WINNER OF THE
ABB TURBOCHARGING
110 YEAR ANNIVERSARY
WHITE PAPER COMPETITION

How 110 Years of Turbocharging Changed the World.

Charles Stuart

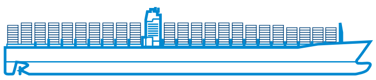
Queen’s University Belfast

In 1905, Dr Alfred Büchi published a patent describing a “highly supercharged compound engine,” referring to the coupling of a four-stroke diesel engine with an axial turbine and axial compressor mounted on a common shaft. It is widely recognised that the issuing of this patent signalled the birth of exhaust gas turbocharging, and the key ideals remain unchanged to this day. From these comparatively humble beginnings, few would have imagined the impact this staple of forced induction would have on the modern world. Far from being an accessory to improving engine performance, turbocharging has become possibly the key enabling technology in engine development. All areas of modern internal combustion engines, from motorcycles through to marine engines avail of the significant advantages brought about by turbocharging.

While it was 1924 before Brown Boveri capitalised on the idea and built the first heavy duty turbocharger for use on an experimental two-stroke engine [1], and 1926 before the first practical application of turbocharging of large marine engines in German passenger liners, the uptake of turbocharging technology in the shipping industry was to undergo an exponential increase over the coming years. In fact, Dr Büchi’s initial proposal for collaboration with Brown Boveri was rejected, and it was not until 1923 when tests carried out by MAN on low pressure electrical supercharging yielded an increase in brake power output of 33% [1] that Brown Boveri recognised they could no longer ignore the potential of turbocharging.

Despite the almost false start for the turbocharger, growth in its application began to increase rapidly. In the fifteen years succeeding 1945, the world’s merchant shipping fleet doubled in size [2], creating the market required for turbocharging to really flourish. Today it is widely accepted that 90% of global trade is carried by sea, equating to approximately 8.4 billion tonnes of cargo in 2010 [3], with turbocharged two-stroke diesels being by far the dominant engine configuration used in deep sea shipping (amounting to 85% of all new orders for merchant ships [4]).

90% of global trade is carried by sea



8.4bn tonnes of cargo in 2010

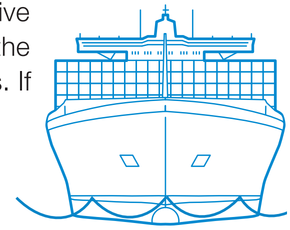
The pinnacle of modern marine engine development is the Wärtsilä-Sulzer RT-flex96C, which in its largest 14 cylinder variant produces 114,800bhp at 102rpm [5], exceeds 50% brake thermal efficiency and is recognised as the largest reciprocating engine in the world. These statistics would quite simply have been unimaginable without the inclusion of exhaust gas turbocharging. Being a two-stroke diesel, the benefits of turbocharging are even more deeply rooted than for four-stroke engines, which although would suffer a reduction in power output and efficiency without a turbocharger, can run quite happily in a naturally aspirated configuration. By comparison, forced induction is essential for the operation of two-stroke engines used in marine applications.

> *These statistics would quite simply have been unimaginable without the inclusion of exhaust gas turbocharging.*

Crosshead two-stroke engines require air above atmospheric pressure to successfully scavenge, and initially used a mechanically driven roots type supercharger to achieve this aim. However, the transmission system between the crankshaft and compressor introduces additional losses and also detracts directly from the useful power output of the engine (which can amount to 30% of the power added by the inclusion of the supercharger in the first place [6]). Replacing a mechanically driven supercharger with a constant pressure turbocharging system allows a proportion of approximately 35% of the total energy supplied to the engine from fuel that is otherwise wasted [7] to be harnessed to do useful work.

With the latest merchant vessels, the cost of transporting one twenty-foot equivalent unit (TEU) for a day by sea is $10.99 for an 18,000 TEU ship [8]. In practical terms, this equates to transporting a pair of shoes the 3390 miles from the Port of New Jersey to Rotterdam for $0.0083, a truly astonishing figure. If the same journey was undertaken by a vessel employing a mechanically driven supercharger to deliver the required boost pressure rather than a turbocharger, a considerable increase in fuel consumption would be expected because up to 15% of engine power output would be required for driving the supercharger [6]. It is stated that transportation costs decrease by 23% for every additional TEU over and above 12,500 [8], but is this sustainable in the long term?

Looking to the future, while the amount of cargo transported by ship is impressive today, it is estimated by Stopford [9] to increase to 23 billion tonnes by 2060 if the growth in world trade continues at the same rate as it has for the last 150 years. If the 2.4% per annum growth in seaborne trade is borne out as expected, it is estimated that carbon dioxide emissions will increase to in excess of 300% of current levels if no changes are made to the current technology. While it has been possible to increase ship size to take advantage of economies of scale to reduce the unit cost of (and also the emissions associated with) each unit transported, the infrastructure in ports and key crossing points such as the Panama Canal have effectively reached their limit in terms of ship size [10].

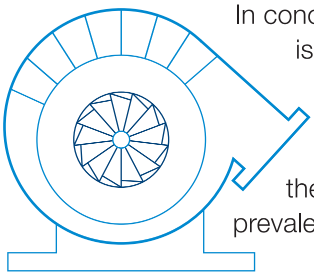


While turbocharging has enjoyed a tenure exceeding 90 years in the shipping sector, it will once again become crucial to meet the ongoing demands to drive down costs while also satisfying increasingly stringent emissions legislation, and will prove to be an enabling technology for additional changes to engine architecture. Due to be brought into force for engines produced from January 2016 onwards, the International Maritime Organisation (IMO) Tier III emissions standards necessitate a reduction in NOx emissions of approximately 76% over Tier II levels in Emission Control Areas [11]. Furthermore, the full force of the Energy Efficiency Design Index (EEDI) will be brought to bear in the coming years after the initial six and a half years of leniency following its introduction in January 2013 [12].

