WASTE HEAT RECOVERY (WHR): FUEL SAVINGS WITH LESS EMISSIONS

Pressure is on the shipping industry to gain further reductions in air pollution from the exhaust gases of marine diesel engines. Thus discussion and development is on either further controlling the generation of the emissions inside engine cylinders, removing the emissions by aftertreatment of the exhaust gases, or in the case of SO_x emissions restricting the fuel specification. However, more fundamental ideas about ship design and operation will be necessary to meet the growing need for significantly less carbon dioxide (CO_2) emissions as part of the fight against global warming.

There is very little margin left in the large marine diesel engine for reducing CO_2 emissions through improving engine thermal efficiency. After the 1973 Oil Crisis, considerable investment was put into reducing engine fuel consumption and for some years the largest-bore engines have had an overall thermal efficiency of around 50%, depending on engine size.

There is also the natural trade-off between engine fuel consumption and NO_x emissions with any reductions in specific fuel consumption involving a natural increase in NO_x emissions.

Yet there is one solution that can help: waste heat recovery is the only technology commercially available today that provides both lower fuel consumption and lower exhaust-gas emissions, including lower CO_2 emissions, without a reduction in ship service speeds. In the new concept developed by Wärtsilä the quantity of energy available for recovery is increased by drawing engine intake air from outside the engine room (ambient air) instead of from within the engine room.

LEADING WHR CONCEPT

A new concept for high-efficiency waste heat recovery combined with Wärtsilä RT-flex common-rail low-speed engines is leading the way in the magnitude of both fuel economy and lower exhaust emissions achieved.

This leaflet focuses on WHR plants for higher-output engines such as the Wärtsilä RT-flex96C engines for which the energy recovered is sufficient to make assisting propulsion financially worthwhile with reasonable payback periods, as well as providing for all shipboard electricity requirements.

In such cases, the new high-efficiency WHR plant can recover up to about 12% of the engine shaft power using both Rankine cycle and turbocompound principles. Exhaust energy is applied in both a steam turbine and an exhaust-gas power turbine to generate electrical power. The electrical power can be employed either in a shaft motor to aid propulsion or in supplying shipboard services.

When the WHR plant can meet all shipboard electrical requirements while the ship is at sea, it will usually be possible to fit one less auxiliary diesel generating set thereby saving on installation costs as well as auxiliary engine running costs. ■ ■ ■

■ ■ RT-flex engines has the additional benefit of helping to keep the economiser cleaner with less soot deposition.

CASE STUDY

The economic benefits of the high-efficiency WHR system can be illustrated by the case of a container ship powered by a 12-cylinder Wärtsilä RT-flex96C engine. In the case, the engine would operate at an average of 85% load for about 6500 hours a year on bunkers costing US$ 250/tonne, with an average total electrical load of 5350kW, including reefer containers. The annual operating costs for the main and auxiliary engines, including fuel, maintenance and lubricating oil, would be US$ 19.54 million without a WHR plant and US$ 17.29 million with a high-efficiency WHR plant.

There would thus be annual savings of US$ 2.25 million. If the bunker price increased from US$ 250 to US$ 400/tonne, then the annual savings would increase to about US$ 3.48 million.

The complete high-efficiency WHR plant and its installation would call for an investment cost of about US$ 9.5 million. This would thus have an expected payback time of less than five years.

HIGH-EFFICIENCY WHR: CASE STUDY

Basis ship:	
Main engine:	Wärtsilä 12RT-flex96C
CMCR power, kW:	80,080
Annual operating hours:	6500
Average engine load, %:	85
Total electrical load, kW:	5350
Auxiliary engines, kWe:	4 x 3000
Bunker fuel price, US$/tonne:	250
Cylinder lubricating oil price, US$/tonne:	1500

Annual engine operating costs	basis ship	with WHR
Fuel costs, US$:	18,449,000	16,359,000
Maintenance costs, US$:	486,000	333,000
Lubricating oil costs, US$:	602,000	559,000
Total, US$:	19,537,000	17,287,000
Annual savings, US$ at US$ 250/tonne fuel:	—	2,250,000
at US$ 400/tonne fuel:	—	3,482,000
Investment cost, US$	—	9,500,000

PAYBACK TIME LESS THAN 5 YEARS

HIGH-EFFICIENCY WHR IN SERVICE

The first installation of this new high-efficiency WHR plant entered service in the 7500 TEU container ship Gudrun Mærsk of the A.P. Moller-Maersk Group in June 2005. It successfully confirmed the benefits of the new WHR plant concept. During sea trials and in operation, the performance of the WHR plant exceeded expectations.

