

Diesel Engines and Gas Turbines in Cruise Vessel Propulsion

Author: Horst W. Koehler, MAN B&W Diesel

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Introduction

With a slight delay and a few technical problems, Celebrity Cruises' gas turbine-driven cruising vessel Millennium made her maiden voyage in summer 2000. The 91 000 gt vessel with a Pax capacity of 1 950 (lower berth) denotes a technological shift in cruise ship design, primarily because she is the first cruise ship powered by a pure gas turbine plant. Apart from this, the ship has the biggest azimuthing pods ever built (two Mermaid pods of 19.5 MW each). Currently there are three further cruise ships of this series under construction.

This certainly is a milestone for gas turbine proponents, the more so as four further new Vantage-class cruise ships for Royal Caribbean International (RCI) are also specified with turbine-based propulsion plants. Each plant consists of two General Electric LM2500+ aero-derived gas turbines of 25 MW_{el} each and an 8 MW_{el} back pressure steam turbine. The steam turbine uses steam from the boilers fired by waste heat from the gas turbines to generate additional electrical power. This arrangement is called COGES, an acronym for "Combined Gas Turbine and Steam Turbine Integrated Electric Drive System".

Depending on the amount of steam required for onboard services, the complete COGES power plant is expected to achieve a combined-cycle efficiency of between 45 and

50%. This system will provide for all onboard power arrangements, such as propulsion, heating, cooling, lighting, ventilation, kitchen and laundry.

However, with about 97% of all existing sea-going ships propelled by two and four-stroke Diesel engines (fig. 1), it seems their manufacturers have so far not seriously been affected by gas turbines in most of their traditional market areas.




Fig. 1

Merits of gas turbines and Diesel engines in marine propulsion

This article concentrates on Diesel engines for cruise vessel applications with a total power requirement of approx. 60 MWeI per installation. A typical Diesel-electric drive with five medium-speed Diesel engines will be compared with the 58 MWeI COGES plant.

Diesel engines versus gas turbines
Pros and cons



Criteria	diesel engines	gas turbines
Weight and size		✓
Initial costs	✓	
Maintenance costs	✓	
Fuel consumption	✓	
HFO capability	✓	
Part-load operation	✓	
Transient response	✓	
Structure-borne noise		✓
Air-borne noise		✓
L.O. consumption		✓
NO _x emission		✓
SO _x emission		✓
CO ₂ emission		✓
Ambient conditions	✓	

Gas turbine

Photo and drawing: MPO-0038

fig. 2 pros of both prime movers in their simple-cycle modes, i.e. without utilising waste heat in a steam turbine

Weight and size

Gas turbines are known to generate lots of power while offering less space and weight than a Diesel engine of the same output. The Diesel engine's size and heavy mass is an undisputable disadvantage in many applications. However in the new Panamax-sized cruise ships with an increased number of decks but unchanged width, much weight is needed in the bottom of a ship for stability purposes - so the value of the weight savings by gas turbines must not be over emphasised. In order to decrease the vertical centre of gravity, this weight deficiency could be compensated by additional freshwater or fuel tanks. Another option is to slightly decrease the main deck height or draught of the vessel. However, all of this would necessitate a new ship design, excluding the use of a common hull form for either Diesel engines or gas turbines which would be highly beneficial in order to cut costs.

As regards the space savings of gas turbines, this potential cannot be fully utilised:

Gas turbines have approx. 15% larger air intake and exhaust ducts as comparable Diesel engines and their starting devices also occupy much space. Onboard cruising vessels with two gas turbines as prime movers, necessary provisions for a rapid replacement of a gas turbine (or at least its gas generator) within a few hours, with the vessel at sea and underway, occupies extra space. The engine room has to be designed with sufficient free space and all the necessary provisions and equipment for this job, including storage space for a complete spare gas turbine. Finally, plant availability and safety considerations make at least one or two additional Diesel engine gensets mandatory to satisfy low power requirements difficult to cover with a gas turbine and as emergency generator. This does not only restrict the freed space further, but also increases first costs, operating costs and maintenance costs.

First and maintenance costs

Contrary to weight and size, first costs and maintenance costs are lower for the Diesel solution, although first costs might be more a political concession. As regards maintenance, RCI has signed a 10 year repair and maintenance contract with General Electric for the vessels' LM2500+ gas turbines at a cost of 3 \$/MWh. The maintenance cost summary of a multi-engine Diesel-electric gives a lower figure.

