A LUMPED-MASS ANALYSIS OF WATER EVAPORATION IN RECIPROCATING-PISTON COMPRESSORS

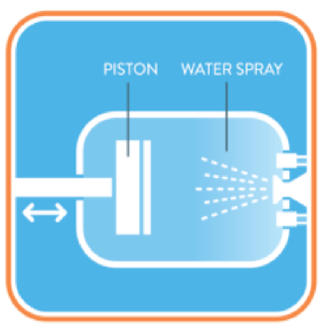
Paul Sapin, Michael C. Simpson, Christoph J. Kirmse, Christos N. Markides*

Clean Energy Processes (CEP) Laboratory, Department of Chemical Engineering, Imperial College London, UK.

***Corresponding author: c.markides@imperial.ac.uk**

INTRODUCTION

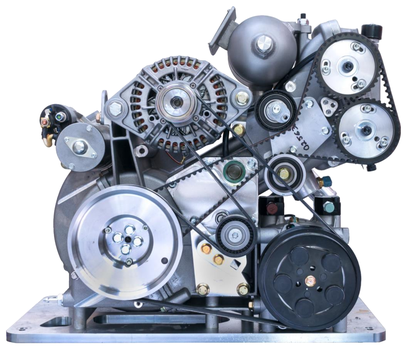
- Injection of liquid spray into a reciprocating-piston cylinder has been proposed for several novel applications.
- Aiming to enhance power density and heat transfer to or from the gas in the cylinder.



Water can be used to transfer heat to / from air for Isothermal Compressed Air Energy Storage[1].



BMW and Bosch water-injection system for petrol engines increases power and fuel efficiency and reduces CO_2 emissions [2].



The Dearman engine combines liquid nitrogen and a water-glycol mixture within the piston cylinder to produce power [3].

- Dynamic multiphase flows are challenging and time-consuming to simulate.
- Typically require advanced CFD methods to solve a three-dimensional unsteady flow.
- For early-stage design work, we considered the use of a simplified one-dimensional model.
- Model predicts the performance of a reciprocating-piston air compressor, with internal water-spray cooling.

RESULTS FOR SPRAY-COOLED AIR COMPRESSION USING WATER

- Water injection triggered at a threshold temperature of 47 °C (320 K).
- Spray cooling reduces the area enclosed by the pressure-volume plot (Figure 2).
- The work required for compression is up to 7.5 % lower for a run at 100 RPM.
- This is a gross reduction, and would need to be offset against the energy demand for high-pressure pumping.

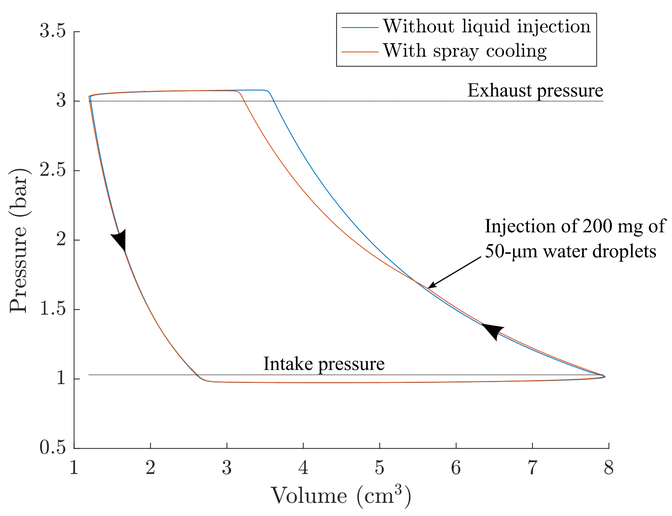


FIGURE 2: Pressure-volume trace for air compressed to 3 bar with and without spray

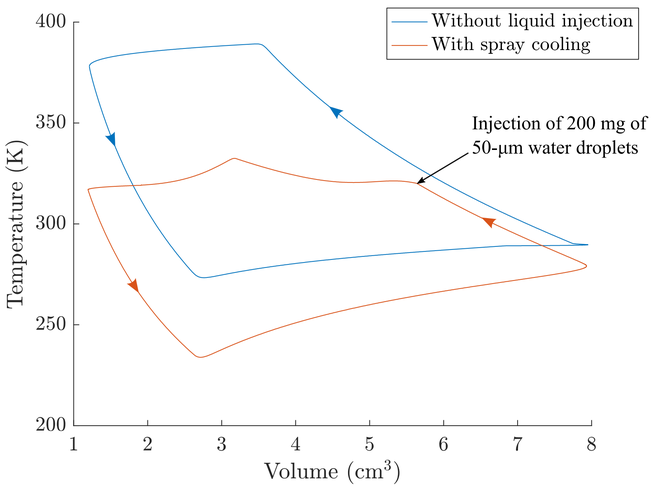


FIGURE 3: Temperature-volume trace for air compressed to 3 bar with and without spray

- Mass loadings of 0 – 0.35 (0 - 200 mg of water) added, in 50- or 100-μm droplets.
- Mean exhaust temperature reduced from 113 °C without injection to 48 °C at highest mass loading with 50-μm droplets.