Similar WHR plants are also now in normal operation in the complete class of six 7500 TEU sister ships. The WHR plant for these vessels was developed in a joint effort headed and integrated by Odense Steel Shipyard Ltd in cooperation with Wärtsilä, Siemens AG, Peter Brotherhood Ltd and Aalborg Industries Ltd.

The ships are each propelled by a Wärtsilä 12RT-flex96C low-speed common-rail engine with a maximum continuous power output of 68,640 kW at 102 rpm. Exhaust gases pass through an dual-pressure exhaust-gas economiser from Aalborg Industries to generate superheated steam which is utilised in a 6 MWe turbogenerator set from Peter Brotherhood. The turbogenerator sets incorporate both a multi-stage dual-pressure steam turbine and an exhaust-gas power turbine. The generated electricity is supplied to the ship's main switchboard and employed both in a Siemens shaft motor/generator to assist in ship propulsion, and in shipboard services. A portion of the steam from the exhaust economiser is utilised in shipboard heating services.

The calculated output of the turbogenerator set is based upon ISO standard reference conditions which include an ambient temperature of 25°C. During the sea trials of the first ship, this performance was exceeded as such output was already achieved at the ambient temperature of 14°C.

The vessels are also each equipped with three eight-cylinder Wärtsilä 32 diesel generating sets having a combined electrical output of 11.2 MWe. The high-efficiency WHR plant enables each ship to be fitted with one fewer diesel generating sets than it would otherwise have.

The high-efficiency WHR concept has been taken a step further in the new 11,000 TEU container ships of the A.P. Moller-Maersk Group. The first of this class, the Emma Mærsk, was delivered in September 2006 from Odense Steel Shipyard. She has since been joined by a number of sister ships.

The ships are each powered by a 14-cylinder Wärtsilä RT-flex96C common-rail engine. These are the world's first 14-cylinder in-line engines and also the world's most powerful electronically-controlled engines –with an MCR power of 80,080 kW each at 102 rpm. This propulsion power is augmented by two shaft motors in each vessel.

The main engines are each associated with a high-efficiency WHR plant incorporating a turbogenerator set having a nominal output of 8.5 MWe. This operates in conjunction with each ship's five diesel generating sets that have a combined output of 20.7 MWe.

SOLELY FOR SHIP'S SERVICE ELECTRICITY

A simplified version of the high-efficiency WHR system described above is offered for ships that require the recovered energy to be only sufficient to cover all shipboard electricity demand while the ship is at sea.

This avoids the running of auxiliary engines while at sea with the corresponding savings in fuel, maintenance and spare parts costs, as well as reductions in exhaust gas emissions. ■ ■ ■

■ ■ ■ Such cases may apply for engines such as the Wärtsilä RT-flex82C, RT-flex82T and RT-flex84T-D types.

The waste heat recovery plant is similar to the higher-output described above but energy is usually only recovered from an exhaust-gas economiser to generate steam for a turbine-driven generator. If necessary, heat is also recovered from the engine's scavenge air and jacket cooling water for feedwater heating. The economiser also operates at a single steam pressure. However the quantity of energy recovered from the exhaust gases is increased by adapting the engine to the lower air intake temperatures that are available by drawing intake air from outside the ship (ambient air) instead of from the ship's engine room. The engine turbochargers are matched for the lower air intake temperatures thereby increasing the exhaust energy.

As today's high-efficiency turbochargers have surplus capacity at the engine's upper load range when matched for ambient air intake, less exhaust gas flow is necessary for the turbochargers. Thus about 8–9% of the engine's exhaust gas flow can bypass the turbochargers to give a further increase in recoverable exhaust gas energy.

