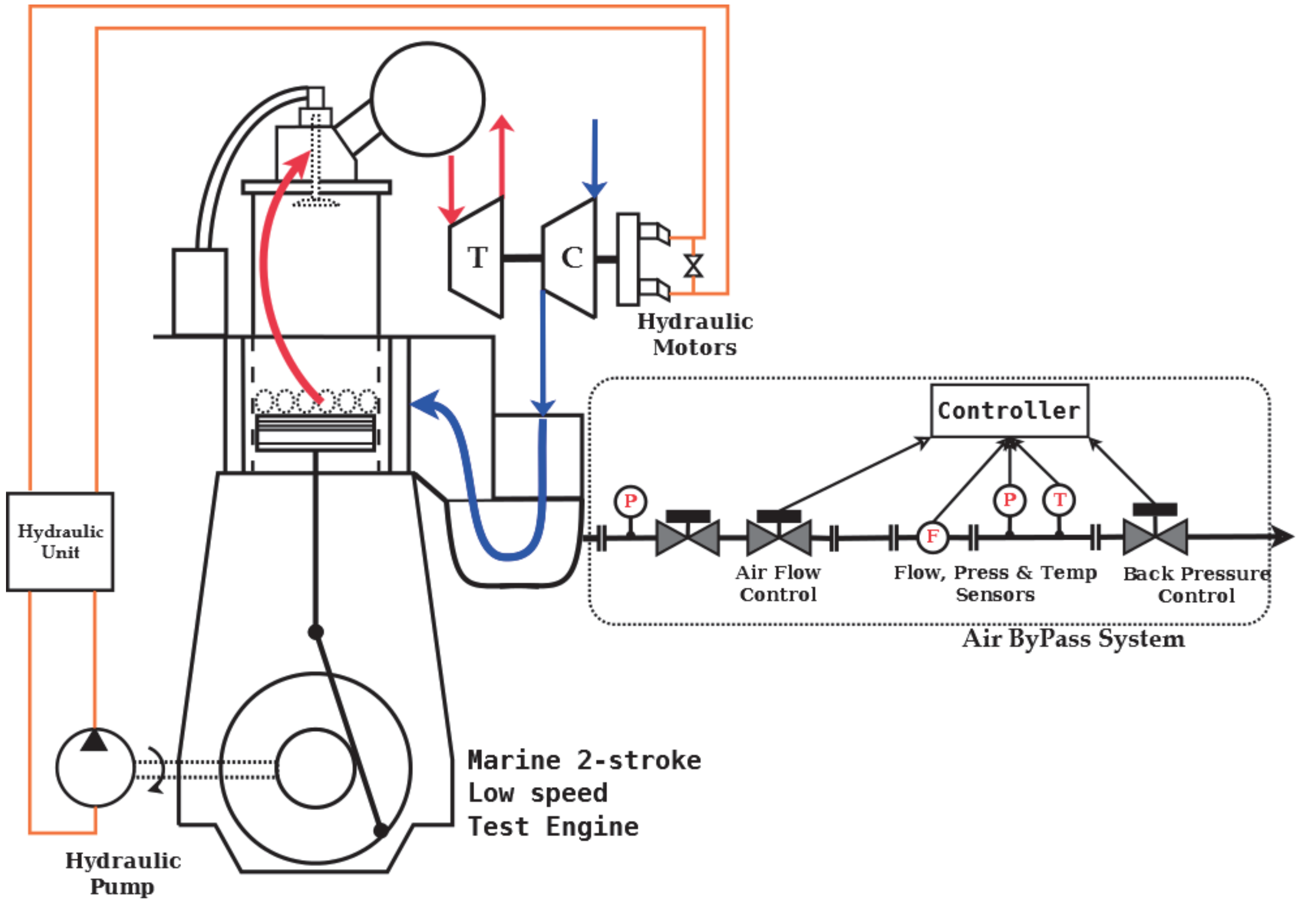


Fig. 7 Test engine equipped with the air bypass and TCH assist systems

The first result to be discussed, beyond doubts, is the assist power demand by the compressor. Figure 8 shows the relation between the air bypass ratio $\delta\left(\Delta G_{bp}\right)$ and assist power demand $\delta W_{as.} \equiv \delta W_c$ for different control strategies. As expected, the implementation of droop control significantly reduces the power demand of the compressor, and what is more, the derived analytical estimation Eqs. (8), (9) agrees fairly well with the experimental data.

