Characterization of wire mesh structure for coalescing oil separation

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Abstract. Oil separation is commonly needed in air conditioning or refrigeration systems to reduce the oil circulation rate and keep the oil inside the compressor. For compactness, the oil separation structure integrated into the compressor is more and more popular than traditional external oil separator. This paper presents coalescence, one of the basic mechanisms of droplet separation, studied by quantitative flow visualization and measurements. The misty oil flow through separator is visualized by a high-speed camera and analyzed quantitatively. Oil droplet size and its distribution are determined by video processing. Important flow details are revealed, including oil droplet collision, oil droplet coalescence, oil film breakup and re-entrainment. Separation efficiency is determined as the ratio between drained and incoming oil mass flow rate. Pressure drop is also measured since it is a cost due to separation structures.

1. Introduction

Oil management is one of the critical issues of vapor compression systems. The objective is to keep oil inside the compressor and to reduce oil circulation in other system components. Oil inside the compressor ensure the lubrication, sealing and cooling of the internal components. Oil circulation in the system brings some undesired effect, like lower heat transfer coefficient in most cases and higher pressure drop. In some cases (stratified flow) we have measured an increase in the heat transfer coefficient even at an almost insignificant increase of pressure drop by introducing the wetting effect of oil/refrigerant foam.

Oil flows as a mist after the discharge valve inside the compressor. Zimmermann and Hrnjak [1], [2] captured the opening and closing process of the discharge valve of a scroll compressor. The video showed atomization of oil at the valve and at the mist at compressor exit. A similar distribution trend was observed at higher compressor speed but with smaller oil droplets. After leaving the compressor, the misty oil flow develops in mist-annular when droplets are attached to the annular film [3]–[5]. Techniques have been developed to quantify the mist-annular flow in the compressor discharge pipe in realistic operating conditions. Xu and Hrnjak [6], [7] analyzed the oil flow details in the plenum of a 10 kW scroll compressor. The behavior of oil droplets in the discharge chamber and near the compressor discharge was predicted by CFD simulation. The results were verified at the exit by visualization.

Oil separators are commonly used in refrigeration or air conditioning systems to reduce the oil circulation ratio (OCR). OCR is defined as the mass flow rate of oil divided by the total mass flow rate of the refrigerant-oil mixture in the system. The ideal goal is to remove all the oil from the refrigerant-oil mixture at compressor discharge so that no oil escapes from the compressor and it has no effect on
heat transfer or pressure drop. In reality, the oil separator has a certain separation efficiency (from 0 to 100%), and it introduces extra pressure drop and has its volume as another cost.

Typically, the oil separator is installed between the compressor discharge and condenser inlet, where the refrigerant is in the vapor phase. The separation structure captures the oil, and drain it by gravity. The volume of the oil separator temporarily holds some oil. The oil returns to the crankcase of the compressor when it reaches a certain level. For compact systems, it is more common to integrate some oil separation structure into the extended volume of the compressor discharge chamber.

The oil separator design relies on the understanding of the basic mechanisms of mist elimination. Widely applied in the chemical and process industry, the coalescing separator is a common option to eliminate the mist in the vapor flow. The basic principle of coalescence is that two or more droplets adhere to the structure when the mist passes through a porous media. Coalescing separators include many subcategories, like wire mesh pad, packed column, woven filler, etc. For compressor oil separation, a structure made of wire mesh is the most common.

This paper focuses on the characterization and design of the coalescing oil separator for compressors. First, experimental measurement and flow visualizations are the primary tools to quantify the flow details of a coalescing oil separator. This paper shows the oil-refrigerant mixture flowing through a coalescing oil separator under the condition of relatively low compressor discharge pressure. Images or videos of the interaction of oil mist and the separator help to understand the separation mechanism. The simultaneous measurement of the separation efficiency and pressure drop of separation structures are used to evaluate the performance of different oil separator designs under different incoming flow conditions. The quantitative results help to provide design guidelines for oil separators. In addition, this paper presents a semi-empirical model that explains and quantifies the observed phenomena. This easy-to-implement model provides guidelines for the oil separator design and is validated by the experiments.

2. Methods

2.1. Experimental Setup

An air conditioning test bench is built for this study to quantify the performance of the oil separation structure and capture the video of refrigerant-oil mixture simultaneously (Figure 1). A swashplate reciprocating compressor is the source of oil mist flowing into the oil separator. The swashplate reciprocating compressor is selected because of the ease of control of the OCR in a relatively large OCR range. The speed of the compressor is controlled by a motor and a variable frequency driver. The refrigerant-oil mixture leaving the compressor enters the visualization chamber. Part of the oil is separated and accumulates forming a steady oil level in the draining zone. The structure is placed in the transparent visualization chamber between the compressor outlet and the condenser inlet.