The overall result of this concept is that the quantity of energy recoverable in an exhaust-gas economiser is increased without affecting the air flow through the engine. There is thus no increase in the thermal loading of the engine and there is no adverse effect on engine reliability.

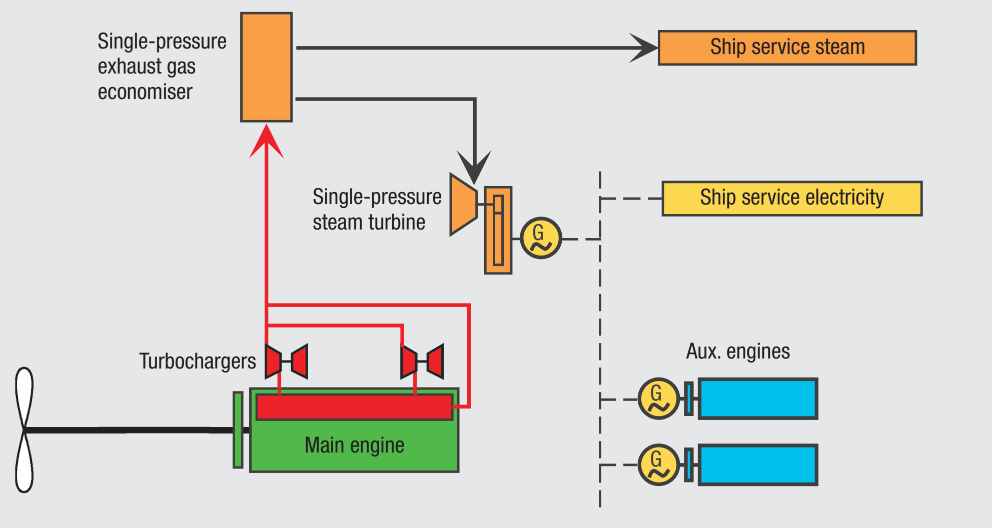
For example, a high-efficiency WHR plant associated with a 29,400 kW seven-cylinder Wärtsilä RT-flex84T-D engine in a VLCC (very large crude oil carrier) could deliver 1645 kWe at engine full load under ISO conditions with 9% exhaust gas bypass using a single-pressure steam system. As such a vessel would need only 1000–1100 kWe for ship services while at sea, the tanker could operate without running its auxiliary engines while at sea under a wide range of ship speeds. It would save more than 1400 tonnes of fuel a year, with corresponding savings in all types of air emissions, especially CO_2.

CONCLUSION

The high-efficiency waste heat recovery plant concept is attracting much attention from shipowners interested in saving fuel costs and reducing CO_2 emissions. It must be remembered that modern large, low-speed engines are very highly developed and there is little potential for achieving significant savings in fuel consumption, and thereby reducing CO_2 emissions by engine developments alone. Yet major improvements can be gained by using proven technology and hardware through applying the high-efficiency WHR plant. It is thus a practical path forward.

The combination of a Wärtsilä RT-flex engine with high-efficiency WHR plant is a major contribution to reducing the environmental impact of shipping.

The turbogenerator set of the Gudrun Mærsk-class container ships. (Photo: Peter Brotherhood Ltd)



Schematic of a simplified high-efficiency WHR plant as might be employed with a Wärtsilä 7RT-flex84T-D engine for a large tanker with the turbogenerator supplying all ship's service electricity while the ship is at sea.

New concept for high-efficiency waste heat recovery (WHR) associated with Wärtsilä RT-flex common-rail low-speed marine engines allows up to 12% of main engine shaft power to be recovered as electrical power for use as additional ship propulsion power and for shipboard services. A number of such high-efficiency WHR installations have entered service since the first in June 2005.

HIGH-EFFICIENCY WHR BENEFITS

Benefits to shipowners of WHR system are thus fourfold:

- Lower annual fuel costs
- Lower running costs for auxiliary engines
- Lower exhaust emissions: CO_2, NO_x, SO_x, etc.
- Improved competitiveness in the freight market.

