Continuous Water Injection – A Cost Effective Solution for Emissions Reduction and Fuel Saving.

Dr. Anatoly Mezheritsky, President of M.A. Turbo/Engine Ltd.

Increasingly, worldwide environmental concern and legislations are causing manufacturers and end-users to focus on the drawbacks of diesel engines.

The days are definitely past when high efficiency was the only criterion for successful engine design. Today the engine concept has to combine optimum efficiency with low emissions. Any credible environmental technology should be capable of reducing operational cost and exhaust gas emissions simultaneously in addition to being able to return an investment on research and development costs.
Is such an objective incompatible and contradictory? Currently, the answer is 'yes' because none of the existing emission control technologies, including direct water injections, fuel/water emulsification, SCR, HAM, EGR, etc., satisfy these requirements. However, the water injection system (CWIS) designed by M.A.Turbo/Engine Ltd. of Vancouver, Canada, meets all the above criteria which is something that has never been achieved by other technologies. Although CWIS is specifically designated for economic retrofit of existing diesel engines, it can also be fitted on newly built engines, either separately or in combination with other technologies.

Briefly, CWIS is based on injection of a controlled quantity of water in the combustion air before/after aircooler and before the turbocharger's compressor. Water Injection directly influences engine performance, emissions, and specific fuel consumption mainly through combustion air quality (pressure, temperature, humidity, velocity, etc.) and its quantity. Rapid evaporation of water droplets promotes local turbulence of air, leading to slightly faster ignition, better air-to-fuel mixing and therefore contributes to more complete combustion. In addition, water evaporation lowers boost air temperature hence increasing air quantity available for combustion, i.e. increases the air excess coefficient Φ. It is well known that an increase of this coefficient also leads to increased engine combustion efficiency. In general, a one percent increase in Φ corresponds to a 0.2% - 0.3% increase in engine combustion efficiency (for the common area of Φ range for turbocharged engines).

However, combustion air quantity and coefficient Φ do not just depend only on water injection. It is known that during normal operation of turbocharged diesel engines a gradual deterioration of the engines performances takes place. One of the main causes of this fact is fouling of the scavenging air coolers, air intake manifolds, scavenging ports or intake/exhaust valves and turbocharger compressor blades (so-called Air Suction Duct or ASD). The most intensive growth of the deposit layer takes place during the first 500-1000 hours of operation. In the next 1000 hours the thickness of the deposit layer grows

relatively slow and then, after approximately 2,500 – 3,000 hours, it stabilizes. This deposit formation reduces ASD efficiency.

To eliminate deposits from the compressor blades of the turbocharger, practically many engine manufacturers supply simple compressor water washing systems which consist of a small water tank (usually 1-2 liters capacity), manually operated valves and connecting tubes. According to the operational manual, water has to be injected once per day under the scavenging air pressure to the compressor. Years of operational experience have proven that this simple system is not effective. In fact, deposits removed by existing water washing devices from compressor blades, settle between the air cooler's fins. This phenomenon makes existing devices impractical and, as a result, during approximately 90% of the period between overhauls, engines are working with restricted combustion air flow, reduced ASD efficiency, resulting in increased fuel consumption, higher exhaust gas temperature, increased cylinder wear, emissions, etc.

The data from numerous tests of ASD efficiency influence on overall engine combustion efficiency indicates that after 3,000 hours of operation, ASD fouling reduces engine combustion efficiency by approximately 2%-3% for four-stroke engines and by 1.5%-3.4 % for two-stroke engines. It is clear that fouling is a serious operational problem and the WIS is the best and probably the only solution to this problem. With CWIS in operation air coolers and turbochargers are maintained in clean conditions at all times, ensuring the required amount of airflow for combustion, hence reducing operational cost and emissions.

All of the above explains why CWIS reduces, simultaneously, emissions and operational cost and capable to return an investment.

Between 2002 and 2012, CWIS was installed on a number of vessels equipped with different engines (Table 1) and accumulated a total of 34,900 hours of constant operation. The longest period of CWIS operation is with the fruit juice tanker *Bebedouro* (23,380 hr of permanent CWIS operation on main and all auxiliary engines), and the ferry *Queen of New Westminster* (main engine, 5,321 hr). The following conclusions were drawn based on these CWIS sea operations.