Fuel and operating costs

As fig. 2 indicates, Diesel engines enjoy further benefits such as lower fuel prices, lower fuel consumption rates at all loads and therefore lower carbon dioxide emission and better load acceptance as well as quicker start-up times after a night stop. For instance, after a night stop, a gas turbine in simple-cycle mode needs 30 minutes until full load is reached, a diesel engine in the same situation less than 5 minutes.

Vibration, noise and lube oil consumption

As regards vibration and noise, multiple cylinder reciprocating engines with their intermittent combustion are at a disadvantage, although sometimes the real differences are exaggerated or erroneously interpreted. By direct-resilient mounting of Diesel engines, their structure-borne vibration transmitted into a ship's foundation is reduced to a level of approx. 50 dB (and less) at frequencies of 1 000 Hz (and higher). Although resiliently seated gas turbines might reach still lower values, design measures aiming at an even further decrease in Diesel engines' structure-borne noise can be omitted as long as the requirements regarding vibration in the cabins are met.

Unexpectedly the newbuilding Millennium experienced vibration problems in some areas of the ship under special sea conditions likely to occur in the Caribbean during the windy winter season. The ship had to be drydocked for technical modifications earlier than planned, following its arrival in New York in November 2000.

Air-borne noise

Air-borne engine room noise of gas turbines is claimed to be less than 85 dB(A), whereas the noise emission of a large-bore medium-speed Diesel engine of the author's company varies between 102 and 108 dB(A) at full load. The main reason for this difference is that marine gas turbines are installed in acoustically insulated enclosures whereas the noise level for free-standing Diesel engines is measured without any sound-attenuating encapsulation or lagging.

Engine machine rooms are not among the places where passengers onboard usually spend their leisure time. Therefore the lower running noise of gas turbines is not of

major importance: outside of the machine room, the Diesel engines can be considered to be encapsulated as well.

Luboil consumption


The specific lube oil consumption of modern gas turbines is typically only 1% of the Diesel engines' figure, but high-priced synthetic lubes have to be used in comparison to the low-priced mineral oils for the Diesel engines. The annual L.O. costs of gas turbines are only about 6% of that of Diesel engines. It has to be pointed out that this merit is of minor importance, since L.O. costs hardly affect the total operating costs.

Exhaust gas emissions

The real advantage of the gas turbine is its eco-friendliness as far as SO_x and NO_x (not CO₂) emissions are concerned. SO_x emission of gas turbines is close to zero because they burn basically sulphur-free fuel (MGO typically contains only about 0.3 % sulphur, HFO for Diesel engines up to 4.5%). If (higher-priced) low-sulphur or sulphur-free marine Diesel oils would be used for Diesel engines, there wouldn't be a SO_x problem with them either.

NO_x emission levels of modern marine gas turbines and Diesel engines are listed in Fig. 3. There is no basic technical restriction in decreasing the Diesel engines' NO_x emission down to a level of 2 g/kWh by adopting SCR-based exhaust-gas cleaning. All today's serial NO_x-optimized marine Diesel engines have to meet IMO's NO_x restrictions for international shipping valid for new ships (achieved by engine-internal measures). By direct injection of water into the cylinder or by adopting water-fuel emulsification (FWE), a similar NO_x emission level as with today's standard marine gas turbines without water injection is achieved.

NOx emission of marine prime movers
in g/kWh

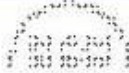


IMO's NO_x limit value for diesels (400-450 rpm)	13
MAN B&W V 48/60, NO_x-opt.	12
V 48/60, NO_x-opt. + fuel-water emulsion (15-20 %)	8 - 9
Engines with direct water injection (50-60 %)	6
Engines with HAM technology	3 - 4
Engines with SCR (Selective Catalytic Reduction)	2
Marine gas turbines without water injection	5
Gas turbines with water injection	2 - 3

fig. 3

Fig. 4 shows latest test results of an MAN B&W 6L48/60 engine from February 2000: a NO_x cycle value of 7.7 g/kWh and a fuel consumption rate still within tolerance (5%) was measured. This is 40% below the NO_x limit set by the IMO. This result was achieved with only 15% water in the water-fuel emulsion and a slightly retarded injection below 80% engine load.

Engine shop test 6L 48/60 with emulsion injection
containing 15 % of water (const.)



Load, %	25	50	75	85	100
Output, kW	1 575	3 150	4 725	5 355	6 300
SFOC, g/kWh	211.7	202.8	191.8	183.9	184.7
NO_x, g/kWh	6.44	7.08	6.97	10.89	9.58

NO_x cycle value (E2): 7.7 g/kWh

Constant speed 514 rpm
 Fuel: MDO
 Fuel consumption: ISO 3046-1, LHV 42,700
 Test date: 17 February 2000

fig. 4 As regards the influence of ambient conditions on output, only the air intake temperature is relevant in marine propulsion. All marine medium-speed Diesel engines of the author's company maintain their full load up to air intake temperatures of 45 °C, whereas gas turbines have to be derated.