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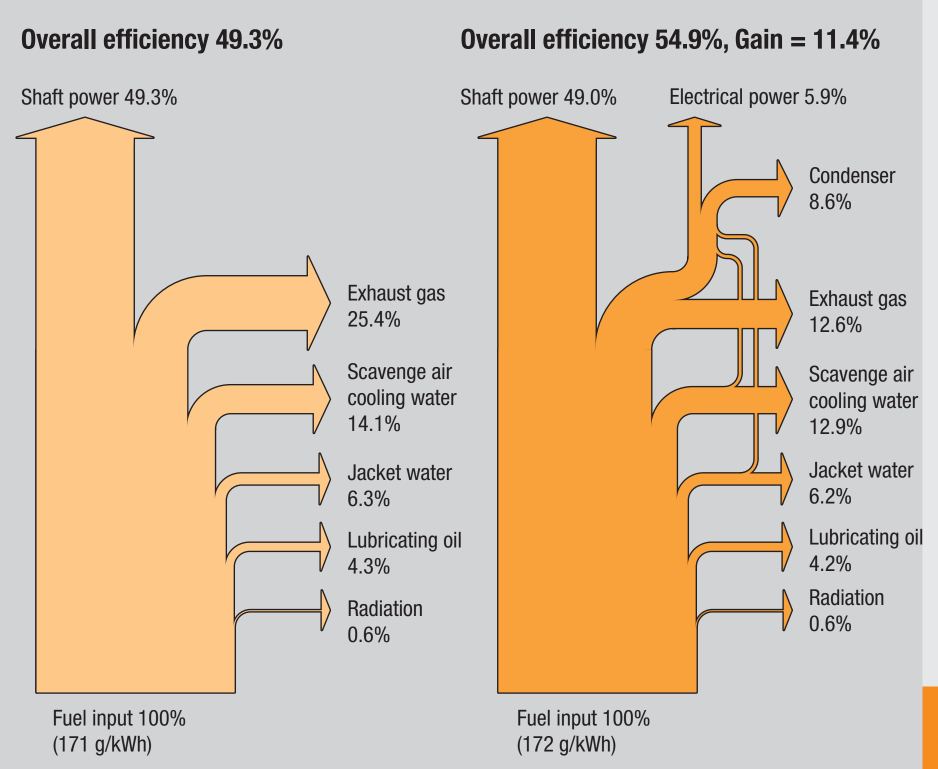
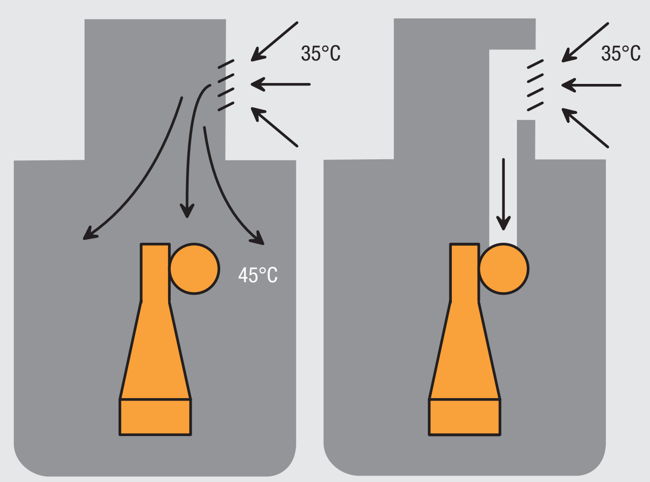
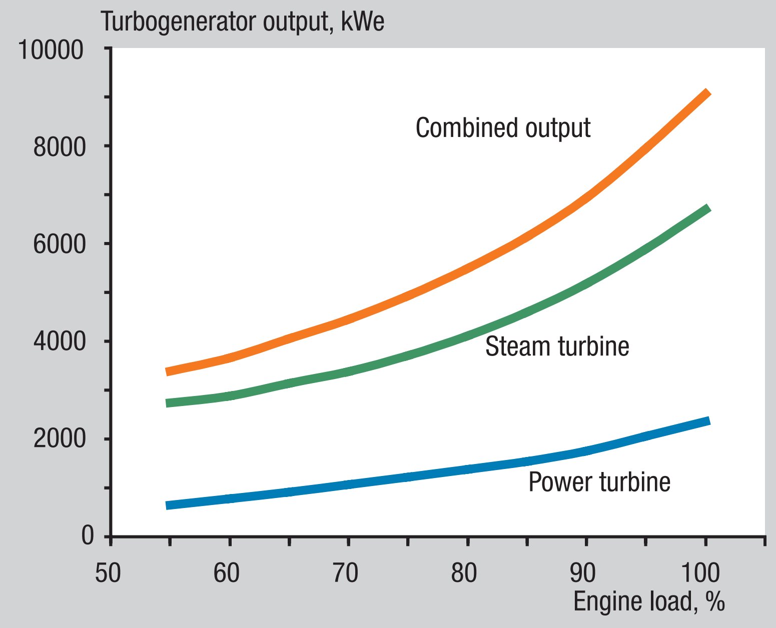