Figure 1. Schematic drawing of the facility
Valves 3 and 4 (shown in Figure 1) control the flow of collected oil from the bottom of the chamber to the suction of the compressor. The mass flow rate ($\dot{m}_{\text{drain}}$) of the returned oil is measured by a Coriolis type mass flow meter 2. Valve 4 is adjusted to ensure that only single-phase oil (liquid) pass the mass flow meter, and the oil level is steady in the system steady state. The steady oil level indicates there is no accumulation or over-draining in the oil level indicator, so $\dot{m}_{\text{drain}}$ reflects the actual draining rate. Refrigerant and the carry-over oil flows through the condenser, expansion valve, evaporator, and finally returns to the compressor.

The mass flow rate of the system ($\dot{m}_{\text{system}}$) is measured by another Coriolis type mass flow meter 1 placed in the liquid line between the condenser and the expansion valve. The OCR is measured by a speed-of-sound type oil concentration meter. The oil concentration meter is calibrated by traditional sampling method [8].

The separation efficiency is the most important performance of an oil separator. In this experimental setup, two separation efficiencies are determined: overall separation efficiency and structure separation efficiency. The overall separation efficiency is defined as the mass flow rate of the actually-separated oil by the whole oil separator divided by the mass flow rate of the oil coming to the oil separator. The overall separation efficiency considers the separation caused by the chamber and the separation structure together. With the measurement of $\dot{m}_{\text{drain}}$ and $\dot{m}_{\text{system}}$, the overall separation efficiency can be calculated by equation (1). Here, $\omega$ is the solubility of refrigerant in the refrigerant-oil mixture, determined by the property correlations by [9]. OCR is the oil circulation ratio measured by the OCR meter in the liquid line.

$$
\eta_o = \frac{\dot{m}_{\text{drain, oil}}}{\dot{m}_{\text{in, oil}}} = \frac{\dot{m}_{\text{drain}}(1 - \omega)}{\dot{m}_{\text{drain}}(1 - \omega) + \dot{m}_{\text{system}} \cdot \text{OCR}}
$$

Compared to the overall separation efficiency, structural separation efficiency is more favorable when we want to compare different separation structures in a specific volume. The structure separation efficiency excludes the effect of the container volume and focuses only on the separation structure itself. It is defined as the mass flow rate of drained oil by the separation structures divided by the total mass flow of oil droplets going to the separation structure. In this project, the structure separation efficiency is determined from the videos taken before and after the filler. The mass flow rate of oil mist before and after the structure are estimated by the sampling videos. The video locations are shown in Figure 2. In this way, the structure separation efficiency is calculated by equation (2). Here the subscript “bs” refers to “before structure” while the subscript “as” refers to “after structure”.

$$
\eta_s = \frac{\dot{m}_{\text{bs, oil}} - \dot{m}_{\text{as, oil}}}{\dot{m}_{\text{bs, oil}}}
$$

Pressure drop is another important measure of performance of the oil separator. A differential pressure transducer is installed to measure the pressure drop across the separation structure. The high-side and low side of the differential pressure transducer are connected to the inlet and the outlet of the separation chamber for visualization.

### 2.2. Flow visualization and video processing

The test section presented in Figure 2 is built by attaching transparent windows to an aluminum frame. One inlet hole and one outlet hole are in the direction of flow while another hole for draining oil is located at the bottom of the frame. Two smaller holes on the top of the block are reserved for connections of the differential pressure transducer. O-rings and gaskets are used to seal the test section and hold the pressure at the compressor discharge. The visualization chamber is designed to provide relatively uniform incoming vapor flow on the cross-sectional area. The design of the test section makes oil mist flow visible, but the disadvantage is that the geometry slightly differs from the typical.
The backlight provides high contrast between the bright background and dark image of the droplets so that the camera can capture the clear video of the oil mist and the details of the separation. Videos of oil mist are taken before and after the separation structure at the steady state. The locations of the video captures are shown in Figure 2 and marked as “video frames”. These videos are then processed to estimate the droplet size distribution and oil volume fraction of the oil mist. Qualitative videos of flow details in the separation structure are also captured to provide a general image of the interaction between the oil droplets and the separation structure. A set of video processing techniques were developed to quantify the videos of the oil mist by [3]. Processed videos of the oil mist before and after the separation structure provide droplet size and velocity distribution as well as liquid volume fraction.

