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Flow visualization and CFD simulation of impinging oil separator for compressors

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ABSTRACT

Oil is needed for most of the compressors in HVAC industry but oil circulating in the system is unfavorable for the heat exchanger performance and cycle efficiency. A common solution for the oil issue is separating oil at the compressor discharge and returning it back to the compressor. For compactness, oil separation structure integrated into the compressor is more and more popular than traditional external oil separator. Therefore, analytical tools and design guidelines of oil separation structure is important, especially for irregular geometry and realistic flow condition at the compressor discharge. As one of the major mechanisms of droplet separation, impinging separation mechanism is studied by flow visualization and CFD simulation in this paper. The video of oil mist flowing through the baffles and plates is captured by a high-speed camera and analyzed quantitatively. CFD simulation is carried out for investigating the flow field and performance of impinging separator. Refrigerant vapor is calculated in the first step and discrete phase model is used to track the droplet movement in the second step. Droplet size distribution and overall separation efficiency are used to validate the CFD simulation results. Both flow visualization and CFD simulation provide useful tools for oil separator design. The results and conclusions from this study give useful guidelines about how to reduce the oil circulation ratio by designing better oil separator for the compressor.

1. INTRODUCTION

Oil separators are commonly used in refrigeration and air conditioning system to ensure the system performance. The role of the oil separator is to remove oil droplets from the refrigerant vapor and return it to the compressor. It is usually installed between the compressor discharge and the condenser inlet. For systems that have compactness requirement, it is more common to integrate oil separation structure into the extended volume of the compressor. To design a good oil separator, engineers need the knowledge of the characteristics of the oil flow at the compressor discharge, basic mechanisms of oil droplet separation and the performance of different separation structures under different working conditions.

Oil flow at the compressor discharge is visualized and identified as oil mist by many researchers. (Toyama et al., 2003; Zimmerman and Hrnjak, 2014; Xu and Hrnjak 2017). The visualization results show the break-up of oil film and formation of oil mist due to periodic motion of discharge valve. The generated oil droplets are entrained by the compressed refrigerant vapor and moving in all directions in the discharge plenum. Some oil droplets deposit on the wall and form a layer of the oil film. Smaller oil droplets may be generated after the interaction between the droplet and oil film. After leaving the compressor plenum, the oil flow is identified as developing mist-annular flow in the discharge pipe by Wujek and Hrnjak (2011). A set of tools has been developed to quantify the mist-annular flow in the compressor discharge pipe in realistic working conditions.

Known as the main separation object is the oil mist, the basic mechanisms of droplet separation are the next main issue. Though different technical terms are used in literature, the author concludes the mechanisms as three main type: coalescence, impingement, and centrifugation. Coalescing separators are usually made of wire mesh or fiber filter, performing well in relatively low vapor phase velocity, but their performance will decrease when re-entainment takes place. The coalescing separator can typically capture much smaller droplets than the other two mechanisms. Impinging separators are a combination of baffles in different shapes that allow vapor flow pass through but block the liquid droplets by inertia. Impinging separators suffer less from the re-entrainment problem so that a wider range of mass
flow rate that can be handled. Centrifugal separators are cylinder-shaped or cone-shaped with tangential or axial inlet and axial outlet. Centrifugal separators are widely used in processing engineering due to its capability to separate at different working conditions. In this paper, we focus on impinging mechanism, especially the performance of impinging separator for compressor application.

To fit the needs of oil separation in air conditioning and refrigeration application, we should consider the realistic compressor geometry and working condition. Xu and Hrnjak (2016a, 2016b, 2017) analyzed the oil flow details in the plenum of a scroll compressor. With the help of CFD simulation, the behavior of oil droplets near the compressor discharge was predicted and the result was verified by experimental measurement. The numerical tool provides an approach to simulate the oil droplets for different geometries of the compressors under different working conditions so that oil separation structure can be designed accordingly.

The purposes of this paper are covered in three aspects. First, use visualization techniques to capture the flow details of oil droplet impinging on the solid surface under the realistic compressor working conditions. Second, measure simultaneously the separation efficiency, pressure drop, droplet size distribution before/after the separator in the realistic vapor compression cycle; Third, simulate the droplet separation by CFD model to predict the performance of different structures and verify the simulation with experimental measurements.

