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QUANTITATIVE VISUALIZATION OF CO_2-OIL MIXTURES IN CO_2 EXPANSION FLOWS

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ABSTRACT

We report the construction of an optically accessible flow test section made of quartz to simulate carbon dioxide flow through throttling devices in refrigeration systems. The existence of traces of lubricant oil (specifically Polyolester (POE)) in the working medium makes the flow amenable to Laser Induced Fluorescence (LIF) diagnostics. The molecular structure of these lubricants is rich in carbon – oxygen bonds which can cause fluorescence when excited by a laser in the near ultra-violet region of the spectrum. This technique was used to visualize the flow of CO_2-oil mixtures through an optically accessible test section under various operating conditions. Upstream pressures as well as oil flow rates are the independent parameters of the experiment. The results of the measurements provide data on the concentration of the lubricant that is entrained by CO_2 in the expansion device as well as information about the form with which the oil is transported through the ejector (liquid films, droplets, mist, etc.). Results from these experiments will guide the design of practical ejector geometries and will also indicate the extent to which various flow models may be employed in the investigation of CO_2 refrigeration systems with ejectors.

1. INTRODUCTION

The recovery of the lost work (destroyed availability) that occurs during a Joule-Thompson throttling upstream the evaporator of a refrigeration facility poses a significant engineering challenge. The practical realization of theoretically proposed expanders, i.e. turbines that would produce power that would in part drive the compressor, involves significant complications with regard to moving parts and appropriate regulation of the power flow in the compressor-turbine cycle (Disawas and Wongwises, 2004).

A significantly simpler idea involves a flow ejector and is outlined in Fig. 1. Flow acceleration in the converging part of the nozzle is used in order to pump the working medium by entrainment whereas the expansion in the diverging part of the nozzle re-compresses the mixture by isentropic deceleration (Elbel and Hrnjak, 2004; Gay, 1931; Butrymowicz *et al.*, 2001). This approach could potentially lead to a 12% increase in COP for R134a (Harrell and Kornhauser, 1995). However, it should be noted that the experiments Harrell and Kornhauser (1995) conducted with R134a have only shown an increase in COP on the order of 5%, mainly due to difficulties in the design of ejectors that would operate as expected in a wide range of flow conditions. The structure of the flows involved remains to a large degree unknown and even the validity of the fluid mechanical assertions made here has not been experimentally verified. The problem becomes particularly exciting for CO_2 refrigeration, since the corresponding thermodynamic potential for COP improvement reaches the order of 45%.

Figure 1: The principle of operation of a refrigerant (CO_2) ejector. (Adapted from Elbel and Hrnjak, 2004)

Additionally, it should be noted that the design of any expansion device for CO_2 refrigeration, such as expansion valves, capillary tubes, or flow ejectors, poses the challenge that the flow is almost trans-critical. Also, of particular importance is the possible presence of compressor oil in the CO_2 working medium during the expansion. The flow of three separate phases (two for CO_2 and one for oil) can significantly affect the flow pattern and therefore the operation of the expansion device by e.g. the formation of oil films that can affect blockage in the relatively small diameter channels involved, or through the formation of mists of oil droplets that can affect flow inertia.

The existence of traces of lubricant oil in the working medium (which is clearly undesirable) makes the flow amenable to Laser Induced Fluorescence (LIF) diagnostics. The molecular structure of typical lubricants (Fig. 2) is rich in carbon – oxygen bonds which can cause fluorescence when excited in the near ultra-violet region of the spectrum (Kang and Kyritsis, 2005). The existence in the molecule of typical lubricants of a high number of C=O bonds is encouraging as to the possibility of extending similar measurements to the field of organic oils.

a. Polyolester (POE)

b. Polyalkylene Glycol (PAG)

Figure 2: Molecular structure of typical lubricant oils for CO_2 refrigeration units

The potential thermodynamic advantages with regard to heating capacity and COP highlighted in detail by Elbel and Hrnjak (2004) with the use of judiciously selected flow models call for a detailed experimental investigation of the flow of the CO_2-oil mixture. Detailed knowledge of the flow across the ejector will indicate the extent to which the employed flow models are justified and the expected thermodynamic advantages that can be realized. Also, visualization of the flow in an optically accessible test section can guide the design of practical ejectors. Our objective is to present an experimental apparatus that allows optical access to CO_2-oil mixture flows through narrow orifices and to present preliminary results on a Laser-Induced-Fluorescence-based technique that can be used for oil concentration measurements.

