CHARGE AIR COOLING PRACTICES FOR UNDERGROUND MINING

Brent Rubeli, CANMET, Natural Resources Canada

ABSTRACT

The construction, operation and maintenance of heavy-duty diesel engine charge air cooling systems are discussed as they relate to the underground mining industry. The functional differences between various engine manufacturer's systems are explained. The effect of charge air cooling on engine emissions is discussed. The potential application of charge air cooling systems to light-duty vehicles are examined, referring to a preliminary study performed at the CANMET diesel emissions test facility.

INTRODUCTION

A decade ago, heavy-duty diesel engine (HDDE) manufacturers faced a new set of on-highway emission regulations promulgated by the US Environmental Protection agency (EPA). These regulations imposed large reductions in oxides of nitrogen (NOx) and particulate matter (PM) targets, and represented a significant technological challenge.[3]

Three major technologies were developed to enable engine compliance: injection timing retard, higher injection pressures and low temperature charge air cooling. Timing retard lowered NOx levels, but at the expense of fuel economy and PM emissions. Higher injection pressures improved fuel economy, and charge air cooling improved air utilisation, lowering PM and NOx simultaneously.[4]

Charge air cooling (CAC) systems derived from on-highway engines have been gradually introduced on underground mining engines.

FUNDAMENTALS

Modern HDDEs employ exhaust-driven turbochargers to improve volumetric efficiency and increase specific power output.[7]

The turbocharger pressurises the intake charge to the engine, increasing its density. This raises the overall air/fuel ratio in the cylinder leading to improved emissions performance.

The degree of air charging is represented by the *boost pressure ratio*. This is the ratio of absolute pressure in the intake manifold to atmospheric pressure.

Table 1: Degree of Air Charging[8]

Charging	**Boost Pressure (bar)**	**Pressure Ratio**
NA	0.0 and below	1.0 and below
Low	0.0 - 0.5	1.0 - 1.5 : 1
Med	0.5 - 1.0	1.5 - 2.0 : 1
High	1.0 and above	2.0 and above

An unfortunate consequence of this compression is a higher charge air temperature that lowers the air density.

The *air charge density ratio* is the ratio of the density of the charge in the cylinder at operating conditions to the density of the charge at standard temperature and pressure.

Charge air cooling systems can recover a significant amount of the air density, keeping the air charge density ratio high. For ambient temperatures around 25°C, the compressed air leaving the turbocharger can be as high as 120°C for a typical diesel engine at rated power.[8]

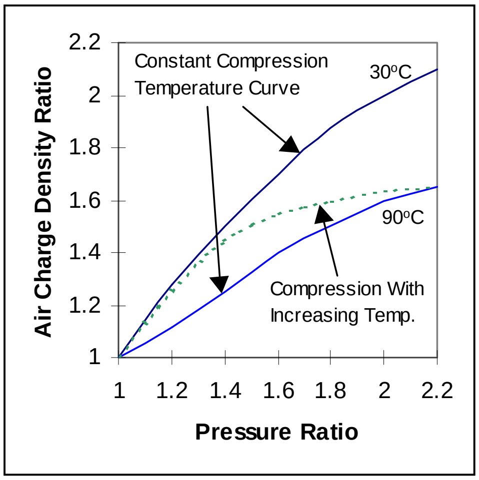

Figure 1: Effect of pressure ratio on increase in charge density if the charge temperature is held constant or allowed to rise.[8]

CONSTRUCTION

Charge air coolers are classified by cooling medium and location in the air intake system.

Air-to-liquid charge air coolers use the engine cooling system to remove heat from the intake charge. Because of the excellent heat transfer characteristics of engine coolant, they are compact and are often integrated into the engine intake manifold. This decreases the loss in boost pressure across the charge air cooler.

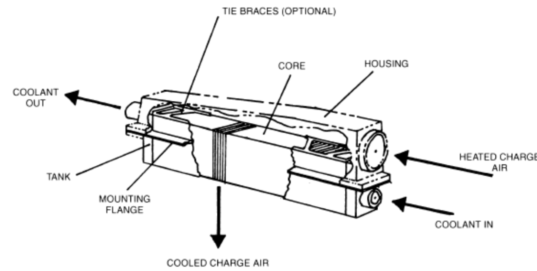

Figure 2: Air-to-liquid CAC[1]

The coolant temperature limits the performance of air-to-liquid CAC. A well-engineered system can typically lower the charge temperature from 120°C to 85°C – 90°C with an engine coolant jacket temperature of 80°C.