The generalised engine performance, in terms of specific fuel oil consumption (SFOC), is depicted in Fig.9. Here it should be noted that since the power required for the assist system was subtracted from the engine shaft, the results of the droop control (6% droop) reflect the combined effect of power take-off by the assist system and engine performance deterioration due to scavenging air pressure drop, whereas other condition includes only the effect of power take-off. Although the assist power demand and thus power take-off was reduced, owing to the droop control, the reduced scavenging pressure affected the performance of the engine significantly, as can be seen from Fig. 9a. In pursuance of making it clear, the combined effect on SFOC was split to the constituent components: due to power take-off and due to scavenging pressure drop, assuming that both components are simply superimposed. Thus, Fig. 9b shows only the effect of scavenging air pressure drop on the engine performance (including also results with the assist system out of operation).

The last results confirmed the tendency obtained in the previous experiment with scavenging air bypass – scavenging air pressure drop significantly deteriorate engine performance, but in this experiment the negative tendency even worse. This fact can be explained by the engine tuning to achieve low NOx emission. The modern engines utilise so-called Miller cycle which results in the late exhaust valve closing. The last, in turn, implies that more than 40% of cylinder swept volume is exhausted, and a small change in the scavenging air pressure affects cylinder filling and thus on combustion significantly.

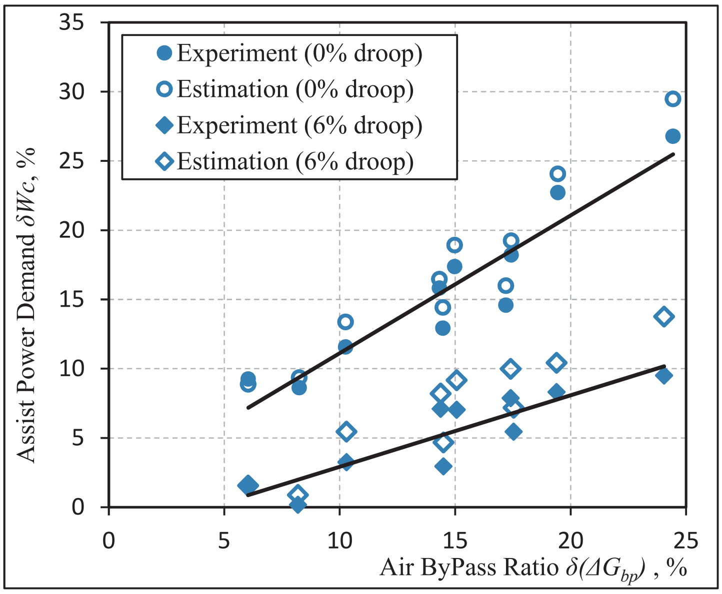
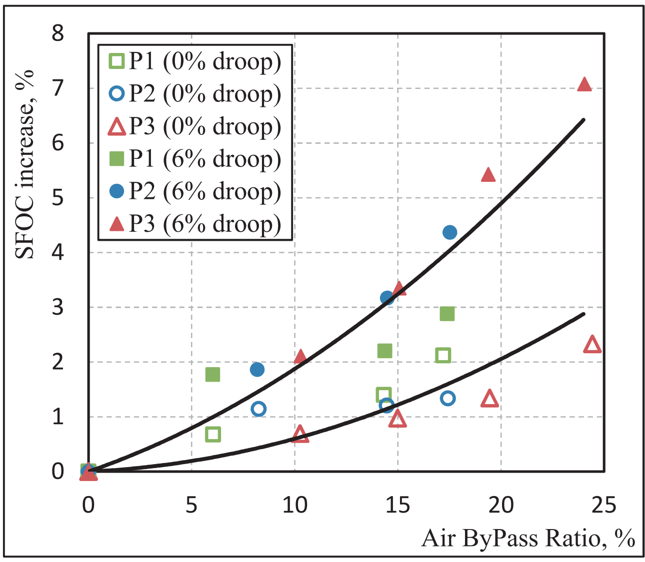
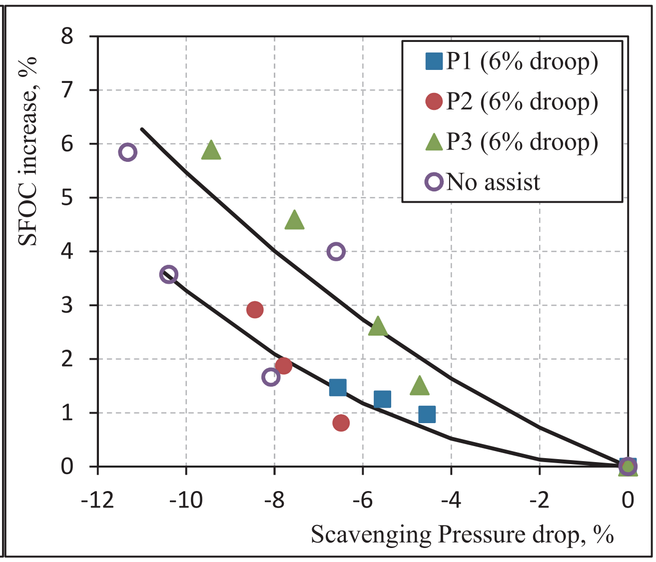