3. Effect of flow conditions

3.1. Test conditions

Each separating structure is tested under the same group of operating conditions. For different conditions, the system mass flow rate changes while the compressor discharge pressure and temperature are maintained at the same level by adjusting the condensing and evaporating capacity. Relatively low temperature and pressure are chosen to reduce the stress at the polycarbonate cover of the visualization chamber. All the measurements are made at steady state. In the transition between steady states, the refrigerant and oil mixture flow in the bypass line. When ready, the flow is diverted through the visualization chamber, so the flow details are captured by the high-speed camera. The test conditions are shown in Table 1.

| Type of refrigerant  | R134a           |
|---------------------|-----------------|
| Type of oil         | PAG 46          |
| Type of compressor  | Swashplate reciprocating |
| With oil sump?      | No              |
| Compressor speed    | 1800 RPM        |
| Mass flow rate      | 6 ~ 20 g/s      |
| OCR before separator| 2 ~ 10%         |
| OCR after separator | 0.5 ~ 1.5%      |
| Compressor discharge pressure | 750 kPa |
| Compressor discharge temperature | 80 °C |

3.2. Refrigerant vapor flow condition

The performance of a particular separation structure is influenced by the vapor flow condition and the characteristics of the oil mist. The actual flow field and the corresponding oil droplet distribution through a coalescer are complex, so we are focused on the overall vapor flow velocity.
The superficial velocity of refrigerant vapor is used to represent the velocity of the refrigerant-oil mixture passing through the separation structure. Vapor superficial velocity is defined as the volumetric flow rate of the refrigerant-oil mixture in the test section divided by the cross-sectional area of the test section, as shown in equation (3). The reason to use vapor superficial velocity instead of mass flow rate as the main variable is that the mass flow rate is strongly affected by the operating condition of the system and compressor type. Conclusions based on vapor superficial velocity are more generalizable so that they can be applied in oil separation for different compressors and fluids. In the plots below, the mass flow rate of the system is also plotted in the secondary horizontal axis as a reference.

\[ u_{vs} = \frac{m_{\text{system}} (1 - \text{OCR})}{\rho_v A} \]  

(3)

3.3. Oil mist characteristics

The oil ejected by the compressor forms annular-mist flow in the discharge pipe before it enters the separation chamber. Since the main target of the separation is the oil mist, a straightforward way to evaluate the separation performance is comparing the oil mist entering and leaving the separator. Comparing two video frames before and after the separation structure in Figure 3, show that lesser number of oil droplets appear in the video of oil mist leaving separator than that in the video of oil mist entering separator, which means some oil droplets are collected and drained to the bottom of the chamber or droplets are larger.

The droplet size distribution provided by the video processing is shown in Figure 3. The droplet diameter of the oil mist follows the log-normal distribution. It is not surprising to see the total mass flow rate contributed by the oil mist decreases after the oil mist passes through the coalescer. Also, the mean droplet diameter becomes smaller when the oil mist passes through the coalescer, which indicates that bigger oil droplets are easier to be separated.

Though the droplet size distribution can explicitly describe the oil mist before or after the separator, it contains too much information for a simple comparison between two operating conditions. We can use the oil droplet volumetric mean diameter as a more concentrated parameter to represent the oil mist characteristics at one particular flow condition. There are many ways to calculate the mean diameter of a group of oil droplets. We use the volume mean diameter. The volumetric mean diameter is a representative description of the size of the oil droplets considering the droplet volume.

Figure 4 shows the effect of system flow rate (vapor superficial velocity) on the oil droplet mean diameter of the benchmark (BM) coalescing structure (geometric specification listed in Table 2) at vapor superficial velocity of 0.27 m/s
mean diameter of the oil droplets after the coalescer is smaller than that before the coalescer, as visible in Figure 3. This is because the separation also happens when smaller droplets coalesce into bigger droplets and bigger droplets tend to deviate from the vapor flow and settled down to the bottom. The sampling video after the coalescer captured the escaped small oil droplets.

Besides the oil droplet size, the oil mass flow rate also changes as the system mass flow rate changes. The effect of vapor superficial velocity on the oil mass flow rate is shown in Figure 5. The oil mass flow rate entering the separation chamber increases as the vapor velocity increases. The majority of the oil coming into the separator is separated and drained back to the compressor suction, and the rest is carried over by the refrigerant vapor. The ratio of the drained oil and the total incoming is the separation efficiency. It indicates that separation efficiency decreases as the vapor velocity increases though the amount of separated oil slightly increases.