Air-to-air charge air coolers use ambient air to remove heat from the intake charge. For most underground mining applications, the charge air cooler is located in front or beside the engine radiator. The engine-cooling fan draws ambient air through the CAC, lowering the intake charge temperature.

Air-to-air CAC must be large to have sufficient surface area for heat transfer from the charge air to ambient air. This often limits the location options and requires high-pressure piping to conduct the intake charge.

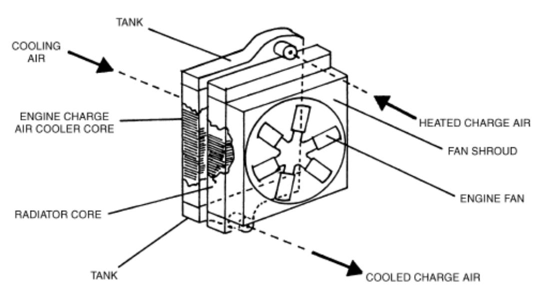

Figure 3: Air-to-air CAC[1]

At ambient temperatures of 25ºC, radiator fan-driven air-to-air CAC can lower the charge temperature from 120ºC to 40ºC – 50ºC. This is a substantial improvement over the air-to-liquid system.

Technically, charge air coolers are referred to as aftercoolers if they are located after the turbocharger compressor and intercoolers if they are located between the compressor and intake manifold or between series compressors.[1]

TYPICAL HDDE SYSTEMS

Most heavy-duty diesel engine manufacturers offer several different types of charge air cooler systems depending on the application. We will look at systems from three major underground mining engine manufacturers; Caterpillar, Detroit Diesel and Deutz.

Caterpillar

Caterpillar uses air-to-liquid or air-to-air CAC on 80% of its turbocharged underground mining engine ratings.[9] Typical charge air cooling systems are shown below.

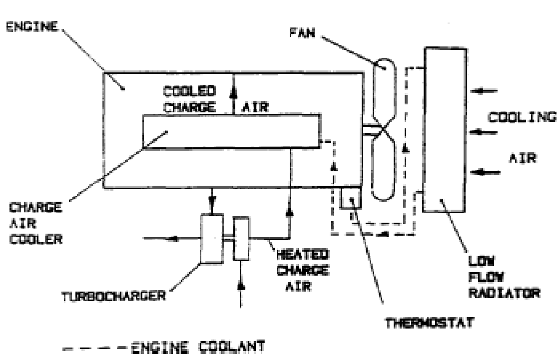

Figure 4: Air-to-liquid Jacket Water Aftercooled (JWAC)[2]

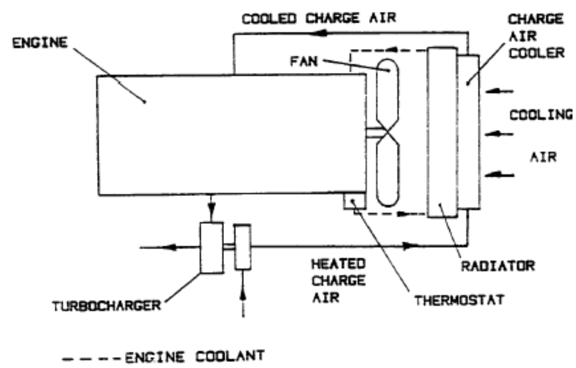

Figure 5: Air-to-air Aftercooled (ATAAC)[2]

The model and type number can identify certified Caterpillar mining engines equipped with charge air cooler systems.

3176C ATAAC (270, 310, 335 HP)[11] (CANMET / CSA certificate number # 1099) [5]

317 – Series number
6 – Number of cylinders
C – Industrial engine rating
ATAAC – Air-to-air aftercooling

3306 DITA (JWAC) (165 – 270 HP)[10] (MSHA certificate 7E-B010-1)[20]

33 – Series number
06 – Number of cylinders
DI – Direct injection
T – Turbocharged
A – Aftercooled (air-to-liquid)
JWAC – Jacket water aftercooled

Detroit Diesel

All Detroit Diesel ***four-stroke*** turbocharged engines use air-to-air CAC for underground mining applications.[13] Series 50 8.5L, Series 60 11.1L and 12.7L engines use the Detroit Diesel air-to-air charge cooling system (A/ACC). This system is mounted conventionally in front of the engine radiator.[15]