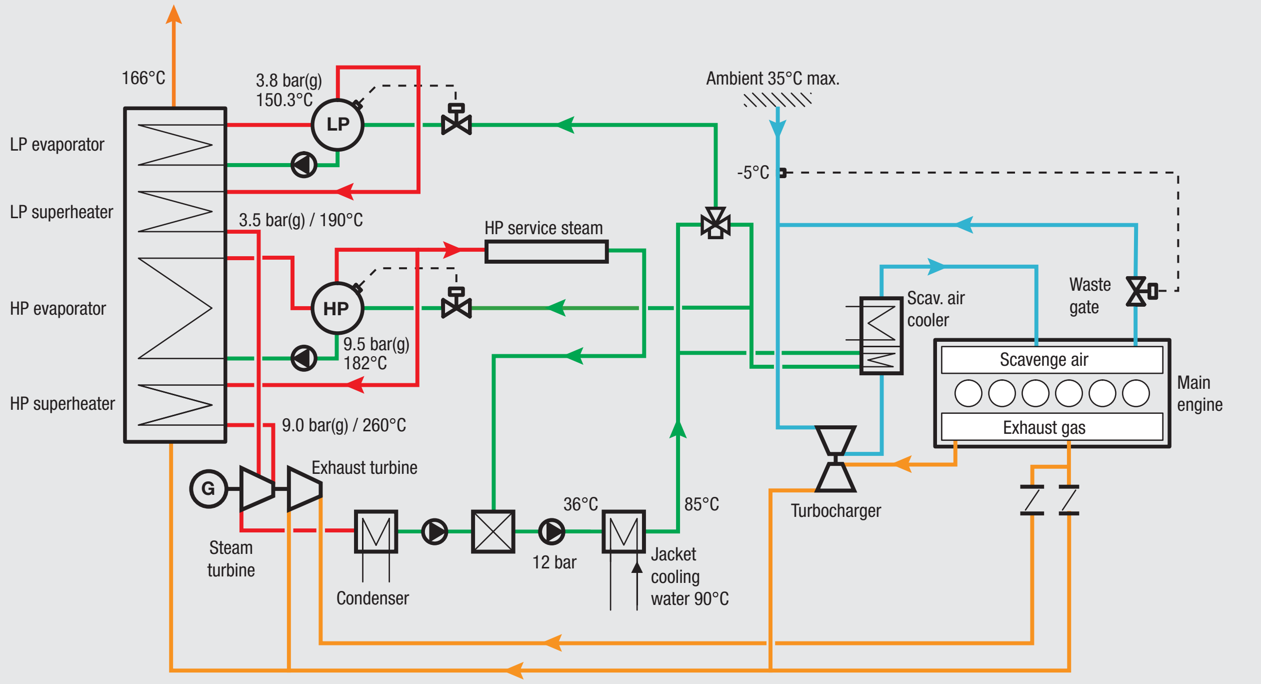
Even with the high, 50% efficiency of modern low-speed engines there is still 50% of fuel input energy not being put to productive use. The possibilities are illustrated by these comparison of Sankey diagrams for Wärtsilä 12RT-flex96C engines without heat recovery (left) and with the high-efficiency waste heat recovery plant (right) showing in this case an 11.4% gain in overall efficiency with WHR.



