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Experimental Investigation of Water Spray Cooling for Temperature Reduction in Liquid Piston Compressor

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ABSTRACT

For many compressor applications achieving an efficient compressor necessitates an isothermal compression process. A high heat transfer rate during the compression process is needed for reaching near-isothermal conditions. In this study, experimental investigations are carried out with water spray injection in a liquid piston compressor during the compression process to absorb the heat and lower the temperature. A low flow full-cone nozzle with 0.045 in (0.1143 cm) diameter is used for the experiments with different injection pressures. Injection of water spray proved to be an effective heat transfer mechanism for a substantial temperature drop of air during the compression process. It is observed that increasing the injection pressure of spray resulted in a temperature reduction of 10-20 K during compression. For a compression ratio of 2.5, a 10-20% efficiency improvement was observed during the compression.

1. INTRODUCTION

Air compressors have large-scale industrial applications and for many compressor applications, development of efficient gas compressors rely on having high heat transfer characteristics. Compression of gas to high pressures is accompanied by a high temperature of the gas. This is because a significant proportion of the compression work is utilized in increasing the internal energy of the gas. Reducing the temperature of a gas during the compression process decreases the compression work. Typical gas compression processes operate at a high rpm which result in poor heat transfer characteristics and improving the heat transfer during compression would significantly reduce the temperature of the gas.

Coney *et al.* (2002) described a reciprocating piston compressor using water spray injection to achieve near-isothermal air compression. They substantially reduce the temperature and compression work by using high mass loading of water. Mass loading is defined as the ratio of the mass of water injected to the mass of air in the compression chamber. Increasing the amount of heat transferred out of the system would result in a near-isothermal process thereby improving the compression efficiency. Several strategies have been researched to achieve near-isothermal gas compression (Heidar et al., 2014).Several researchers have studied droplet dynamics and heat transfer between air and water spray (Jia & Qiu, 2003). Sureshkumar *et al.* (2008) performed experiments on water spray and ambient air to study evaporative cooling. They investigated spray cooling for parallel flow and counter-flow configurations with different nozzle pressures, nozzle diameters, environmental conditions, and air velocities. Accordingly, they observed that for a given flow-rate, higher injection pressure with a smaller nozzle diameter resulted in a higher temperature drop of air.

The liquid piston gas compressor was proposed by Van de Ven and Li (2009). In a liquid piston setup, a column of liquid is used to compress the gas to required pressures for a given chamber volume. In a liquid piston compressor, the surface area to volume ratio can be maximized to improve the heat transfer. By increasing the heat transfer, the compression process shifts to a near-isothermal condition with lower temperatures compared to typical reciprocating compressors and the heat transfer coefficient observed was significantly higher compared to a reciprocating compression process. This resulted in a lower bulk temperature of the compressed gas. As the temperature is lower during the liquid piston compression process, the internal energy of the gas at the end of compression is lower thus shifting the compression process to near-isothermal conditions and requiring less compression work. The liquid piston compressor concept has significant advantages. The surface area to volume ratio can be increased multi-fold compared to reciprocating compressors by increasing the number of liquid pistons. Additionally, it reduces air leakage from the system. It also replaces sliding friction of the piston rings to viscous friction of the liquid. Additionally, it is convenient to accommodate water spray cooling in the chamber as the droplets eventually fall in the liquid surface. To achieve the same pressure ratio, a liquid piston compression process reduces the compression work required, resulting in high compression efficiency. They estimated that the liquid piston compression required 19% less work compared to the reciprocating piston compression, and improved the compression efficiency by 13%.