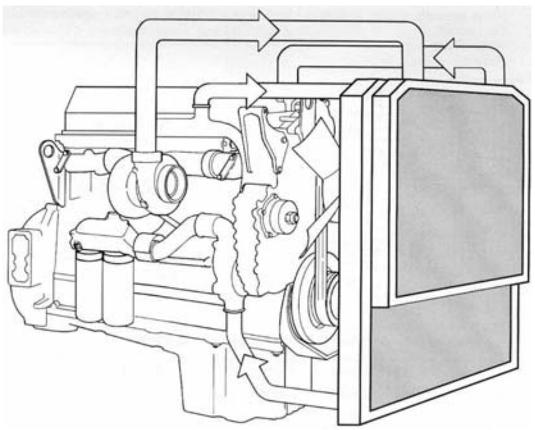

Figure 6: Series 60 A/ACC Air-to-air Charge Air Cooler System

Some CANMET / CSA certified engines equipped with A/ACC are:

Series 60 12.7 L (350-475HP) #996[5]
Series 60 11.1 L (285-325HP) #1007[5]
Series 50 8.5L (250-315HP) #1058[5]

All Detroit Diesel ***two-stroke*** turbocharged engines use air-to-liquid CAC for underground mining applications.[13] If the charge air cooler is located between the turbocharger and the scavenge air blower it is identified as a jacket water intercooler (JWIC) system. If the charge air cooler is located after the scavenge air blower it is identified as a jacket water aftercooler (JWAC).[12]

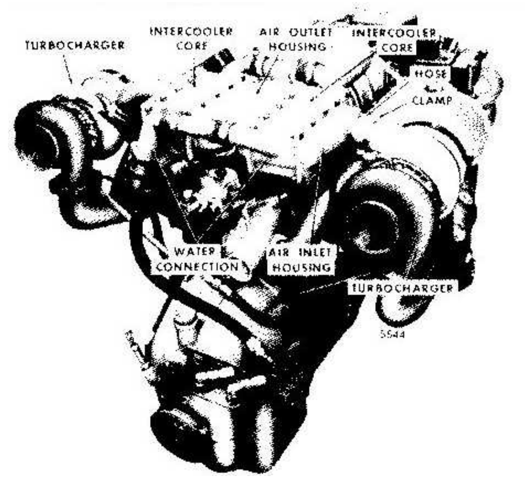

Figure 7: Series 92 JWIC System

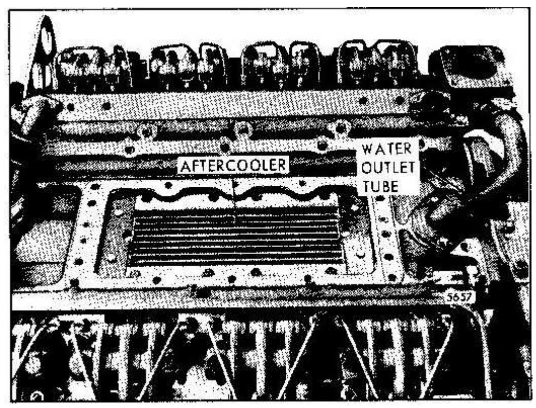

Figure 8: Series 92 JWAC System

Some CANMET / CSA certified two-stroke engines are:

Series 92 6V92TA (250-300HP) #1059[5]

Deutz Corporation

Deutz ***air-cooled*** engines must use air-to-air CAC since no liquid coolant circuit is available. The engine fan forces a portion of the cooling air through the charge air cooler attached to the top of the airbox.[16]

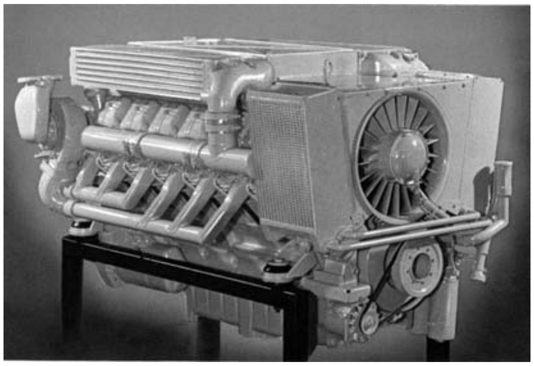

Figure 9: Deutz Air-to-air CAC

No air-cooled Deutz engines certified for use in underground mines are currently equipped with charge air cooling.

Deutz ***liquid-cooled*** engines employ air-to-air and air-to-liquid charge air cooling, however, only air-to-air systems have been used on certified mining engines. [17]

BF6M1013CP (253 HP)
(CANMET/CSA certificate number 1082)[5]

B – Exhaust turbocharged
F- Four-stroke, high speed engine
6 – Number of cylinders
M – Liquid-cooled
10 – Engine series
13 – Piston stroke (cm)
C – Air-to-air charge air cooling
P - Uprating

Deutz liquid-cooled engines are currently offered with an integrated or external cooling package. On engines with external cooling, the CAC is located conventionally in front of the engine radiator.