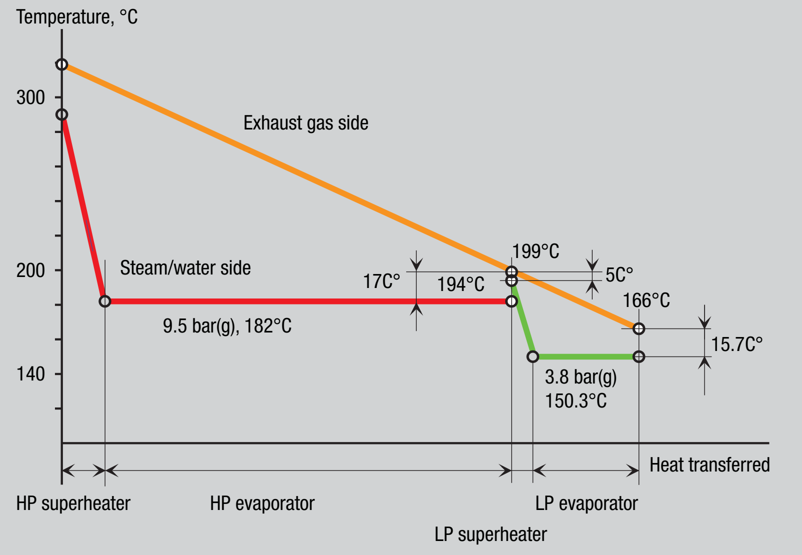
Left: Engine room air suction. Right: Ambient air suction from outside the ship's engine room.



Energy recovered (kWe) by the turbogenerator set in a high-efficiency WHR plant on a 12RT-flex96C engine with Delta Tuning (for improved part-load fuel savings) and ambient suction.



Process diagram for the high-efficiency waste heat recovery plant.



Typical economiser diagram for the high-efficiency waste heat recovery plant.

In any case, the resulting payback time would depend upon the installation design and bunker fuel prices but should in general be about five years which is commercially attractive. Increasing fuel prices make such plants more attractive. A WHR plant thus leads to considerable financial benefits over a ship's life.

The new concept developed by Wärtsilä follows the well-established arrangement of passing the exhaust gases of the ship's main engine through an exhaust-gas economiser to generate steam for a turbine-driven generator. However, the quantity of energy recovered from the exhaust gases is maximised by adapting the engine to the lower air intake temperatures that are available by drawing intake air from outside the ship (ambient air) instead of from the ship's engine room.

Usually marine engines are designed for intake temperatures of up to 45°C for tropical conditions with turbochargers drawing intake air from the engine room. If instead the intake air is drawn from outside the engine room through an air intake duct, the maximum intake temperature can be assumed to be no more than 35°C.

In such a case, the lower air intake temperature allows the turbochargers to be rematched to return the thermal load of the engine back down to what prevails for the intake temperature at 45°C. When considering gas temperature, it is important that the thermal load of the adapted engine is no greater than that of the usual engine so as not to jeopardise engine reliability.