Spray cooling concept can be utilized for increasing the heat transfer during the compression process. This would lead to the development of a highly efficient compressor for Compressed Air Energy Storage (CAES) systems. Investigations by Qin et al. (2014) suggested that CAES can be combined with off-shore wind farms to harness the wind energy. As typical air compressors have rapid compression cycles and do not have adequate heat transfer, the temperature of the compressed air increases. This high pressure compressed air is then stored in pressurized vessels where the compressed gas gradually cools down to ambient conditions. This loss of thermal energy can be avoided with the use of a liquid piston compressor which improves the heat transfer to the surroundings. Furthermore, introducing droplets into the liquid piston can achieve a near-isothermal compression by providing an increased surface area for heat transfer and having high mass loading. Qin and Loth (2014) studied droplet heat transfer for different droplet diameters, total mass injection, and various methods of injection. Direct injection had higher heat transfer compared to premixed injection cases due to the fact that the droplets were airborne at the end of compression stroke period. They found that for a constant mass loading, reducing the droplet diameter increased the heat transfer till 20 µm after which no significant improvement was observed. The difference in the temperatures at the end of the adiabatic compression process and isothermal compression process was about 300 K, thus, a significant temperature reduction is required to bring the compression process to near –isothermal conditions. Spray cooling is a highly effective heat transfer mechanism due to a large interfacial surface area with a large number of droplets. Therefore, spray cooling estimated to show an improvement in the compression efficiency from 71 % for an adiabatic compression to a maximum of 98% with spray cooling for a tenfold pressure ratio.

Further enhancement in spray cooling characteristics in liquid piston compression can be achieved by optimizing its trajectories (Saadat *et al.* 2012). The spray profile and water-air mass ratio can be optimized to obtain maximum isothermal efficiency for a variable flow rate compared to a constant spray flow rate. Qin *et al.* (2014) also describe the spray cooling concept with an injection of water droplets in the liquid piston compressor that can be used for wind-based CAES. They perform simulations over a three-stage compressor and observed a substantial increase in the overall compression efficiency compared to the adiabatic compression process. This increase in efficiency could be used to reduce the capacity of the wind turbines and electrical generators as they do not need to be sized for a maximum output capacity.

In this study, water spray cooling is investigated in a liquid piston compressor on a table-top setup to observe its effect on temperature reduction during compression. The experiments are performed with and without spray injection. Further, spray injection pressure is varied from 10-70 psi (69-483 kPa) to study the effect of variation of injection pressure on the temperature reduction. The effect of injection pressure is evaluated based on the isothermal efficiency of compression and compared with no spray injection in the liquid piston.

2. EXPERIMENTAL SETUP

The experimental setup is built to test spray cooling during the liquid piston compression process with water as the medium and a polypropylene chamber for compression vessel. Figure 1 shows the experimental setup. The setup consists of a compression chamber, solenoid valves, intake and exhaust valves, pneumatic cylinder, hydraulic pump, controller, Data Acquisition System (DAQ), and measurement instruments. The outer cylinder contains water acting as a surrounding environment for the compression chamber. This helps achieve a higher heat transfer rate between the chamber wall and the surrounding water during the compression process compared to air as the surrounding medium. Water from a hydraulic pump drives the liquid piston interface in the innermost chamber during the compression process which compresses the air and is retracted by a coupled pneumatic piston-hydraulic pump for the intake stroke. A cycle consists of the compression stroke followed by the exhaust of high-pressure air, ending in the intake stroke where atmospheric air fills the chamber to reach initial conditions. During the compression process, the liquid piston moves in the upward direction and continuously reduces the air volume while increasing the pressure and temperature. Each experimental test case is run for about 10-12 continuous cycles to confirm repeatability and evaluate the cyclic variability. The controller actuates the solenoid valves which regulates the intake and exhaust of air at the end of compression. LabVIEW was used to program the continuous operation of the liquid piston. The pressure is measured using a pressure transducer mounted on the top plate of the cylinder along with the solenoid valves. Two thermocouples are placed inside the compression chamber for measuring the temperatures. The thermocouples used are K-type 40 gauge diameter which are placed in radially opposite directions about 1 in from the center of the spray nozzle. These measurements are connected with the DAQ to measure the interior conditions during the compression and expansion process. The measurement instruments and their uncertainties are mentioned in Table 1.