Engines with integrated cooling have the engine radiator and oil/hydraulic cooler located along the right side of the engine. The front-mounted engine fan directs cooling air through the integrated radiators. Charge air coolers used with the integrated cooling system are mounted in front of the engine fan.

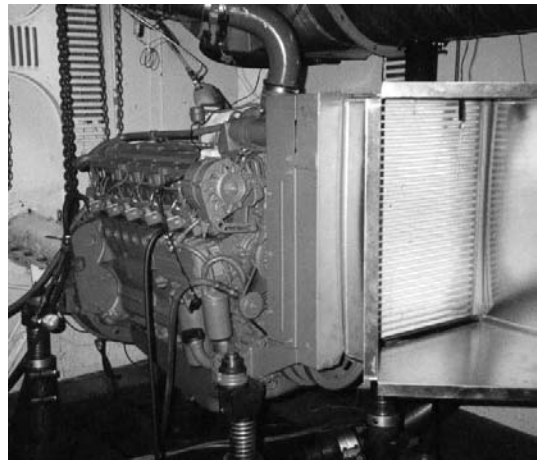

Figure 10: Deutz Air-to-air CAC with integrated cooling package

MAINTENANCE

Problems with CAC systems seriously degrade both engine and emissions performance.

The multi-stakeholder Diesel Emissions Evaluation Program (DEEP) sponsored investigations into the relationship between maintenance and emissions performance.[19]

Figure 11: JCI Scoop at Strathcona mine.

A case study of a JCI 250M equipped with a Deutz BF4M1013C engine identified a number of faults caused by poor maintenance. An initial check had indicated low turbo boost pressure. Further investigation revealed leaking CAC hose connections, damage to the CAC matrix and high intake air filter restriction.

An emissions test was performed on the vehicle in the as-found condition. After repairing the intake system faults, the system was tested again.

Table 2: CAC Maintenance Findings

	As Found	**After CAC Maintenance**	**Improvement**
CO (ppm)	590.06	302.67	49%
NOx (ppm)	667.08	529.7	21%
PM (mg/m3)	61.67	25.83	58%

Maintenance of the CAC system is critical to ensure high engine air utilisation and emissions compliance. Air-to-air systems in particular are more prone to leakage due to the complex CAC piping and coupling elements.

Mechanical checking of the system integrity can be performed by temporarily sealing the engine intake system and pressurising it to 172 kPa. Leaks can be detected by spraying the CAC piping with a soap and water solution. System leakage should be compared to manufacturer's specifications.

For example: Detroit Diesel Series 60 CAC systems are required to hold 172 kPa with less than 34.5 kPa drop over 15 seconds to meet leakage requirements.[14]

Quantitative CAC performance at rated power can be determined by calculating effectiveness factor, ε.

$$\varepsilon = \frac{T_2 - T_3}{T_2 - T_1}$$

Where:
T_1 = cooling media temperature
T_2 = turbo outlet air temperature
T_3 = charge air cooler outlet air temp.

The effectiveness factor is used to evaluate the actual heat transfer available from the maximum possible.[8] This can be used as a preventative maintenance tool.

For an air-to-air system in peak condition;

$T_1 = 25^oC$ (ambient), $T_2 = 120^oC$,
$T_3 = 40^oC$

$$\varepsilon = \frac{120 - 40}{120 - 25} = 0.84$$

CAC system effectiveness should be determined as a baseline when the system is new and monitored periodically to ensure system compliance.

Dirt and debris collecting on the surface of the air-to-air cooler reduces the effectiveness. A preventative maintenance plan should include regular cleaning and testing of the CAC system.

Air-to liquid systems can lose effectiveness due to accumulation of scale deposits in the cooling passages. These deposits should be removed periodically by dismantling the CAC and immersing it in a commercial de-scaling solution.[12]

All HDDE manufacturers publish service bulletins for CAC maintenance and performance testing. A good example is Detroit Diesel Bulletin 48: CAC System Recommendations for Series 50 and Series 60 Engines.[14]

LIGHT DUTY ENGINES

Light-duty diesel engines (LDDE) have not adopted CAC technology as quickly as heavy-duty engines. This is due partly because the CAC system would represent a large percentage of the overall engine cost.

In addition, LDDE tend to have a longer life span in underground mines, so new units do not replace them as quickly. As a result, LDDE have been losing ground to HDDE on an emissions quality basis.[18]

Turbocharged LDDE can benefit from charge air cooling technology. To demonstrate this concept, an air-to-liquid charge air cooling system was installed on a light-duty diesel engine at the CANMET diesel emissions test facility.