Efficiency

Fig. 5 shows the achievable overall (brake) efficiency level of today's major prime movers. Large-bore medium-speed engines reach up to 47% in simple-cycle operation and low-speed Diesel engines even up to 51%. With lower unit ratings (smaller engines) the difference in efficiency (and in fuel consumption) between Diesel engines and gas turbines increases considerably.

Fig. 5 is indicative of the high efficiency level which combined-cycle gas turbines of high unit output (50 MW plus) reach today. Up to now there are only few Diesel combined-cycle (DCC) installations in operation. Their number will increase in future although this technology will increase the Diesel's efficiency level only by a few percentage points.

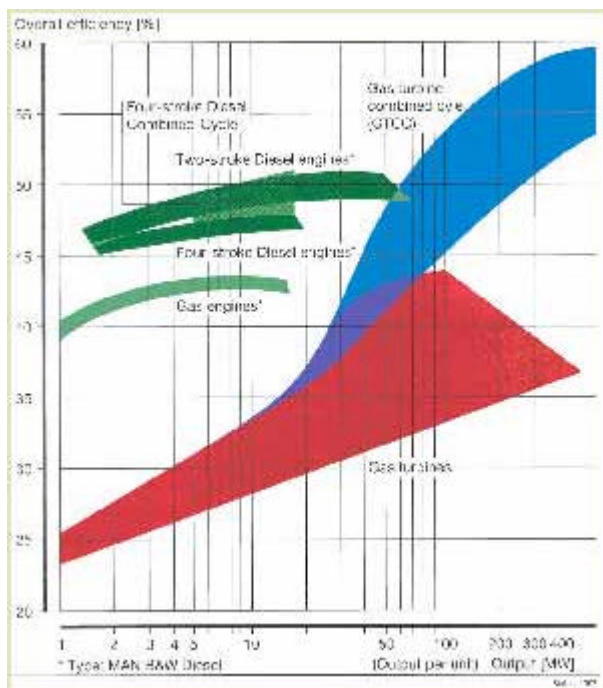


fig. 5

Operating costs: Diesel-electric versus COGES

The actual fuel costs of a cruising vessel highly depend on the ship's operational profile. In a study we have compared a 61 MWel Diesel-electric plant consisting of five MAN B&W 12V 48/60 medium-speed Diesel engines (5 x

12.2 MWe) with several COGES variations of about the same output.

Efficiency

The specific fuel consumption rates (SFOC) in g/kWh over the total electrical plant output for the various propulsion concepts is plotted in Fig. 6.

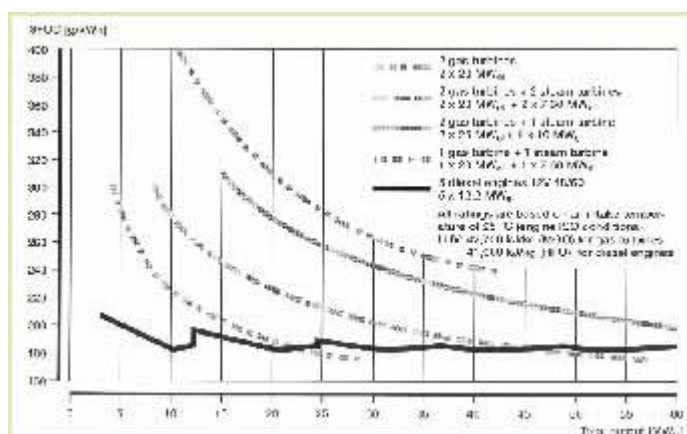


fig. 6

The dark solid line at the bottom of the diagramme is the consumption curve of the Diesel-electric plant. From full power down to approx. 8 MWe, fuel consumption is almost constant at a mean level of 190 g/kWh. Contrary to this favourably flat fuel consumption line, the turbines' consumption rates are highly load-dependent. At very high loads, above 50 MWe, COGES has a specific fuel consumption rate of around 210 g/kWh, a value which is only 10% above the Diesel engines' figure indeed. However, this high electrical power is hardly used in cruising: most of the time the turbines have to operate at part load with much higher specific fuel consumption rates.

The upper two curves show the fuel-saving effect of COGES' steam turbine. Should the steam turbine be switched off or fail, the fuel consumption will follow the upper curve instead of the lower one, penalising the fuel amount by 8 - 10%.