2. EXPERIMENTAL APPARATUS

Figures 3 and 4 describe the apparatus used for experimentation. The heart of the apparatus is the optically accessible flow test section which is made of quartz and mounted appropriately in a manner that is secure from leaks, is structurally safe, and provides optical access (Fig. 3a). The optically accessible test section of Fig. 3a is a 2 mm ID, 8 mm OD quartz tube that has been shown to take pressure differences of 8 MPa without fracture or leaks. It is realized that this geometry is very simple compared to the geometry of practical injectors but the focus here is on the establishment of the Laser-Induced-Fluorescence based technique.

(a)   **(b)**
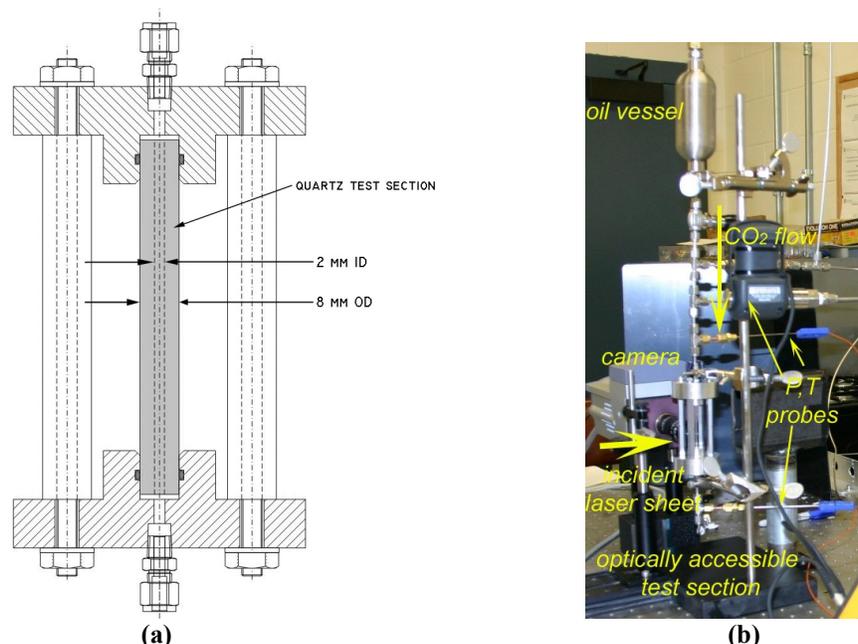
Figure 3: (a) Optically accessible test section, and (b) flow apparatus
(Figure 3a is by Stefan Elbel of UIUC)

A photograph of the flow test section is shown in Fig. 3b and a schematic of the complete apparatus is shown in Fig. 4. Both the inlet and outlet sides of the quartz test section are fitted with pressure transducers (Model 209) and thermocouples (T-Type) that provide pressure and temperature measurements upstream and downstream the cross section. A Coriolis mass flow-meter (CMF025M) is installed upstream of the test section for accurate measurement of the CO_2 density and mass flow. The instrument has been installed in the single-phase CO_2 line so that measurements are taken before the full three-phase (2 phases of CO_2 + oil) flow develops. All of the instrumentation is monitored and recorded through a DAQ board (BNC-2110) and data acquisition software.

Oil is metered from a piston accumulator (A2N0010D3K) that is pressurized with nitrogen at elevated pressure. At this point, measurement of the oil flow-rate, which is an absolute pre-requisite for a well-controlled experiment, is not performed directly and the results will be reported as a function of the differential pressure across the accumulator with which the oil is injected. The apparatus will soon be equipped with a load cell for on-line recording of the accumulator weight and subsequent oil mass-flow rate measurement.