Aside from the implementation of a Selective Catalytic Reduction (SCR) system similar to what is present in most heavy duty trucks to ensure EURO VI compliance, turbocharging has a hand in all of the possible solutions to improving the cleanliness and efficiency of marine engines. Starting with four-stroke engines, it has been noted for some time that application of Miller Timing (through variable inlet valve timing) with exhaust gas recirculation (EGR) would form the basis for further NOx emissions reductions and engine efficiency improvements [13]. Both of these technologies place additional demands on the efficiency and pressure ratio delivered by the turbocharger, bringing two-stage turbocharging forward as an almost essential addition [14].

For two-stroke engines, further NOx reductions will arise from application of the two-stroke Miller cycle, which involves late closing of the exhaust valve, coupled with internal EGR. The area with what is perceived to be greater potential is the adoption of dual-fuel engines, with liquefied natural gas (LNG) providing the primary energy source. Two different versions of this idea are being pursued by two of the largest marine engine manufacturers – Wärtsilä and MAN. Despite fundamental differences in the methodologies employed, both approaches demand increased performance from the turbocharger to ensure that the LNG engine is not de-rated in comparison to the existing heavy oil fuelled engine.

On the 110th anniversary of the birth of turbocharging, the technology is every bit as relevant and important today as it was at its inception.



In conclusion, on the 110th anniversary of the birth of turbocharging, the technology is every bit as relevant and important today as it was at its inception. The same basic challenges remain, but have now been supplemented by an increased environmental awareness that has brought about legislation which can only be met with the help of further developments to the turbocharger. In spite of the passage of time and the development of innumerable new technologies, the prevalence of and challenges presented for turbocharging in the marine sector show no signs of abating.

References

[1] ABB Turbocharging, 2005, "Turbo Magazine Centenary Issue – A Century of Turbocharging," Reprinted from Turbo Magazine 2/2005

[2] Summers M., 2007, "ABB Turbochargers – history and milestones," ABB Review 2/2007

[3] International Maritime Organisation, 2012, "International Shipping Facts and Figures – Information Resources on Trade, Safety, Security, Environment."

[4] Wärtsilä Marine Engines, "Wärtsilä Merchant Shipping Applications," http://www.wartsila.com/marine/applications/merchant, Accessed 20/09/2015

[5] Wärtsilä Engines, 2008, "WärtsiläRT-flex96C and Wärtsilä RTA96C Technology Review," pg 23

[6] Hartman, J., 2007, "Turbocharging Performance Handbook," MBI Publishing Company, Minneapolis, USA, pg10, ISBN 978-0-7603-2805-7

[7] Woodyard, D., 2004, "Pounder's Marine Diesel Engines," Elsevier Butterworth-Heinemann, Massachusetts, USA, pg 175, ISBN 0 7506 5846 0

[8] ABB Group, "Maritime Cargo Vessels – Is bigger better?," http://new.abb.com/turbocharging/maritime-cargo-vessels---is-bigger-better, Accessed 18/09/2015

[9] Stopford, M., 2010, "How shipping has changed the world & the social impact of shipping," Global Maritime Environmental Congress, Hamburg, Germany.

[10] Ship Technology, "Turbocharging the World's Largest Container Ships," http://www.ship-technology.com/features/featureturbocharging-the-worlds-largest-container-ships-4627524/, Accessed 25/09/2015

[11] International Maritime Organisation, "Nitrogen Oxides (NOx) – Regulation 13," http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Nitrogen-oxides-(NOx)-%E2%80%93-Regulation-13.aspx, Accessed 25/09/2015

[12] DieselNet, "IMO Marine Engine Regulations." https://www.dieselnet.com/standards/inter/imo.php, Accessed 24/09/2015

[13] ABB Turbocharging, "Turbocharging medium speed diesel engines with extreme miller timing," https://library.e.abb.com/public/bb370e9ea2e5e464c12578800056520c/ABB%20Turbocharging_Turbocharging%20medium%20speed%20diesel%20engines....pdf, Accessed 21/09/2015

[14] ABB Group, 2014, "Advanced turbocharging and variable valve timing for improving engine performance," CIMAC Circle @ POWER GEN / Cologne 2014-06-03

APPENDIX - Calculation of Shipping Cost

Shipping cost from Port of New Jersey to Rotterdam. As Basel cannot accommodate an 18,000 TEU ship, the remaining journey from Rotterdam to Basel would have to be undertaken by rail, truck or smaller ship.

Port of New Jersey to Rotterdam = 3390 nautical miles
MSC Oscar Optimum Speed = 22.8 knots [8]
∴Time at sea = 6.2 days

1TEU for 1 day by sea = $10.99 (18000 TEU ship) [8]
Total journey cost for 1TEU = $68.14

$$\text{Number of shoe boxes per TEU} = \frac{\text{Volume of TEU}}{\text{Volume of shoebox}} = \frac{39}{0.0047195}\ (m^3) = 8263$$

$$\text{Shipping cost for 1 pair of shoes} = \frac{68.14}{8263} = \$0.00825$$