1. Emissions reduction.

In general, each percentage of water injected reduces NOx by 1%. However, results depend upon engine specific design and operational conditions. For example, the higher the boost pressure, the better NOx reduction achieved; the same with the aircooler cooling water temperature, etc. Test results of CWIS for different engines are shown in Table 2, Table 3 and Table 4 (NOx and WFR are average)

Table 1. Vessels equipped with Water Injection System

Vessel	Owner	Vessel type	Engine, type	
1. Bebedouro	Cargill International SA	fruit carrier	Sulzer 4RTA 58 Wartsilä 6-8R22	2 stroke, main 4 stroke, aux.
2. Queen of New Westminster	BC Ferries Services Inc	ferry	Wartsila 9R32D Cat. 3508	4 stroke, main 4 stroke, aux
5. Oski*	Blue & Gold Fleet	ferry	Detroit 7122	2 stroke, main
6. Peter Creswell	Algoma Central Marine	bulk carrier	MAK 6M552	4 stroke, main
7.Algosoo	Algoma Central Marine	bulk carrier	10PC2V MK2 Cat. 399	4 stroke, main 4 stroke, aux
8. Algocape	Algoma Central Marine	bulk carrier	Sulzer 6RD76	2 stroke, main
9. WaveRider	SXC, Inc. San Diego	fast ferry	Detroit 12V92	2 stroke, main
10. APL Jade	APL Pte, Co, Singapore	container	Wartsila 6R32D	4 stroke, aux
11. APL Coral	APL Pte Co, Singapore	container	Yanmar 8N280L	4 stroke, aux
12. APL Cyprine	APL Pte Co, Singapore	container	Yanmar 8N280L	4 stroke, aux
13. APL Sardonyx	APL Pte Co, Singapore	container	Wartsila 6R32D	4 stroke, aux
14. APL Pearl	APL Pte Co, Singapore	container	Yanmar 8N280L	4 stroke, aux
15. APL Agate	APL Pte Co, Singapore	container	Yanmar 8N280L	4 stroke, aux
16. APL Garnet	APL Pte Co, Singapore	container	Wartsila 6R32D	4 stroke, aux
17. APL Spinel	APL Pte Co, Singapore	container	Yanmar 8N280L	4 stroke, aux
18. APl Alexandrite	APL Pte Co, Singapore	container	Yanmar 8N280L	4 stroke, aux
19. APL Amazonite	APL Pte Co, Singapore	container	Yanmar 8N280L	4 stroke, aux
20. Capilano	BC Ferries Services Inc	ferry	Bergen KRG 9	4 stroke, main
21. Froyanes	Froyanes AS, Norway	fishery	Yanmar 6N21AL	4 stroke, main
22. Atlantic	Atlantic AS, Norway	fishery	Cat. 3512 Cat 3406	4 stroke, main 4 stroke, aux,
23. Froyanes Senior, 24. Vesteinen , 25. Seliveare.	Froyanes AS, Norway Froyanes AS, Norway Froyanes AS, Norway	fishery fishery fishery	Cat. 3512 Cat 3406	4 stroke, main 4 stroke, aux,
26. APL Holland	APL Pte., Co, Singapore	container	MAN B/W	4 stroke, aux
27. Seaspan Corsair	Seaspan International.,	sea tug	MTU	4 stroke, main
28. Mapleglen	Canadian Steamship lines	bulk carrier	B&W 6K67GFC	2 stroke, main

Table 2. Weighted Emission results from 1995 Caterpillar 3406E done by ERMD of Canada.

Water/Air Flow Ratio %	CO_2	CO	NOx	P.M.*	BSFC	Temp.after Intercooler [*deg.C*]	Temp. Exhaust [*deg.C*]	Turbo out [*psia*]	Engine Power [*bhp*]
Baseline initial	456.36	0.70	1.06	0.033	141.2	71.2	424.7	26.6	314.7
1.8	453.30	0.52	0.78	0.032	140.5	53.0	403.8	26.8	315.1
2.2	455.46	0.50	0.76	0.031	139.9	51.9	401.6	26.8	314.3
2.35	461.69	0.48	0.73	0.030	139.2	50.8	400.0	26.7	314.2
2.40	void	void	void	void	void	void	void	void	void
2.45	455.84	0.46	0.70	0.032	138.6	49.4	398.5	26.8	314.5
Baseline final.	455.41	0.68	1.03	0.035	141.1	71.4	426.2	26.5	314.7

Note: all emissions data as well as BSFC data are in g/bhp-hr.