Table 1: Measurement devices and corresponding uncertainties

Measurement	**Description**	**Accuracy**
Temperature	K –Type Thermocouple	+/-2.2 °C
Pressure	Electronic Pressure Transducer 0-100psig (0-689 kPa)	+/-0.25%
Flowmeter	Electronic Flowmeter 0.5-5 L/min	+/- 3%
Volume	Location Sensor	+/-0.001”

To incorporate water spray into the system, a closed water loop was set up for the experiments. A positive displacement pump set to a maximum pressure of 100 psi (689 kPa) is used to drive the water spray into the chamber. For a closed loop, the exit of the outer cylinder is connected as an inlet to the pump, this ensured that the volume of air at the start of each cycle remained the same. The spray injection pressure is controlled using a pressure regulator and varied from 10 to 70 psi (69-483 kPa).

To measure the flow rate of water during the compression process, a flowmeter was connected after the pressure regulator. The flowmeter and pump are powered using a 12VDC power supply, with the flowmeter readings being captured by the DAQ. The DAQ sends the voltage signal inputs into a LabVIEW program recording the data. The spray nozzle is mounted on the top surface of the compression chamber and radially centered to generate a symmetric spray pattern on the liquid piston surface. A low flow full-cone nozzle was used with a nozzle diameter of 0.043 in (0.1092 cm). The spray nozzle angle of 120° was used for the current study as it covered a larger air volume towards the end of the compression stroke. All the compression experiments were performed till 750 mL of water from the liquid piston was added into the compression chamber.

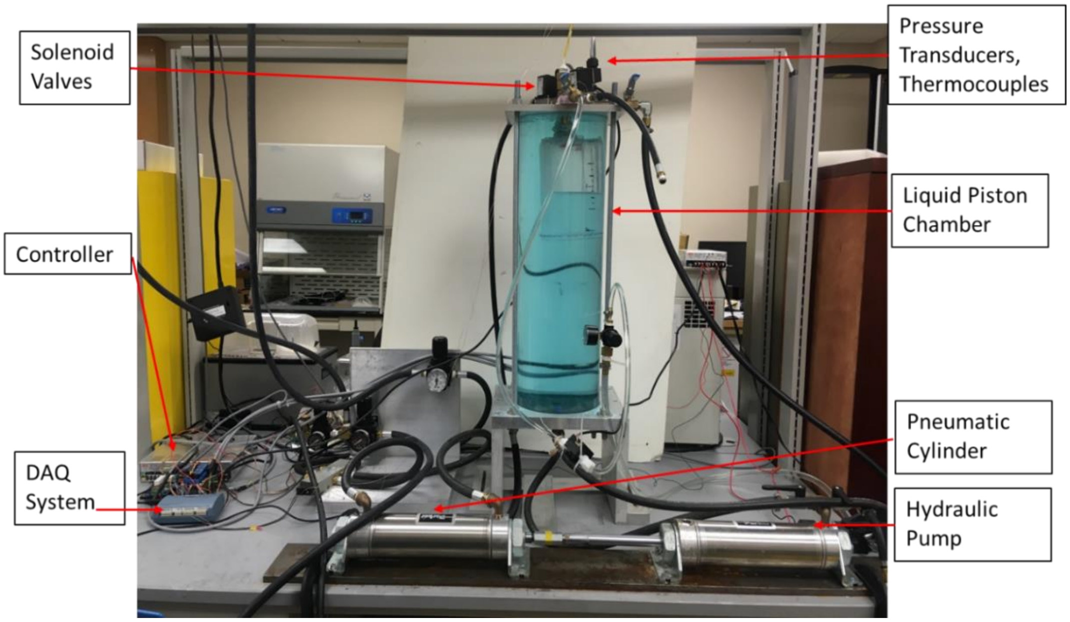

Figure 1: A table-top setup of Liquid piston compressor with spray cooling

3. RESULTS AND DISCUSSION

3.1 Analytical Model

Assuming air to be an ideal gas, and being compressed the thermodynamic equation of state can be given by equation (1).

$$\left(\frac{T_2}{T_1}\right)=\left(\frac{P_2}{P_1}\right)^{\left(\frac{n-1}{n}\right)} \tag{1}$$

As the air is compressed it's pressure increases and the temperature increases as well. If water droplets are introduced during the compression process and heat transfer occurs between the air and the droplets, Coney et al., (2002) presented a modified form of the state equation can be given by equation (2).