The fourth harmonic (266 nm) of an Nd-YAG laser (PRO-250-10) was used to excite fluorescence from the oil in the mixture. Signal was collected through high pass glass filters in the 280 – 350 nm region using an intensified CCD detector positioned perpendicular to the laser sheet. For all images discussed in this paper, the CCD was set to a gain of 100 and a TTL width of 10 µs. Laser pulses and signal collection was synchronized using a DG535 delay generator. All images obtained are the result of an integration of three consecutive images on the CCD chip.
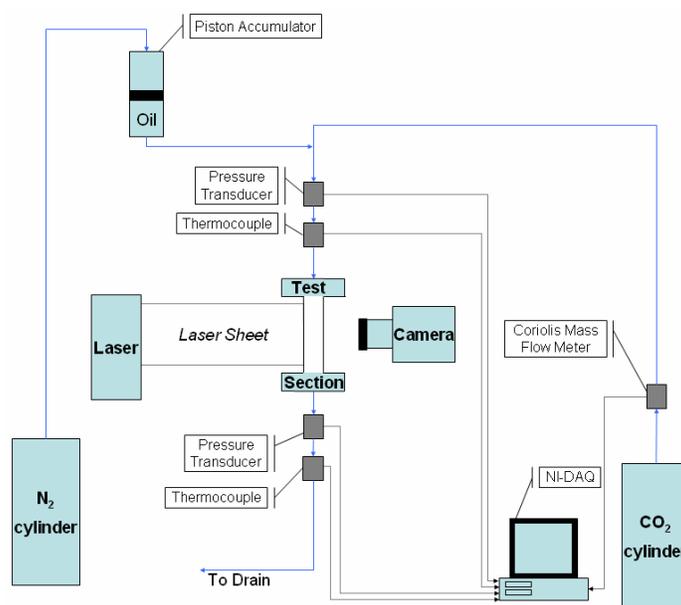
Figure 4: Schematic of experimental apparatus

3. RESULTS AND DISCUSSION

At this phase of experimentation, polyolester (POE) laser-induced-fluorescence signal was measured as a function of injection pressure on the hydraulic accumulator, i.e. of the differential pressure ΔP across the accumulator. CO_2 inlet pressure was maintained at 2.41 MPa and N_2 pressure was varied between 3.03 and 4.00 MPa in order to effectively vary POE flow rate. All other parameters, including upstream and downstream CO_2 pressures and temperatures, CO_2 mass flow rate and laser power were held constant for all POE flow rates. Representative values for these parameters are reported in Table 1. It is realized that the pressures are smaller than the ones encountered in practical CO_2 throttling, but as far as establishment of the optical diagnostic is concerned, operating with smaller number densities is actually a conservative test for the technique.

Upstream P (MPa)	2.41
Upstream T (K)	273 - 283
Downstream P (MPa)	.1
Downstream T (°C)	273-283
CO_2 Mass Flow (g/sec)	~ 8