Table 3. Relative Difference of the Weighted Initial Baseline Values (1995 Caterpillar 3406E)

Water/Air Ratio %	NOx	P.M.*	BSFC	Temp. Exhaust[*deg.C*] .	Turbo out pressure	Engine power
Baseline init.	datum	datum	datum	datum	datum	datum
1.80	-26.4%	-2.1%	-0.6%	-20.9	+0.4%	+0.1%
2.20	-28.7%	-5.6%	-0.9%	-23.0	+0.5%	+0.1%
2.35	-31.0%	-8.4%	-1.4%	-24.6	+0.3%	-0.2%
2.40	void	void	void	void	void	void
2.45	-33.5%	-10.9%	-1.8%	-26.2	+0.7%	+0.1%

Table 4. Emission reduction tests results

Engine	**Load, hp**	**NOx/CO/PM reduction %**	**WFR, %**
Sulzer 4RTA 58	5,600-6,000	26.3/18/n.a.	28.5
Wärtsilä 6R22	500-600	27.4/22/n.a.	28.0
Wartsila 9R32D	2,400-3,600	25.7/14/18	26.0
Cat. 3508	250-300	25.5/20/11	27.0
Cat. 3406E	400	33.5/24/2.9	38.0
Cummins NTC -350	260 - 270	27.4/19/0.0	39.0
Detroit 12V-7122	300 -320	25.4/14/9.0	30.0
MAK 6M552	3,600	27.0/13/n.a.	29.6
Pielstick 10PC2V MK2	4,200	26.2/17.5n.a	30.0
Sulzer 6RD76	7,400	28.7/21/n.a.	29.7
Detroit 12V92	730 – 850	25.5/23/4.6	29.0
Wartsila 6R32D	1,840	27.1/24/10.2	25.8
Yanmar 8N280L	1,400	26.4/19/n.a.	23.0

2. Engine reliability/cylinder wear.

The main concerns for operators have always been possibility of corrosion and excessive cylinder wear. “Diesel water syndrome” has been encountered by many generations of marine engineers. However, when water is introduced as fine droplets under relatively low pressure it cannot adversely affect oil film. Due to a very high temperature within the cylinders (300 – 1200°C) and relatively small WFR, condensation within the combustion chamber is not possible. Operational experience backs up this

theoretical reasoning and, in fact, specific cylinder wear (SCW) is reduced (see Table 5.) There has been no single instance when engine reliability was compromised by CWIS. Based on this, the ship owner, Cargill International, increased the cylinder overhaul period by 4,000 hours.

Table 5. Specific cylinders wear reduction due to **CWIS** operation

Engine	Operational hr		SCW, mm/1000 hr		Wear Reduction %
	Before CWI installation	After CWI installation	Before CWI installation	After CWI installation	
Wartsila 9R32D Cyl. #3	7,254	13,207	0.049	0.0229	21.6
Caterpillar 3508					
Cyl. #4	30,257	1,362	0.0260	0.0188	27.7
Cyl. #6	30,257	1,362	0.0254	0.0206	19.0
Sulzer 4RTA 58	62,530	22,420	0.049	0.0447	8.77*

* Average for four cylinders

3. Specific fuel consumption.

An accurate and statistically sound measurement of SFC is a very challenging task, especially when someone talks about 1% to 3% differences and therefore was measured not on all engines with CWIS. The most accurate tests of CWIS were performed by Emission Research and Measurement Division (ERMD) of Environment Canada at their test-bed facilities in Ottawa. The results of these tests are shown in Tables 2 and 3 above. As it can be seen from the results, SFC has decreased by up to 1.8% due to improved combustion only.

The data with respect to SFC measurements on other engines is shown in Table 6. It should be underlined that Detroit 12V92, Cummins NTC and Cat. 3406E were new, clean engines and therefore difference in SFC illustrates influence of CWIS on combustion efficiency only, while results on Wartsila 9R32D and Cat. 3508 illustrate combined influence of CWIS on combustion efficiency and ASD fouling.

4. Lubricating Oil.

In general, CWIS improves lube oil quality. For example, Table 7 illustrates comparable analysis of the Wartsila 9R32D engine where practically all of the oil quality elements had improved after the

application of CWIS. The most important is the difference in Fe components, which is an indicator of cylinder wear. Similar results were registered on all tested engines.