The OCR (oil circulation ratio) in the system rises with the increase of refrigerant flow rate but the OCR before the separator decreases. OCR is the oil mass flow rate divided by the refrigerant-oil mixture mass flow rate. The OCR before the oil separator decreases because the denominator (system mass flow rate) increases faster.

Overall, the refrigerant-oil mixture entering the oil separator shows the following trends as the system mass flow rate getting higher: 1) Refrigerant vapor superficial velocity increases; 2) Mass flow rate of oil rises; 3) Number of oil droplet in a specific volume for a certain period of time increases; 4) Oil droplet volumetric diameter decreases.
3.4. Separation efficiency and pressure drop

Figure 7 shows the separation efficiency of the benchmark structure as a function of vapor superficial velocity and system mass flow rate. Both overall separation efficiency and structure separation efficiency are measured and presented in the chart. The uncertainty of the overall separation efficiency is significantly smaller than that of the structure separation efficiency and shown by the vertical error bar in Figure 7. So, we will use overall separation efficiency as the only separation efficiency to discuss in the following sections.

The separation efficiency drops as the vapor superficial velocity increases. As mentioned previously, the flow parameters of refrigerant and oil are coupled. Higher vapor superficial velocity also brings higher oil fraction and smaller oil droplets. Therefore, the trend of separation efficiency can be explained in three aspects. First, refrigerant vapor with higher vapor velocity may blow off the captured oil from the wire. Some oil ligaments break into smaller droplets due to the kinetic energy introduced by the refrigerant vapor. Second, higher oil volume fraction before the separator means higher loads for separation. If the separator is saturated, the separation efficiency may decrease. Third, smaller oil droplets tend to follow the streamline of the vapor and are generally more difficult to capture.

Besides extra volume and components to the system, the pressure drop is the main cost of introducing an oil separator. Figure 8 presents the pressure drop of different wire mesh pads plotted against the vapor superficial velocity. The overall pressure drop includes both the pressure drop introduced by the inlet and outlet of the separation chamber and the pressure drop by the coalescing structure. The base pressure drop is the pressure drop measured when the separation chamber is empty. Here we assume the pressure drop is only contributed by the chamber inlet/outlet and the structure. So, the structural pressure drop is calculated by deriving the base pressure drop from the overall pressure drop.

As expected the pressure drop increases as the velocity of the vapor phase increases. By linking separation efficiency to pressure drop, it is obvious that a separator with higher separation efficiency usually generates higher pressure drop. This indicates a trade-off between separation efficiency and pressure drop, important in the design of oil separators.

4. Effect of separator design

4.1. Geometric specification

Three independent geometric parameters are chosen to evaluate the effect of geometry on the performance of the coalescers: 1) wire diameter ($d_w$), 2) pad thickness ($H$) and 3) solid fraction ($s$). Figure 9 shows the key geometric parameters of a wire-mesh coalescer used in this study.

![Figure 9: Key geometric parameters of a wire-mesh coalescer](image)

The diameter of the wire mesh pad also represents the minimum characteristic length of the separation structure. In the wire-scale view of Figure 9, ‘$d_p$’ is the mean size of the pore and ‘d’ is the diameter of the oil droplet.
The pad thickness (the dimension along the vapor flow direction of the apparent volume occupied by the wire mesh pad) determines the number of effective layers further affects the separation efficiency and pressure drop.

Solid fraction is a parameter to evaluate the density of a wire mesh pad. As shown in equation (4), it is defined as the ratio between the volume of solid wire and the total volume it occupies. The total occupied volume is given by the product of the cross-sectional area facing the flow \((A)\) and the thickness along the flow direction \((H)\). For a coalescing oil separator, a typical solid fraction value is 1 to 5%. In the experiments, the total volume of the solid wire \((V_w)\) can be determined by the weight of the wire and the density of the material (stainless steel 304 in this study).

\[
s = \frac{V_w}{AH} \quad (4)
\]

Seven different wire mesh geometries are tested in this study. The benchmark geometry is chosen as a reference of other geometries. Three pairs of wire mesh pads are tested to evaluate the effect of different geometric parameters. For example, “d−” represents a wire mesh pad with a smaller wire diameter but the same solid fraction and the same thickness. “s+” represents a wire mesh pad with a larger solid fraction but the same wire diameter and the same thickness. All the other geometries have a similar nomenclature. These geometries are tested in the same set of test conditions to study the effect of different geometric specification independently. The details of these wire mesh pads are listed in Table 2.