Table 1: Conditions of operation

Indicative results of POE LIF imaging for three flow rates are presented in Fig. 5, which shows the mostly homogeneous signal the oil mist generates across the tube cross-section. It is interesting to note that under no test conditions were we able to observe either oil films or droplets of substantial diameter in the quartz test section. Given that the spatial resolution of our measurements is 8 μm, it is safe to state that oil nebulizes to very small droplet diameters for the particular conditions presented in this paper. The independent parameter for Figures 5a-b is ΔP, which represents the differential pressure across the accumulator, under which injection is occurring (i.e. the difference in pressure between pressurizing nitrogen and injected CO_2). Furthermore, an increase in POE fluorescence signal as ΔP increases from 1.00 MPa to 1.56 MPa can be qualitatively established, just by visual inspection.
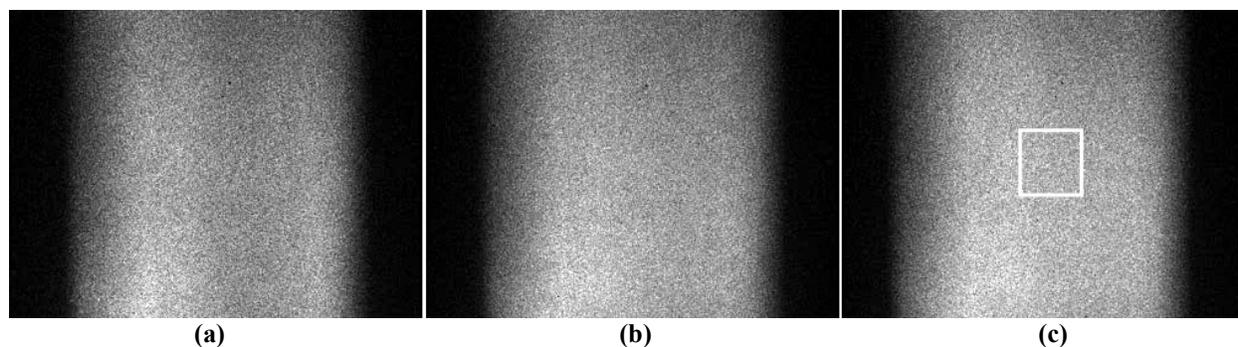
(a)   (b)   (c)

Figure 5: LIF images of CO$_2$-POE mixture in the test section for several values of ΔP. (a) ΔP=1.00 MPa (b) ΔP=1.26 MPa, (c) ΔP=1.56 MPa, also indicates size and location of integration window

In order to acquire a quantitative measurement of relative oil concentration, we assume that the LIF signal is proportional to oil number density, something that requires that the partition function and quenching corrections are negligible. This is not an unreasonable assumption given the low temperatures at which the experiment is taking place (Eckbreth, 1996). Given the homogeneity of the signal from the oil mist, we integrate the signal from a window of 50 x 50 pixels as shown in Fig. 5c. The process is performed using a Matlab code that converts the grayscale intensity values corresponding to each pixel from 16-bit integers to double-accuracy real values ranging from 0 (black) to 1 (white). Comparisons were made of each ΔP value by computing the average signal intensity of all 2500 pixels in the representative sample. Average signal intensity measurements were also taken for the zero oil flow condition to create a zero flow LIF signal intensity baseline for all oil flow conditions. This baseline average LIF signal was subtracted from the average measured LIF signal for each reading taken with oil flowing. These averages, as a function of ΔP, are reported in Fig. 6 below.
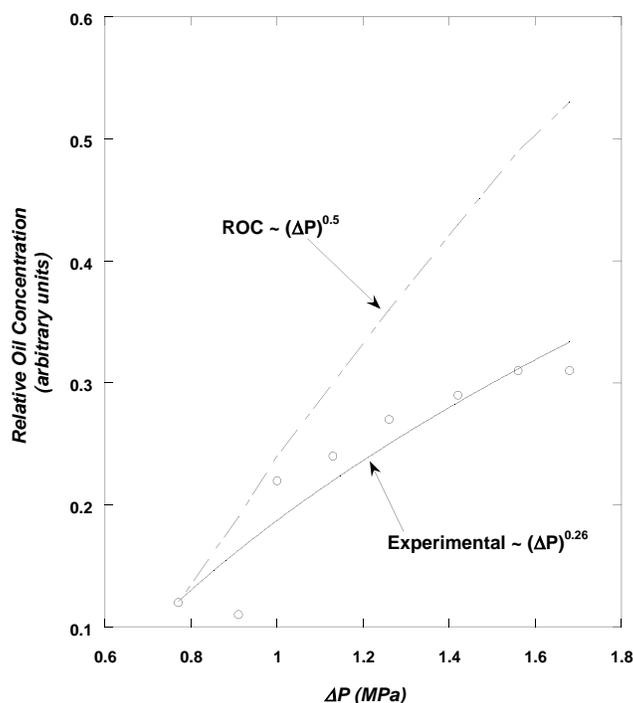

Figure 6: Relative oil concentration as a function of ΔP across the oil accumulator. The dashed line represents the theoretically expected behavior for incompressible flow. The solid line represents an experimental curve fit of the form (ΔP)$^{0.26}$.