$$\left(\frac{T_2}{T_1}\right)=\left(\frac{P_2}{P_1}\right)^{\left(\frac{n-1}{n}\right)}\exp\left[-\frac{ua}{C_p}\left(1-\frac{T_w}{T_1}\right)\Delta t\right] \tag{2}$$

This equation includes the heat transfer from the droplets to the air during the compression process for a time interval Δt. Subscripts 1 and 2 refer to the initial and next time step respectively. T_w is the mean spray temperature, C_p is the specific heat of air in the cylinder, n is the polytropic index, u is the heat transfer coefficient between air and the droplets and a is the droplet surface area per kg of air. If the ua term tends to 0, it refers to the original polytropic state equation while if the ua term is large, then T_2 approaches T_w quickly.

3.2 Experimental Results

Figure 2 shows the pressure in the compression chamber for a single cycle with and without spray injection. The plot shows the compression and intake stroke. The maximum pressure at the end of the compression stroke was observed with the case of no spray injection. On injection of spray during compression, the final pressure reached was lower than that of without spray injection. The final pressure reached decreased with the increase of spray injection pressure and the pressure ratio dropped from 3 to around 2.5 when water spray is introduced. The lower pressure achieved with spray injection was due to the lower temperature reached at the end of the compression period.

The effect of spray injection pressure is shown in Figure 3. In the plots, a single cycle is depicted to discuss the effect of injection pressure. As injection of water spray during compression provides water droplets for heat transfer enhancement, this effect is observed through the compression work and the temperature during the compression process. The polytropic compression curves along with the ideal isothermal and adiabatic polytropic curves are also plotted. The plot shows that the injection of water spray during the compression shifts the polytropic curve towards the isothermal conditions compared to no spray being injected. A trend is observed in a zoomed view of the pressure-volume plot where on increasing the injection pressure towards 70 psi (483 kPa) the curve shifts towards near-isothermal conditions. From the pressure-volume plot, the compression work can also be calculated as the area under the curve. With an injection of water spray, the compression work required reduced compared to compression without any spray injection. However, this shift towards isothermal conditions costs additional pump work for higher injection pressures.

As lower compression work is required at near-isothermal conditions compared to adiabatic conditions, the pressure achieved is lower for the same final volume. From the pressure-volume plot, the polytropic index of compression can also be calculated and is reflected in the isothermal efficiency of compression. Increasing the spray injection pressure changes the polytropic index from 1.25 to 1.09-1.03 at higher injection pressures. This is further used in calculating the isothermal efficiency of compression.