| Structure name | Wire diameter \(d_w\) (mm) | Solid fraction \(s\) (%) | Thickness \(H\) (mm) |
|----------------|----------------------------|-------------------------|--------------------|
| Benchmark (BM) | 0.178                      | 2.81%                   | 50                 |
| d−             | 0.152                      | 2.81%                   | 50                 |
| d+             | 0.279                      | 2.81%                   | 50                 |
| s−             | 0.178                      | 1.53%                   | 50                 |
| s+             | 0.178                      | 3.64%                   | 50                 |
| H−             | 0.178                      | 2.81%                   | 25                 |
| H+             | 0.178                      | 2.81%                   | 100                |

4.2. Effect of different geometric parameters

Flow condition entering the separator has a significant impact on the performance of a coalescing oil separator. The upstream flow is mainly determined by the compressor working condition. Therefore, for the design of oil separator, we put most of our effort in the geometry design to fit this condition. This section discusses the effect brought by different geometric feature for seven different wire mesh pads tested in this study.

The effect of the wire diameter can be derived from the comparison of the separation efficiency and pressure drop of ‘BM’, ‘d−’ and ‘d+’. As shown in Figure 10, each separator geometry is tested under five different working conditions from low vapor velocity to high vapor velocity (high system mass flow rate).

Higher system mass flow rate increases superficial vapor velocity and more but smaller oil droplets. As a result, the separation efficiency decreases and the pressure drop increases as the vapor velocity increases, for all the separating geometry. When the solid fraction is kept the same, reducing the wire diameter means increasing the surface area and increasing the probability that droplets can be captured. Therefore, the separation efficiency of ‘d−’ is higher than that of ‘d+’. Expansion of surface area also adds to the friction to the flow, so the pressure drop of wire mesh pad with thinner wire diameter is larger than that of thicker wire.
The effect of the solid fraction can be observed by comparing structure ‘BM’, ‘s’- and ‘s’+, as shown in Figure 11. By comparing these three geometries, it can be concluded that the separating structure with higher solid fraction has a higher separation efficiency and a higher pressure drop if the thickness and wire diameter are controlled to be the same. Also, there is a threshold of the solid fraction above which the separation efficiency gain is not very significant.

The effect of the thickness can be concluded by comparing structure ‘BM’, ‘H’- and ‘H’+. Additional thickness to the coalescer means more layers available to capture the droplets along the flow direction. Figure 12 shows the increment of thickness is beneficial to the separation efficiency. Also, the pressure drop increases as the pad get thicker, as we would intuitively expect.

Overall, it can be concluded that reducing wire diameter, increasing solid fraction and adding coalescer thickness can increase the separation efficiency but also introduces extra pressure drop. Figure 13 is a “design map” that plots the separation efficiency and pressure drop of seven coalescing separators at a low-vapor-velocity condition ($u_{vs} = 0.2 \text{ m/s}$) and higher-vapor-velocity condition ($u_{vs} = 0.4 \text{ m/s}$). The data points are calculated from the extrapolation of the separation efficiency and pressure drop as functions of the vapor superficial velocity. In this map, the upper left corner is the best design, where
separation efficiency is high, and the pressure drop is low. The lower right corner is the opposite. When the vapor superficial velocity gets higher, the overall performance of the coalescer gets worse. This trend is shown graphically in Figure 13 as the data points moving from the upper left towards the lower right. By comparing the performance of different geometries under the same flow condition, it can be concluded that the separation efficiency is positively correlated with the pressure drop of a particular structure. In other words, there is no shortcut that can increase the separation efficiency and decrease the pressure drop simultaneously by changing geometric features only.

5. Summary

This paper focuses on the analysis of the coalescing structure used as an oil separator. Experimental measurement and flow visualization are used to analyze the oil mist flowing through the structure under realistic compressor discharge conditions. Flow visualization provides flow details of the oil mist entering and leaving the oil separator, including droplet size distribution and droplet mean diameter.

Experimental data also show that separation efficiency decreases when vapor velocity increases. This trend can be explained by the fine atomization, high oil flow load and elevated probability of re-entrainment under higher vapor velocity. Pressure drop introduced by the separation structure increases as the vapor velocity increases.

For different oil separator geometries under the same flow conditions, denser separation structure provides better separation efficiency at the cost of more significant pressure drop. For a certain flow cross-sectional area, three independent parameters can be used to describe the geometry of a certain wire mesh separator: wire diameter, solid fraction and thickness. Tuning these parameters can achieve a balance between the separation efficiency and the pressure drop. The comparison of different geometries also indicates that few designs can achieve high separation efficiency and low pressure drop at the same time without changing the volume.

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