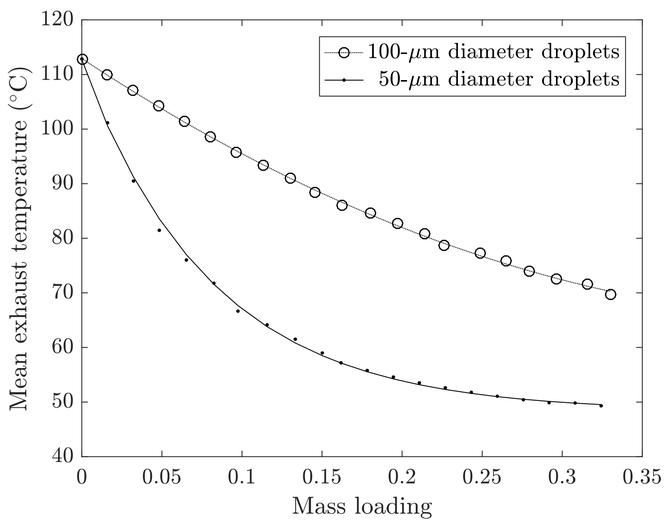


FIGURE 4: Effect of increasing the mass of injected water on mean exhaust temperature

NUMERICAL METHODS

- Lagrangian tracking for each droplet.
- Lumped-mass approach for the gas phase.
- Control volume varies in time according to the fixed-speed motion of the crankshaft, and connecting rod.

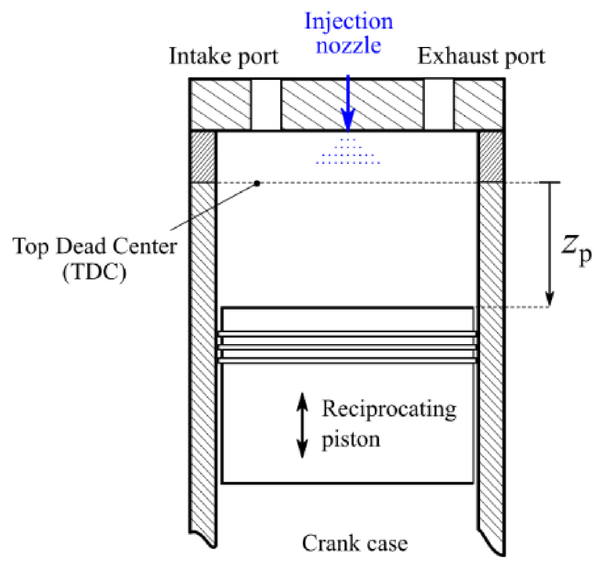


FIGURE 1: Schematic of piston configuration

Droplet evaporation model

$$m_d c_{p,d} \frac{dT_d}{dt} = \dot{Q}_{gd} - \dot{m}_{vap} \Delta h_{vap}$$

where:

$$\dot{Q}_{gd} = 2\pi R_d \cdot \overline{k_g} \cdot Nu \cdot (T_g - T_d)$$

$$\dot{m}_{vap} = 2\pi R_d \cdot \overline{\rho_g} \cdot \overline{\mathcal{D}} \cdot Sh \cdot B_M$$

Here, Nu and Sh are the Nusselt and Sherwood numbers calculated according to the method proposed by Abramzon and Sirignanon [4], based on the Frossling correlations.

Furthermore, B_M is the Spalding mass transfer number calculated as:

$$B_M = \frac{Y_{w,s} - Y_w}{1 - Y_{w,s}}$$

where $Y_{w,s}$ and Y_w are the water mass fraction at the surface of the droplet and in the bulk humid air.

Heat balance for the gas phase

$$m_g \frac{dh_g}{dt} = V_g \frac{dP}{dt} + \dot{Q}_{wall} + \sum_j^{N_d} \left[\dot{m}_{vap}(h_{g,s} - h_g) - \dot{Q}_{gd}\right]_j + \sum_{in/ex} \dot{m}_{in/ex}(h_{g,in/ex} - h_g)$$

where $\dot{Q}_{wall}$ is the gas-to-wall heat transfer, calculated with the correlation proposed by Lekic [5].

Mass loading

Mass loading is defined as $\frac{m_{d,in}}{m_{g,in}}$ for a cycle.

Engine dimensions

Bore diameter = 105 mm / Stroke length = 78 mm
Clearance height = 14 mm.

CONCLUSIONS

- A one-dimensional lumped-mass method has been developed for simulating liquid injection into a reciprocating-piston chamber.
- Injecting 200 mg of 50-μm water droplets (a mass loading of 0.33) was found to reduce the mean exhaust temperature by almost 65 °C.
- Indicated compression work can be reduced by 7.5 % (from 119 W to 110 W) for a run at 100 RPM.

REFERENCES

[1] D. A. Fong, S. E. Crane, and E. P. Berlin, “Compressed air energy storage system utilizing two-phase flow to facilitate heat exchange”, US 2010/0326062 A1, 2010.
[2] BMW, “BMW Concept M4 GTS”, 2016. [Online]. Available: http://www.bmw.co.uk/en_GB/topics/discover-bmw/concept-cars/m4-concept-gts.html.
[3] Centre for Low Carbon Futures, “Liquid Air on the Highway”, 2014.
[4] B. Abramzon, W.A. Sirignano, “Droplet vaporization model for spray combustion calculations”, Int. J. Heat Mass Transfer, vol. 32, no. 9, pp.1605-1618, 1989.
[5] U. Lekic, “Fluid flow and heat transfer in a helium gas spring-computational fluid dynamics and experiments”, PhD thesis, University of Twente, 2011.