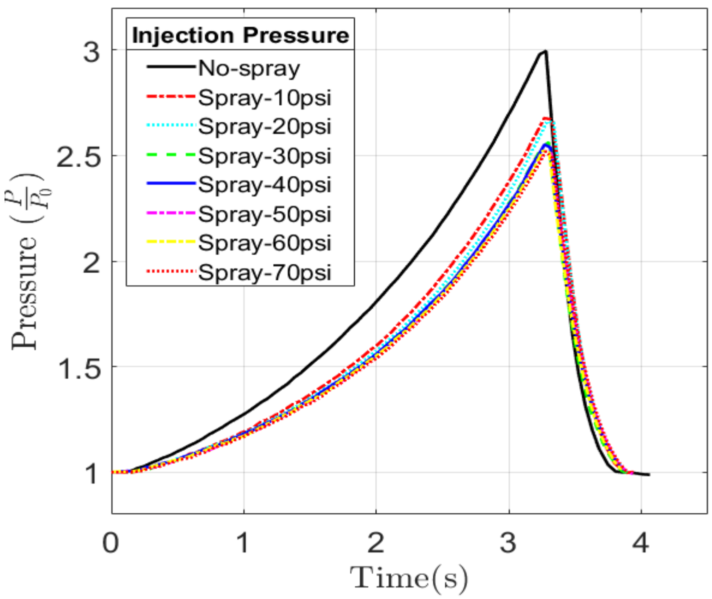

Figure 2: Pressure-time for a single cycle

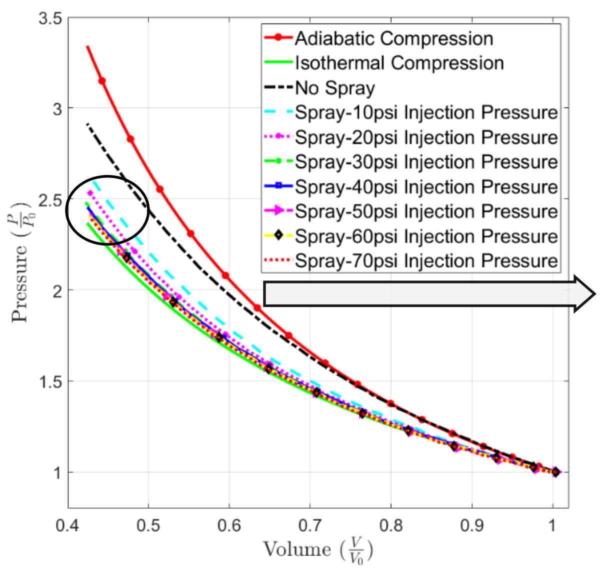

Figure 3: Pressure-volume during compression

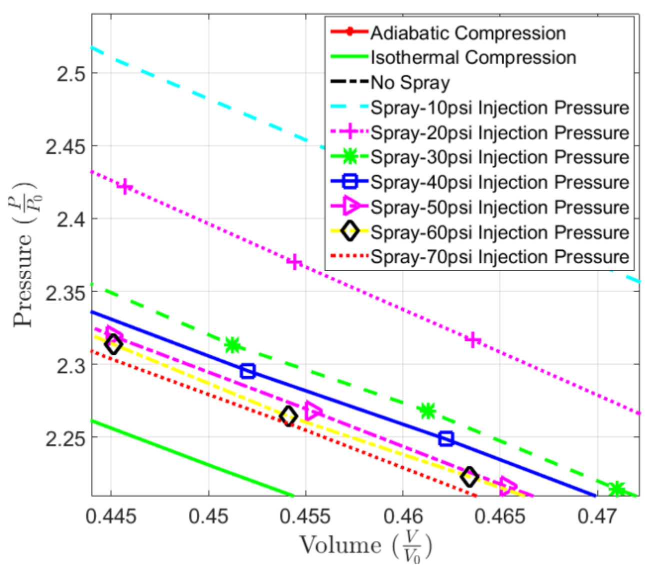

Figure 4: Zoomed view of Pressure-volume plot

Figure 5 shows temperature vs pressure plot with and without any spray injection. From Figure 5 it can be observed that the maximum temperature obtained is without any spray injection. With increasing pressure during the compression process, the temperature increased accordingly. The temperature reached without any spray injection is considerably higher than the temperatures reached with spray injection. On addition of spray of 10 psi (69 kPa) injection pressure, the temperature at the end of compression is not as high during compression without any spray injection, however not as low as with injection pressure from 30-70 psi (206-483 kPa). A temperature drop of 15-20K is observed from no spray injection to injection of spray with varying injection pressures. Similar to the pressure-volume plot, a trend is observed with temperature reducing consistently with increasing injection pressure. This increase in injection pressure increases the flow rate of spray which results in absorption of a larger amount of heat during compression. As a result of higher mass loading and finer droplets being injected, the heat transfer rate increases resulting in a higher temperature drop with higher injection pressure.