It is noted that although simple fluid mechanical arguments for incompressible flow would predict a scaling of the injected amount of oil and therefore LIF signal with $\Delta P^{0.50}$, a $\Delta P^{0.26}$ dependence is instead observed experimentally.

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(shown as the solid line in Fig. 6). This points to the need for an accurate measurement of the oil flow rate and for a thorough investigation of the structure of the flow.

The result reported above is not sensitive to the data processing algorithm. Figure 7 shows that differences on the order of 10% in relative oil concentration exist as the integration window size is varied from a 10 x 10 pixel window to a 100 x 100 pixel window. These relatively small differences confirm quantitatively that nebulized oil mists form that are homogenous across the quartz test section. It is important to note that the five window sizes selected were all centered on the same pixel and were selected to fall well within the ID of the tube, so that interferences to the signal due to stray light reflections from the tube walls are avoided. There is a slight decrease with increasing window size, which should be attributed to large scale inhomogeneities in the oil mist.
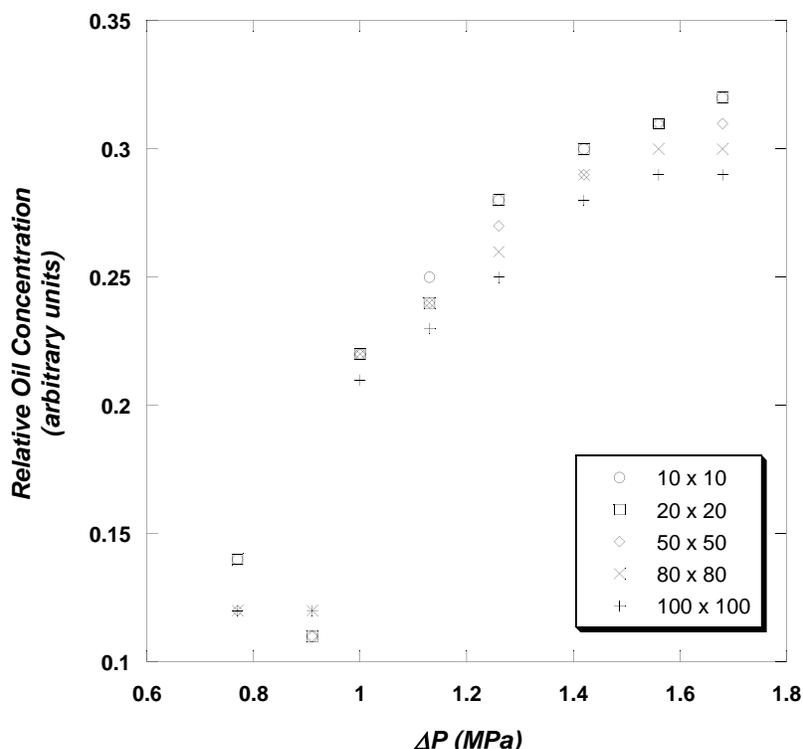

Figure 7: Relative oil concentration as a function of ΔP across the oil accumulator for varying integration window sizes (measured in pixels).

4. CONCLUSIONS

An optically accessible test section was constructed to simulate the flow of CO_2-polyolester mixtures through ejectors. Under all flow conditions established in this experiment, oil flow was only observed as a finely nebulized mist. Under no test conditions were we able to produce droplets of substantial diameter or oil films at the walls of the quartz test section. Oil LIF signal was measured as a difference in pressure between nitrogen pressure in the hydraulic accumulator and CO2 inlet pressure. It was established that this was an inaccurate way to monitor oil flow and an accurate measurement of oil flow rate must be pursued. As a result, further experimentation will proceed using a dynamic load cell that will measure load cell weight as a function of time and signal conditioning software will be used to provide a more accurate indication of oil mass flow. It was also determined that the oil mist is homogenous across the test section, and varying window size does very little to change the outcome of signal processing.

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