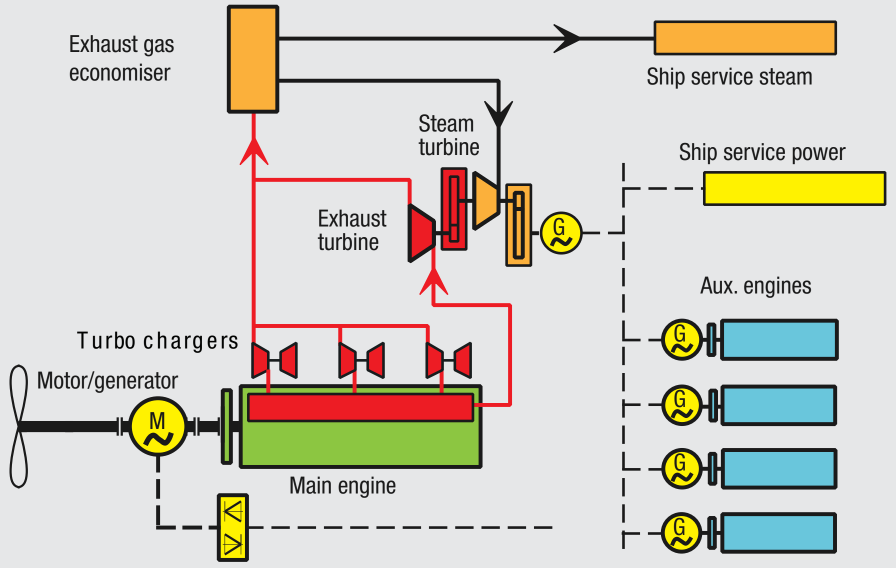
Even with a certain quantity of exhaust gas branched off for the power turbine and therefore not then available for the turbocharger, the thermal loading of the engine remains the same as for the conventional engine. This is possible because the special turbocharger matching in combination with the exhaust power turbine allows full utilisation of the available efficiency of the turbocharger, and also because of the ambient suction tuning.

This adapted tuning, however, incurs a penalty in a slightly increased fuel consumption at ISO reference conditions. But the gain in recovered energy more then compensates for the loss in efficiency from the higher fuel consumption. The engine needs to be equipped with an air waste gate to ensure that the maximum cylinder pressure stays within permissible limits at very low ambient temperature.

Modern, high-efficiency turbochargers also have a small surplus in efficiency capability in the upper load range. This allows a certain exhaust gas flow to be branched off before the turbocharger to drive a gas turbine, or as it is called in this application an exhaust power turbine. With normal engine tuning it is not worth taking advantage of this possibility. However, the rematched turbochargers for ambient suction allow even more exhaust gas to be branched off under ISO conditions compared with the conventional tuning with maximum 45°C suction air temperature. Therefore, the rematched engine supercharging system gives an increased exhaust gas energy and allows a good amount of exhaust gas to be branched off before the turbocharger thereby allowing a worthwhile heat recovery potential to be achieved.

Heat is also recovered from the engine's scavenge air and jacket cooling water for feedwater heating. The scavenge air coolers are designed in such a way that the boiler feed water can be heated close to the evaporation temperature.

The overall result of the new concept is that the quantity of energy recoverable in an exhaust-gas economiser and in the exhaust power turbine is increased without affecting the air flow through the engine. There is thus no increase in the thermal loading of the engine and there is no adverse effect on engine reliability.



Schematic of a high-efficiency waste heat recovery plant typical for large container ships with the turbogenerator supplying both assisted propulsion and ship's service power. The shaft motor can also serve as a shaft generator for added flexibility in operation.

The change in engine suction also has the benefit of reducing the electrical power required for engine-room ventilation with consequent fuel cost savings. In the case of a container ship with a 12RT-flex96C engine, the total power for ventilation fans may be cut from 400 to 200 kW.

WHR PLANT CONFIGURATION

The high-efficiency WHR plant consists of a dual-pressure economiser, a multiple-stage dual-pressure steam turbine, an exhaust power turbine, an alternator driven by both the steam turbine and the power turbine, a feed water pre-heating system and a shaft motor/ alternator system.

In the rematched system, about 10% of the engine's exhaust gas flow can be employed to drive an exhaust power turbine which is incorporated in the turbogenerator set.

ECONOMISER

The exhaust gas economiser consists of a high-pressure part with HP evaporator and superheating section and a low-pressure part with LP evaporator and superheating section. The pressure in the high-pressure steam drum is at about 9.5 bar(g) pressure, and about 3.8 bar(g) in the low-pressure steam drum. The economiser outlet temperature is not less then 160°C to avoid sulphur corrosion in the economiser outlet. Saturated steam is drawn from the HP steam drum for ship service heating.