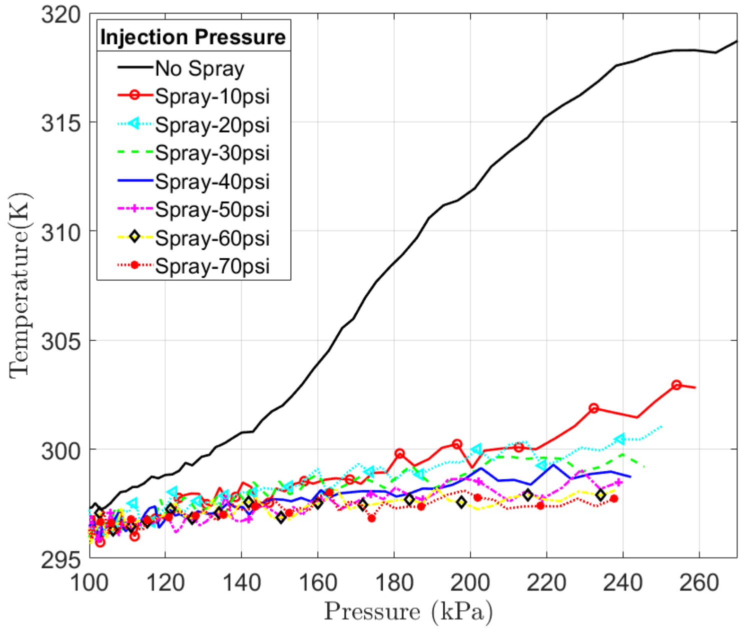

Figure 5: Temperature-pressure plot during compression

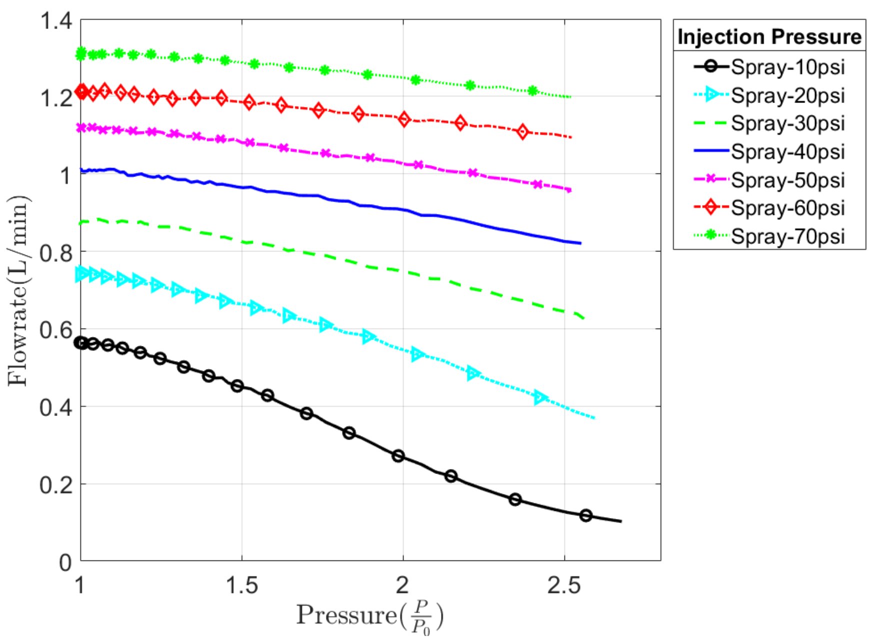

Figure 6: Flowrate of spray water for different injection pressures during compression

The flow-rate for different injection pressure is shown in Figure 6. During the compression process, the flow-rate reduces consistently for all the injection pressures. This is due to the backpressure created on the spray nozzle with the increasing pressure in the compression chamber. This leads to the compression similar to without spray injection towards the end of compression, particularly for lower injection pressures.

Addition of spray injection to a compression process achieved a lower temperature at the end of compression compared to no spray injection. From the pressure-volume plot, the shift towards isothermal conditions and reduction of compression work is observed. The shift towards near-isothermal conditions is also observed from the temperature-pressure plot. A combined parameter such as isothermal efficiency of compression can be used to explain the improvement in temperature reduction for air compressors. For a liquid piston compression process, Patil and Ro (2018) characterized the isothermal efficiency of compression given in equation 3. The isothermal efficiency of compression is given as the ratio of the stored energy to the input work. The stored energy is the amount of isothermal work extracted during expansion of compressed air to the atmosphere. The input work consists of the compression work, cooling work, and the frictional work. For liquid piston compression, the frictional work can be neglected. The cooling work is the work required to cool the system to initial temperature.

$$\eta_C = \frac{\overbrace{\ln\left(P_r\right)+\frac{1}{\mathrm{P}_r}-1}^{\text{Energy Stored}}}{\underbrace{\frac{P_r^{\frac{n-1}{n}}-1}{n-1}+P_r^{\frac{-1}{n}}-1}_{\text{Compression Work}}+\underbrace{\left(P_r-1\right)\left(\mathrm{P}_r^{\frac{-1}{n}}-\frac{1}{P_r}\right)}_{\text{Cooling Work}}} \tag{3}$$

where Pr is the compression pressure ratio and n is the polytropic index of compression.

