Combination of Propulsion Engine with Air Lubrication System for Ultimate Ship Efficiency*

Tetsugo Fukuda** Oleksiy Bondarenko**

Gradually toughening requirements on reducing ships energy consumption and gas emissions raise the importance of adoption of various energy saving systems on engine and ship. However, a correct coupling of the various systems is of great importance in achieving the ultimate ship efficiency. One of the examples of such a coupling is the application of air lubrication for the ship hull resistance reduction, air for which is bled from the scavenging system of the main engine. This system has found an application on a real ship, the range of operation is limited though. This paper proposes the way of extending operation of air lubrication system by taking advantage of power take-in capabilities of recently developed assist systems for turbochargers. As was found experimentally and confirmed analytically the increase of air bleeding rate requires a proportional increase of compressor's assist power and droop control of scavenging pressure can reduce assist power demand considerably.

1. Introduction

Globalisation is one of the driving factors of maritime transport growth, which in the last analysis contributes to global warming through increasing greenhouse emissions. In response to this, the International Maritime Organization (IMO) has introduced in 2013 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. In order to address this challenge, the marine industry has been developing various energy saving technologies, among which air lubrication system (ALS) is one of the efficient and promising technologies^{[1], [2], [3]}. Air lubrication is the effect of hull frictional resistance reduction, which is achieved by air bubbles under ship bottom and this effect is proportional to the air layer thickness^[4]. However, the net efficiency greatly depends on the way the air is injected under the ship's hull. It is clear that the supplying air by the blower is the easiest one but less efficient. Meanwhile, the efficiency of modern turbochargers (TCH) has come to be overestimated for the engine

need, and this surplus energy can be utilised, to some extent, supplying the air for ALS operation. On the other hand, often the engine is operated at partial loads in order to reduce the ship's energy consumption, and this fact limits the utilisation of engine as the source of air. This is because at partial and 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 for ALS, improving only the TCH design is not enough.

Variable geometry turbine is a well-proven technology to optimise engine operation at partial loads, and it is already was combined with the ALS^[5]. At the same time, waste heat recovery systems found an application to modern TCHs, such as a turbo hydraulic system (THS)^[6] and a hybrid TCH^[7]. 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. Inspired by this concept, the power take-in capabilities of the TCH assist system in conjunction with the scavenging air bypass were checked experimentally providing that the ALS operation range can be extended

*Received October 31, 2017

** National Maritime Research Institute, Energy and Power System Department

significantly, especially at partial loads.

2. Compressor Assist Power Estimation

When the propulsion engine operates at the steady-state condition, the power developed by the TCH turbine is fully absorbed by the TCH compressor resulting in air mass flow and pressure developed in a scavenging receiver. If part of this air is bypassed, then the pressure in the receiver inevitably drops affecting performance of the engine. The additional air bleeding from the compressor acts as power take-off, and at the same time power input from the turbine stays constant. In this respect, in order to restore power balance of the TCH and thus avoid engine performance deterioration, the additional energy should be supplied to the turbine in response to the air bleeding rate change. The required assist power can be estimated, at the preliminary stage, through the analysis of the compressor specific work applying a method of small increments^[8]. Following the 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:

$$\begin{aligned}
 W_c &= \frac{C_{pair} T_a G_c}{\eta_{iC}} \left[(\pi_c)^{\frac{\kappa_a-1}{\kappa_a}} - 1 \right] \\
 \Downarrow \\
 \frac{d[\ln(W_c)]}{dW_c} dW_c &\approx \frac{d[\ln(C_{pair})]}{dC_{pair}} dC_{pair} \dots \\
 &\quad + \frac{d[\ln(T_a)]}{dT_a} dT_a \dots \\
 &\quad + \frac{d[\ln(G_c)]}{dG_c} dG_c \dots \\
 &\quad - \frac{d[\ln(\eta_{iC})]}{d\eta_{iC}} d\eta_{iC} \dots \\
 &\quad + \frac{d\left[\ln\left((\pi_c)^{\frac{\kappa_a-1}{\kappa_a}} - 1\right)\right]}{d\pi_c} d\pi_c \\
 \Downarrow \\
 \delta W_c &= \delta G_c - \delta \eta_{iC} + K_c \delta \pi_c
 \end{aligned} \tag{1}$$

From the Eq. (1) it is readily seen that the increment of air flow requires the same increment of power, if the other parameters stay constant. However, from the theory of centrifugal compressors^[9] it is known that the isentropic efficiency drops with the increase of airflow and pressure ratio constant, thus contributing to the assist power demand:

$$\delta \eta_{iC} \propto -\delta G_c \Big|_{\delta \pi_c=0} \tag{2}$$

Thus, for the correct estimation of the required assist power, the explicit relation of the compressor isentropic efficiency with the airflow and pressure ratio increments is necessary. Based on the processed data of several two stroke engine's compressor maps, the following relation is proposed:

$$\delta \eta_{iC} = \frac{1}{3} \delta \pi_c - \frac{1}{2} \delta G_c \tag{3}$$

As can be seen from Fig. 1, the Eq. 3 gives fairly well estimate of compressor isentropic efficiency change with respect to airflow and pressure ratio change.