Fig. 8 Assist power demand for astatic and droop control



a) Effect of air bypass ratio on SFOC



b) Engine performance sensitivity to scav. air pressure drop

Fig. 9 Generalised results of the engine performance

4. Conclusions

With the increasing awareness of the environmental concerns of CO2 emission in shipping, the maritime industry proposes and introduces to market various systems, which improve the energy efficiency of a ship. Neither of them alone is able to assure ultimate efficiency and only the combinations of different systems can do so. Thus, the combination of ALS with the propulsion engine can be a promising candidate to improve the ship energy efficiency in wide operating range. For instance, simple modifications of the turbocharger – higher efficiency and variable geometry are able to provide, to some extent, scavenging air bypass for the ALS. Furthermore, the combination of ALS with TCH assist technologies can further improve the ship energy efficiency in wide operating range considering the operation profile of the ship: the TCH assist system can be utilised as a waste heat recovery system at high engine loads and as the assist system for ALS at the partial engine loads.

In this study, the combined operation of the ALS and TCH systems was analysed, both analytically and experimentally. At the same time, it was found that the advanced propulsion engines, operating on Miller cycle (retarded exhaust valve close timing) for superior efficiency and low emissions are susceptible to the deviation of scavenging air pressure, and the exhaust valve timing adjustment can mitigate this in view of ALS and THS systems operation. The last fact is worthwhile to study further for efficient utilisation of both systems potential through intelligent management of engine scavenging system.

Last but not least, the obtained vast experimental data and knowledge about integrated system behaviour were applied to build the simulation model of the propulsion plant[10)]. The developed system modelling framework provides understanding system behaviour through simulation and gives insight into the complex transients revealing essential interactions between the components.

References

1) Kodama Y., Kakugawa A., et al., 2000, Experimental study on microbubbles and their applicability to ships for skin friction reduction, Int. J. Heat Fluid Flow Vol.21, Issue 5, pp582-588.
2) Kato H., Kodama Y., 2003, Microbubles as a skin friction reduction device – a midterm review of the research, Proc. In Proc. The 4th Symposium on Smart Control of Turbulence.
3) Hoang C.L., Toda Y., et al., 2009, Full Scale Experiment for Frictional Resistance Reduction using Air Lubrication Method, In Proc. The 9th International Offshore and Polar Engineering Conf., Osaka.
4) Hinatsu, M., 2013, Recent Activity on the Energy Saving for Ships Using Air Lubrication Method, (in Japanese), Japanese Journal on Multiphase Flow, Vol. 27.
5) Kodama, Y., Takahashi T., et al., 2005, Practical application of microbubbles to ships – Large scale model experiments and a new full-scale experiment, Proc. of The 5th Osaka colloquium.
6) Cherkez A., 1975, Engineering design of the turbocharged engines employing a method of small increments, (in Russian), Machinostroenie, Moscow.
7) Yoshihisa O., 2013, Solutions for better engine performance at low load by Mitsubishi turbochargers, Proc. of The CIMAC Congress, Paper No. 15.
8) New Coal Carrier Prepares to Sail with an Innovative Air-Lubrication System, News released from NYK on July 30, 2012, https://www.nyk.com/english/release/1964/NE_120730.html.
9) Sakairi, N., Tanaka, I., et al., 2013, Development of Turbo Hydraulic System on Large Marine Diesel Engine, Proc. of The CIMAC Congress, Paper No. 146.
10) Bondarenko O., Fukuda T., 2018, Assessment of Propulsion System Integration via Process Modeling, Proc. of Research Report of NMRI, Issue 17, No. 4.