Table 6. Influence of **CWIS** on specific fuel consumption

Engine	Tester	Conditions	SFC reduction, %
Wartsila 9R32D	Environment Canada	Sea trials	1.4-1.75
Cat. 3508	BC Ferries, M.A.Turbo/Engine	Sea trials	2.75
Wartsila 6R32D	APL Pte Co, Singapore	Sea trial	1.80
Yanmar 8N280L	APL Pte Co, Singapore	Sea trial	2.64
Cummins NTC-350	Environment Canada	Test bed	1.75
Detroit 12V92	West Virginia University, USA	Sea trials	0.75

Table 7. Results of Oil Analysis; main Wartsila 9R32D engine (based on B.C. Ferries monthly reports)

	Spectro-chemical analysis of elements, ppm														
	Si	Na	K	Fe	Cr	Pb	Cu	Sn	Al	Ni	Ag	Ti	B	Mg	V
New Oil	10	0	0	1	0	0	0	1	1	0	1	0	3.0	17.0	0
1	15.7	3.34	0.36	2.65	1.1	0	0.55	0.19	0.45	0	0	0	0.68	10.7	0
2	15.1	0.22	0.22	2.44	0.9	0	0.33	0	0.66	0	0.11	0	0.11	10	0

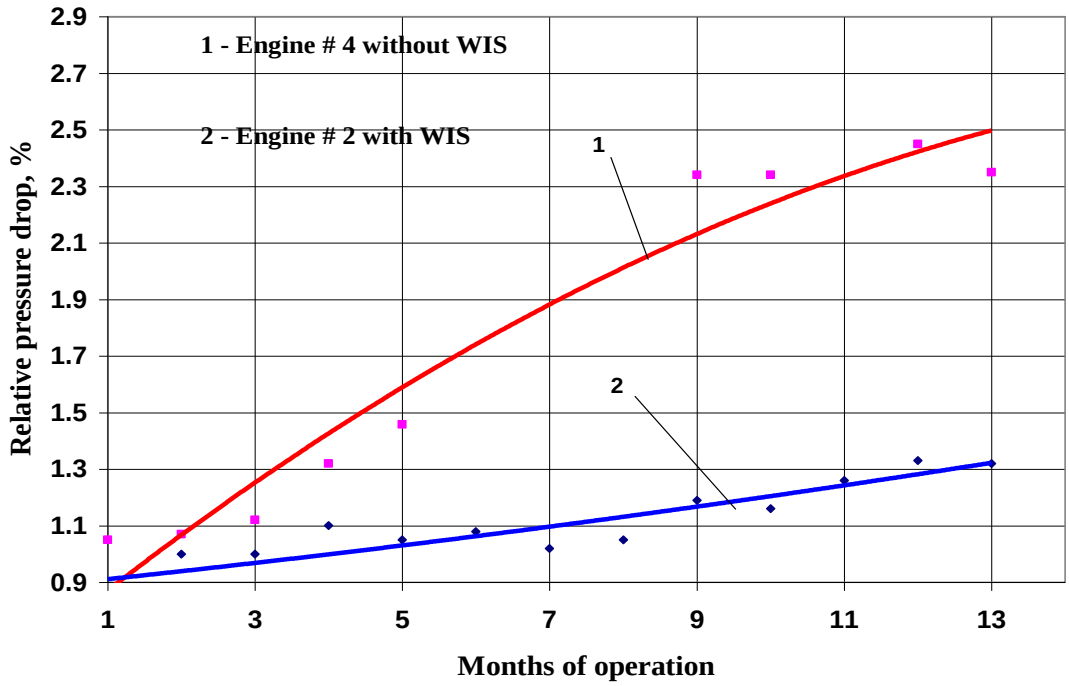
1 –data for 11 months before WIS installation; 2 –data for 9 months with WIS in operation.

5. Aircooler conditions analyses.

The condition of the aircooler surface can be determined by drop in pressure. Pressure drops over the aircooler were measured onboard the *Queen of New Westminster* on engine # 2 and on engine # 4 by identical devices. Results of the measurements are presented in Fig.1 below and this experimental data confirms that the air cooler passages remain relatively clean due to CWIS operation. As results of this, the aircooler was not removed from the engine fitted with CWIS for cleaning during the vessel's most recent

overhaul while aircoolers from all three other main engines had to be dismantled and cleaned. This saved BC Ferries $1,400.

Fig.1. Influence of **CWIS** on pressure drop over aircoolers (Wartsila 9R32D engines)



CONCLUSION

All of the above facts confirm that the water injection technology offers a very effective emission control system providing simultaneous GHG and operational cost reductions with guaranteed returns on investment.

In summary, the proved benefits of water injection technology are:

- Increased efficiency of the combustion process and reduced operational fuel consumption up to 4%;
- Exhaust gases temperature reduction up to 30°C;
- Reduced formation of NOx up to 30% and smoke emission up to 15%;
- Reduction in peak combustion temperature;
- Minimized thermal stresses on the engine components;
- Prevention of carbon buildup on the cylinder walls, turbochargers, air coolers, suction valves, scavenging manifolds, etc.;
- Increased overhaul period;
- Reduced maintenance cost up to 25%;
- Usual pay-back period 1-1.5 years