Fig.1. Compressor efficiency relative departure from the initial point; estimated and read from the map

The last term in the Eq. (1), notably compressor pressure ratio increment, can be considered as a controllable variable. Depending on the way of control, astatic $\delta \pi_c = 0$ or droop $\delta \pi_c = -\kappa \delta G_c$, the assist power demand can be reduced significantly. This is because of the influence coefficient K_c , in

front of pressure ratio increment $\delta\pi_c$, defined as:

$$K_c = \left(\frac{\kappa_a - 1}{\kappa_a} \pi_{c0} \right) \left(\frac{\kappa_a - 1}{\pi_{c0}} - 1 \right)^{-1} \quad (4)$$

is greater than 1.0 in the operating range of pressure ratios.

Finally, the characteristics of assist power demand as a function of compressor flow increment for astatic and droop control of compressor pressure ratio are shown in Fig. 2.

Fig.2. Compressor assist power demand

3. TCH Assist System Experiment

3.1 Experiment arrangement and conditions

As was mentioned, the excess turbine power is available at high engine loads, typically above 60%, the common practice of ship slow steaming requires engine power of less than that, however. Thus the aim of the experiment is to investigate the combined operation of ALS system and TCH assist system at engine part loads.

The experiment was performed on a two-stroke low-speed Diesel engine of 4S50ME-T type, installed at Mitsui Engineering and Shipbuilding Co. Ltd. (MES) Tamano works. Specification of the engine and test conditions are shown in Table 1. The test engine was equipped with the scavenging air by-pass system as shown in Fig. 3. The by-pass system is comprised of control valves, flow, pressure and temperature gauges as well as a control system

and directly connected to the engine's air manifold after air cooler. The TCH's compressor was equipped with an assist system of THS type developed by MES^[6], the system outline is also shown in Fig. 3.

Turbo Hydraulic System. The THS was initially developed as a waste heat recovery system to convert the surplus TCH's turbine energy into the engine crankshaft power, but for the purpose of the present experiment, it was modified to operate in reverse direction. 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 hydraulic power, required to assist the compressor, is taken off from the crankshaft by the fixed volume hydraulic pump. A separate hydraulic unit controls system and hydraulic energy flow.

Measurements. At each measuring point, the engine speed and water brake torque were fixed. At first, the reference engine performance was measured. Next, the performance was measured at different air by-pass ratios with the activated assist system realising astatic and droop control of scavenging pressure (with air by-pass ratio one should understand the ratio of air bleeding flow to the engine air flow at the reference point, expressed in percent). The assist power was estimated based on datasheets of hydraulic motors and efficiency of the reduction gear. The take-off power was estimated as the difference between reference indicated power and other indicated power considering that the mechanical losses are constant. The indicated power was obtained processing the measured in-cylinder pressure. Indeed, the information value of the take-off power itself is negligible, since it varies significantly with the transmission efficiency and is used only to estimate engine performance deterioration affected by the scavenging pressure change.

3.2 Experiment results and analysis

During the experiment, a massive volume of data was collected and for the sake of compactness, only the relevant results are reported. The first result to be discussed, beyond doubts, is the assist power demand by the compressor. The Fig.4 shows the

relation between air bypass ratio and assist power demand 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, Eq. (1) agrees fairly well with the experimental data. In spite of good results achieved with pressure droop control the effect on engine performance is not so bright. The generalised engine performance, in terms of specific fuel oil consumption (SFOC), is depicted in Fig.5b. Figure 5a shows the 6% droop control characteristic of scavenging air pressure. Here it should be noted that the engine performance measured with the astatic control (0% droop) reflects only power take-off by the assist

system, whereas other condition includes the combined effect of power take-off and scavenging pressure drop. 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 the Fig.5b. 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, the Fig. 6 shows the only effect of scavenging pressure drop on engine performance deterioration.