In a first stage, the feed water is heated from the engine's jacket cooling water to a temperature of 85°C. Only the feed water for the high-pressure section is further heated in the engine's scavenge air cooler to about 150°C to 170°C. The scavenge air cooler is designed such that the feed water heating section can run dry with the total scavenge heat dissipated in the scavenge air cooler.

STEAM TURBINE

A dual-pressure steam turbine running at about 6750 rev/min is used. The high-pressure side works at about 8.0–9.0 bar(g) inlet pressure. This requires three turbine stages at a condenser pressure of 0.065 bar. With an economiser outlet temperature of 160°C, a low-pressure steam pressure at the turbine inlet of 3.0–3.5 bar(g) pressure is considered. This requires six turbine stages at a condenser pressure of 0.065 bar. A speed-reduction gear between steam turbine and generator reduces the turbine speed to 1800 rev/min generator speed.

EXHAUST POWER TURBINE

The power turbine uses a part of the exhaust gas stream (about 10%) from the diesel engine to generate shaft power which can be added to the steam turbine driving the generator. The turbine is a derivative of a well-proven model of turbocharger turbine with minor adaptions for use as a power turbine. A special matching of the power turbine is necessary for the application in a waste heat recovery system because the turbine operates on a constant-speed operating profile as it is coupled to the generator unlike in a turbocharger with a free-running rotor. The torque of the power turbine is fed to the steam turbine rotor through a reduction gear and an overrunning clutch.

The power turbine operates between 55% and 100% engine load. The flow of exhaust gas from the exhaust gas manifold is controlled by an orifice at the outlet of the exhaust gas manifold. At less than 55% engine load, the gas flow to the power turbine is shut off as the efficiency of the turbochargers at less than 55% load is not sufficiently high and therefore does not allow exhaust gas to be branched off to drive a power turbine. As the power turbine has about the same expansion ratio and efficiency as the turbochargers of the engine, the outlet temperature of the exhaust gas is about the same as from the turbochargers.

WASTE GATE

The engine is tuned to operate within the intake temperature range of –5°C to 35°C. The engine maximum pressure stays within the permissible range when the engine operates within this intake suction temperature range. If the ship shall be operated at ambient temperatures below –5°C, the engine has to be protected from excessive maximum cylinder pressure occurring owing to the high specific density of the cold air. This can be achieved by applying a waste gate (blow-off valve) for either scavenge air or exhaust gas.

Although an exhaust waste gate offers certain thermodynamic advantages, the best choice is a scavenge air waste gate because it offers a much higher reliability by avoiding contact with high-temperature exhaust gas. The valve operates on a simple on/off function. If the ambient air temperature drops below –5°C, the waste gate opens and scavenge air is diverted to the air inlet pipe.

SHAFT MOTOR/ALTERNATOR SYSTEM

The shaft motor/alternator is of the low-speed type, directly mounted in the propeller shaft line. It operates on variable electrical supply frequency. A frequency control system controls the frequency to and from the electrical supply. The system operates on 6600V. It is arranged to operate as either a motor or an alternator.

The shaft motor/alternator gives the additional benefit of operational flexibility. The shaft motor can be employed to reduce the overall fuel consumption by reducing the main engine power required for a given ship speed, or it can be used to boost the propulsion power for a higher ship speed or to provide extra sea margin. It can also be used as a generator to supply electrical power for ship services while the ship is at sea if the WHR plant is not operational.

RT-flex COMMON-RAIL ENGINES

Wärtsilä RT-flex common-rail engines are ideal partners for high-efficiency WHR plants. The precision and flexibility available in engine setting given by the fully electronically controlled RT-flex common-rail system deliver clear benefits such as smokeless operation at all engine speeds, lower stable running speeds, lower fuel consumption, lower exhaust emissions and consistent engine settings for reduced maintenance.

The RT-flex system also has the option of Delta Tuning that provides lower fuel consumption at part loads compared with conventional camshaft-type engines. This tuning option takes advantage of the complete flexibility in fuel injection and valve operation allowed by the common-rail system.

In both the versions with original tuning and Delta Tuning, the RT-flex engines comply fully with the NO_x regulation of Annex VI of the MARPOL 73/78 convention.

The cleaner combustion achieved by