Between 20 and 28 MW_{el}, the COGES arrangement with one gas turbine and one steam turbine in operation (with the second gas turbine switched off) offers fuel consumptions equal to and even slightly lower than the Diesel-electric drive. But at any other load, the Diesel engines have a strong advantage in specific fuel consumption, particularly below 20 MW_{el} and above 30 MW_{el}.

A promising COGES arrangement would be possible with two gas turbines and two steam turbines (Fig. 6, third curve from above). In spite of the attractive fuel consumption levels at ratings in excess of 45 MW_{el} such a system has not been adopted - most likely due to cost, safety and simplification considerations.

Calculation of the annual fuel costs was based on the following typical weekly load scenario:


60 hours per week in ports (power requirement 10 MW_{el}):
one 12V 48/60 Diesel engine or one gas turbine with the steam turbine in operation

This sums up to 3 840 operating hours per year for each of the five Diesel engines, and 6 150 hours for each of the two gas turbines.

For this load profile and for average August 2000 fuel prices for North West Europe, the total fuel costs are shown in Fig. 7.

The difference in annual fuel costs between COGES and the Diesel-electric option is US-\$ 7 million!

Annual fuel costs COGES (80 MWe) vs. diesel-electric (81 MWe) in m US-\$



Fuel	COGES	diesel-electric
	MGO	HFO 380 cSt
Fuel price, \$/ton*	300	145
Fuel consumption, tons	45,120	39,540
Fuel costs, m \$	13.54	5.73
Additional fuel amount for steam production (17 tons/hr), tons	1,000	7,060
Additional fuel costs, m \$	0.3	1.03
Total annual fuel costs, m \$	13.84	6.76

*) Fairplay August 31, 2000 (fuel prices North West Europe listed August 25, 2000)

fig. 7

The costs for the extra fuel burnt in oil-fired boilers for production of the necessary steam amount (17 tons/h) is already included. COGES needs only little additional fuel for steam production, actually only what is needed during stays in ports. One of the main reasons for the higher fuel amount of the Diesel-electric power plant used for steam production is that more steam has to be produced by the oil-fired boilers with decreasing numbers of Diesel engines in operation.

Can revenues from the extra cabins offset these higher fuel costs?

The crucial question is, whether or not the much higher fuel costs of the COGES plant can be compensated by higher revenues from selling (up to) 50 extra twin cabins in the lower decks. Repeatedly, it has been stated from the gas turbine proponents, that "the extra revenue yielded will comfortably offset the higher turbine fuel costs of COGES".

First of all, it cannot be taken for granted that 50 additional twin cabins, plus other new public recreation areas and spaces, are achievable with a comparable ship design - without penalising the passengers' comfort standard. Consultants outlined that perhaps only half of this amount is realistic, but in spite of these concerns, the claimed num-

ber of 50 additional cabins is used for the following economy estimate.

Assuming that 90% of the beds in these 50 extra cabins are always sold, 50 weeks per year, and let for an average of US-\$ 200 per person and day (a reasonable rate for small cabins without windows), the additional income is about US-\$ 7 million per year. This already includes the turnover yielded by the passengers' personal expenses onboard. Assuming a profit margin of 30%, the overall annual net profit is US-\$ 2.1 million (70% are costs of the operators to build and equip the cabins, for food, cabin cleaning, laundry, costs for increased staff, taxes, etc.).

Commercial result

The total sum of fuel costs (Fig. 7) and lube oil costs is US-\$ 13.86 million for COGES and US-\$ 7.04 m for the Diesel-electric system. The difference is US-\$ 6.8 million per year. With the total annual net profit of only US-\$ 2.1 million, it is impossible to compensate COGES' higher fuel bill. With today's (September 2000) bunker prices, there is a loss of US-\$ 4.7 million every year and for every ship - and this does not include the higher first and maintenance costs.

Summary

In comparison to a COGES system, Diesel-electric solutions have clear advantages in many aspects, with the exception of weight and size, and NOx emission and noise. These advantages are:

uniform machinery, lower fuel costs and lower fuel consumptions and therefore lower CO2 emission, lower first costs, operating costs, easier maintenance, lower maintenance costs and wider operational flexibility and redundancy on account of the larger number of Diesel engines that are able to burn widely varying fuel qualities. The gas

turbine itself, as an intrinsically simple rotating machine, is highly reliable and durable as it has fewer moving parts and lower friction losses, but the more complicated (new) COGES system involving a steam turbine genset had no chance up to now to prove its availability and long-term reliability in cruise shipping.

Diesel engine manufacturers are convinced that the Diesel engine, after a proving career of more than one century, will maintain its leading role in merchant shipping in the second century of Diesel engine development, too.