The engine is representative of a modern, high-speed, light duty engine.

The engine turbocharger outlet temperature was 78ºC at rated power. The laboratory charge air cooler system was set to maintain charge air temperature at 38ºC (using water at 15ºC) giving an effectiveness of 0.65.

No modifications were made to the engine and no attempt at system optimisation was made for this proof-of-concept study.

Figure 10: Laboratory charge air cooler in CANMET test facility

The engine was tested according to the ISO 8178-C1[6] test procedure with the exception that the intermediate speed was replaced with the peak torque speed at 1400 rpm. The engine was tested first in stock configuration and then with the air-to-liquid charge air cooler installed.

Table 4: Integrated Performance

	Stock	CAC	Improvement
CO (g/hphr)	0.42	0.49	-17%
NO (g/hphr)	2.64	2.42	8%
PM (g/hphr)	0.15	0.13	13%
Fuel (g/hphr)	186.2	180.3	3%
Power (hp)	42.0	44.3	5%

Significant improvements were found in NO and PM emissions with the CAC in operation. An additional benefit was an increase in integrated horsepower and a decrease in fuel consumption over the cycle.

It should be noted that the laboratory CAC system piping was relatively long, causing the manufacturer's recommended intake restriction to be exceeded. This likely contributed to the increase in CO emissions. In addition the restrictive CAC piping lowered the turbo boost pressure by 0.7 – 1.4 kPa. An optimised system would eliminate this problem and likely see further improvements in NO and PM emissions.

Charge air cooling can be an enabling technology for light-duty turbocharged engines.

CONCLUSIONS

Charge air cooling systems are an emissions-critical engine HDDE component. Air-to-air CAC provides the most benefit due to the lower ambient temperature of the cooling medium, but it is particularly vulnerable to damage.

Defects in the CAC system can seriously degrade engine emissions and lower mine air quality. Fortunately, inspection and testing is relatively simple and should become part of a regular preventative maintenance program.

CAC usage is slowly increasing on light duty diesel engines. Mines should recognise that CAC represents a significant step forward in emissions quality for these engines and begin putting them into service as needed.

ACKNOWLEDGEMENTS

The author would like to acknowledge the invaluable assistance of Vince Feres, David Young and Mark Deziel.

The author would also like to thank Sean McGinn for permission to publish data from the DEEP maintenance study.

REFERENCES

1) SAE J1148, Charge Air Cooler Nomenclature, SAE 1997-03
2) SAE J1937, Engine Testing With Low-temperature Charge Air Cooler Systems in a Dynamometer Test Cell, SAE 1995-01
3) SAE 920470, Herzog, P. et.al. NOx Reduction Strategies for DI Diesel Engines, SAE 1992
4) SAE Diesel Engine Technology Seminar, 1998
5) CANMET MMSL 97-041(TR), List of Diesel Engines Approved by CANMET in Accordance with CSA Standards M424.1-88 & M424.2-90 (1995-97, 98), CANMET 1998
6) ISO 8178-1,4 Reciprocating Internal Combustion Engines – Exhaust Emission Measurement – Part 1: Test Bed Measurement of gaseous and Particulate Exhaust Emissions. Part 4: Test Cycles for Different Engine Applications. ISO 1996(E)
7) Lilly, L. Diesel Engine Reference Book, Butterworths, 1984
8) Heisler, H. Advanced Engine Technology, SAE 1995
9) Engines for Underground Mining, LECK8232, Caterpillar 1998
10) Underground Mining Equipment, 3306, LEHH8583-01, Caterpillar, 1998

11) Underground Mining Equipment, 3176C, LEHH8348-01, Caterpillar, 1998
12) Detroit Diesel Series 92 Service Manual, 6SE379-88
13) Detroit Diesel Underground Mining, 14SA2-95
14) Detroit Diesel Bulletin 48: Charge Air Cooling Recommendations for Series 50 and Series 60 Engines, 18SA0354- 93
15) Detroit Diesel Bulletin 50: Cooling System Guidelines for Radiator Cooled Engine Applications, 18SA0353-93
16) Garthe, H., The Development of Deutz Air-cooled Diesel Engines, Deutz, 1977
17) Deutz Engines for Underground Operation, Deutz, 1996
18) Evaluation of the Contribution of Light Duty Vehicles to the Underground Atmosphere Diesel Emissions Burden. DEEP 2000, www.deep.org
19) The Relationship Between Diesel Engine Maintenance and Exhaust Emissions, DEEP, 2000. www.deep.org
20) http://www.msha.gov/S&HINFO/DESLREG/1909a.HTM