Fig.3. Test engine equipped with the air by-pass and TCH assist systems

Table 1. Mitsui-MAN 4S50ME-T9 Specification test Engine Specification and Experiment Conditions

No of Cylinders	--	4
Bore/Stroke	mm/mm	500/2214
Power	kW	7120
Speed	rpm	117
Scavenging air pressure	barA	4.4
Scavenging air flow	Nm³/h	41000

Experiment Points	--	P1	P2	P3
Power	kW (%)	4272 (60)	3560 (50)	2848 (40)
Speed	rpm (%)	99 (84.5)	93 (79.5)	86 (73.5)
Air by-pass ratio, max	%	17	17	24
Pressure droop	%	0%, 6%	0%, 6%	0%, 6%

Fig. 4. Assist power demand for astatic and droop control

b) Relative SFOC change

Fig. 5. Generalised results of engine performance during TCH assist experiment

a) Scavenging air pressure

Fig. 5. Generalised results of engine performance during TCH assist experiment

Fig. 6. Engine performance sensitivity to scavenging pressure drop

In order to confirm the tendency and avoid any uncertainties in SFOC components separation, the addition tests were performed at the same test points but without assist system. The results are also depicted in Fig. 6 by blank keys. The obtained

results confirmed high sensitivity of engine to the deviation of scavenging air pressure. The engine tuning for low NOx emission explains the fact of the great engine performance degradation. The late exhaust valve close timing implies that more than 40% of cylinder swept volume is exhausted, and a small change in air pressure affects cylinder filling and consequently the air-to-fuel ratio significantly.

4. Conclusion

With the increasing awareness of the environmental concerns of CO2 emission in shipping, the maritime industry proposes various systems, which improve the energy efficiency of a ship. However, nor one system can assure ultimate efficiency and only the combinations of different systems can do. Thus the combination of ALS with TCH assist technologies can improve the ship energy efficiency in wide operating range. For instance, the THS can be utilised as a waste heat recovery system at high engine loads and as the assist system for ALS at partial engine loads.

In this study, it was confirmed the combined operation of ALS system and TCH assist system for partial and low engine loads experimentally. The proposed analytical expression for assist power estimation showed good agreement with the experimental measurements, as well as the method reducing assist power demand was proposed and validated. At the same time, it was found that the modern propulsion engines, operating on Miller cycle (retarded exhaust valve close timing) for superior efficiency and low emissions are very sensitive to the deviation of scavenging air pressure and this can be mitigated by the exhaust valve timing adjustment 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.

References

[1] Y. Kodama, A. Kakugawa, et al., "Experimental study on microbubbles and their applicability to ships for skin friction reduction", Int. J. Heat Fluid Flow 21:582-588

- [2] H. Kato, Y. Kodama, "Microbubbles as a skin friction reduction device – a midterm review of the research", Proc. the 4th Symposium on Smart Control of Turbulence, (2003)
- [3] Y. Kodama, T. Takahashi, et al., "Practical application of microbubbles to ships – Large scale model experiments and a new full scale experiment", Proc. of the 5th Osaka colloquium, (2005)
- [4] M. Hinatsu, "Recent Activity on the Energy Saving for Ships Using Air Lubrication Method", (in Japanese), Japanese J. Multiphase Flow Vol. 27, (2013)
- [5] T. Fukuda, "Air lubrication method of hull using scavenging air of large marine engine", (in Japanese), J. of the JIME, Vol. 50(2), pp.89-92, (2015)
- [6] N. Sakairi, I. Tanaka, et al., "Development of Turbo Hydraulic System on Large Marine Diesel Engine", Proc. of the CIMAC Congress, Paper No.: 146, (2013)
- [7] Y. Ono, "Solutions for better engine performance at low load by Mitsubishi turbochargers", Proc. of the CIMAC Congress, Paper No.: 15, (2013)
- [8] A. Cherkez, "Engineering design of the turbocharged engines employing method of small increments", (in Russian), Machinostroenie, Moscow, (1975)
- [9] L.I. Slobodyanyuk, V.I. Polyakov, "Ship's steam and gas turbines operation", (in Russian), Shipbuilding, Leningrad, (1983)

Nomenclature

C_{pair}	: Specific heat of air [J/(kg K)]
G_c	: Air mass flow [kg/sec]
T_a	: Ambient air temperature [K]
W_c	: Compressor power [w]
$\delta \equiv \frac{\Delta \chi}{\chi_0}$	: Relative increment [--]
γ_a	: Specific heats ratio [--]
κ	: Droop coefficient [--]
π_c	: Compressor pressure ratio [--]
η_{pC}	: Isentropic efficiency [--]

subscript

O	: value of variable at reference condition.
-----	---