Figure 7 shows the isothermal efficiency of compression. For each spray injection pressure, the efficiency is calculated using the respective compression ratio achieved. The liquid piston setup has an efficiency of 74-76% with liquid piston compression without any spray injection. It is observed that the increasing the injection pressure of spray increases the isothermal efficiency of compression. The isothermal efficiency reaches a maximum of 94-96 % for injection pressure of 70 psi. The incremental improvement in efficiency reduces after injection pressure of 30 psi (206 kPa). However, a higher spray work is required with an increasing injection pressure of spray which may affect the overall compression efficiency. Further investigations to evaluate and optimize the overall compression efficiency would be needed to find the optimum injection pressure of spray.

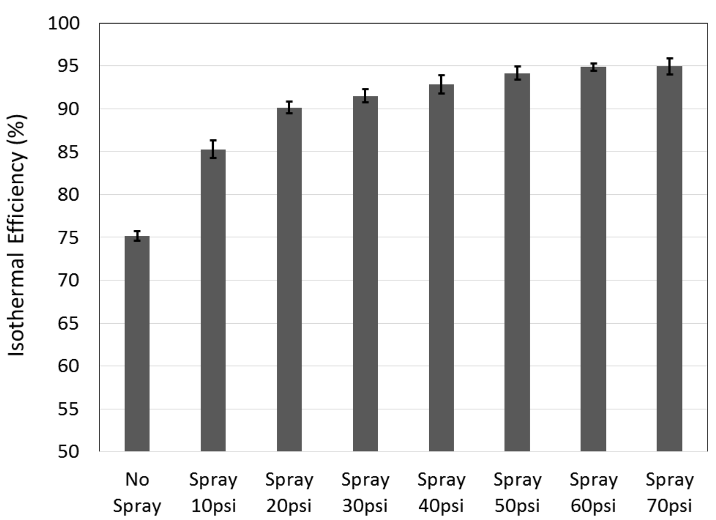

Figure 7: Isothermal Efficiency of Compression

4. CONCLUSIONS

Introduction of water spray cooling during the liquid piston compression process was experimentally investigated for temperature reduction and efficiency improvement. Water sprays with different injection pressures were tested and the flow rate measurement indicated that the flow rate of spray increases with increase in injection pressure. However, during the compression process, the flow rate reduced for each injection pressure towards the end of the compression stroke. Spray cooling was observed to be effective in temperature reduction during the compression process. With varying injection pressures during the compression process, the shift towards near-isothermal compression was observed. This shift was reflected in the reduction in temperature with the temperature dropping 15-20 K near the end of the compression stroke for a compression ratio of about 2.5. Injection of spray even at a low injection pressure of 10 psi (69 kPa) resulted in improvement of isothermal efficiency of compression to 84-86%. Further, higher injection pressures resulted in higher isothermal efficiencies. This incremental improvement in injection reaches a maximum at 94-96%. Further optimization in spray profiles, along with variation in nozzle diameters can be studied for improving the efficiency of the compressor with the use of spray cooling.

NOMENCLATURE

P	Pressure	(kPa)
T	Temperature	(k)
P_r	Pressure ratio	(-)
T_w	Water Temperature	(K)
a	Total droplet area	(m^2)
u	Heat transfer coefficient	($W/m^2.K$)
Δt	Time step	(s)
n	polytropic index	(-)
η_c	Isothermal efficiency of Compression	(%)
C_p	Specific Heat of air	(kJ/kg.K)
DAQ	Data Acquisition	(-)

Subscript

1	Initial time-step
2	Next time-step

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