2. FACILITIES AND METHODS

2.1 System facilities

The facilities for experiments are built based on an automotive air conditioning system test bench (Figure 1). A swashplate reciprocating compressor, driven by a variable speed motor, is the source of oil mist coming into the test section of oil separation. A visualization chamber is installed as the test section between the compressor and the condenser. Separation structure of various geometries is integrated into the chamber for the test. Valve 1 and 2 are used to control the flow of collected oil from the bottom of the separator to the suction of the compressor. A mass flow meter in the oil return pipe measures the mass flow rate of drained oil ($\dot{m}_{\text{drain}}$). Valve 1 and 2 are adjusted so that only single-phase oil will pass the mass flow meter. Valve 3 to 6 are used to switch between the visualization chamber and the bypass line. In the transition between system steady state, the refrigerant and oil mixture flow in the bypass line. At the steady state, the flow goes through the visualization chamber and the flow details are captured by a high-speed camera.

![Figure 1: Facilities for oil separation visualization and measurement](image)

To ensure the conclusion can be applied to different compressor applications, the mass flow rate of the system is varied from 8 g/s to 20 g/s. In the liquid line between the condenser and the expansion valve, the mass flow rate of the system ($\dot{m}_{\text{system}}$) is measured by a Coriolis type mass flow meter and the oil circulation ratio (OCR) is provided by a speed-of-sound oil concentration meter. The oil concentration meter is calibrated by comparing with sampling method according to ASHRAE standard 41.4. As shown in Figure 2, OCR value measured by oil concentration meter agrees well with that measured by sampling method.

After measuring the key parameters, separation efficiency can be calculated by equation (1). Here $\omega$ is the mass fraction of refrigerant in the refrigerant-oil mixture, which can be calculated by property correlations.
Tests were carried out in different compressor discharge temperature and pressure conditions and the results did not show a significant difference. In other words, the separation performance and pressure drop are not very sensitive with temperature variation (from 70 to 90 °C) and pressure variation (from 700 to 1000 kPa). In this study, the discharge pressure is maintained at 700 kPa and the discharge temperature is maintained at around 75 °C. Relative low temperature and pressure are chosen because the durability of polycarbonate cover of the visualization chamber decreases as the temperature and pressure increase. Besides the absolute pressure and temperature at the discharge side, the pressure drop between the inlet and outlet of the visualization chamber is also measured by a differential pressure transducer.

2.2 Flow visualization setup

Flow visualization is realized by capturing video of the oil mist inside the test section, assembled with an aluminum frame and transparent window (Figure 3). Two transparent windows are installed symmetrically on both sides of the aluminum body. One inlet hole and one outlet hole are located in the direction of flow while another hole for oil drainage is located at the bottom. Two smaller holes on the top of the block are reserved for differential pressure transducer connections. 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 flow in the cross-sectional area. This makes it possible for visualization but brings the potential difference between test geometry and real geometry.

To capture the clear video of the oil mist and the details of the separation, a LED pad is used as the backlight. It provides high contrast between the bright background and dark image of the droplets (shown in Figure 3). Videos of oil mist are taken before and after the separation structure at the steady state of the system. These videos are then processed to estimate the droplet size distribution and oil volume fraction of the oil mist. The flow of oil mist passing through the impinging oil separator is also captured to characterize the interaction between the oil droplets and the solid surfaces.

Video processing techniques developed by Wujek and Hrnjak (2011) are used to quantify the videos of the oil mist flow. The video processing program is briefly described in following steps. First, eliminate the wave pattern by subtracting the average pixel value in the period of time. Second, estimate the droplet size by identifying the boundary of the droplets. The boundary is determined by steepest grayscale gradient and modification of focal distance. Third, compare two consecutive images in small sections to interrogate potential displacement. Last, calculate the droplet size distribution and the droplet velocity distribution of the droplet bulk by processing thousands of frames.
In this study, videos of oil mist before and after the separation structure are processed to get the droplet size distribution and liquid volume fraction of a cluster of oil droplets. By quantification of the oil flow videos, droplet size distribution, droplet velocity distribution and liquid volume fraction can be obtained for further analysis. Detailed results will be shown in later sections.

2.3 Specification of separation structures

Three transparent wave plates prototypes are tested under the same set of compressor discharge conditions. The prototypes are made of an optically clear resin called WaterClear Ultra 10122 by Stereolithography. The wave plates are then attached to the top inner wall of visualization chamber for test and visualization. The details of the wave plates are listed in Table 1. As shown in Figure 4, the plate length $l$ defines the distance between two neighboring bends; the gap width $w$ defines the distance between two zigzag plates; the bend angle reflects the direction change of the flow. Gap width and number of bends are selected as the main variables here because they have a stronger effect on the final performance than other parameters, according to Wilkinson (1999).

<table>
<thead>
<tr>
<th>Plate length $l$ (mm)</th>
<th>Gap width $w$ (mm)</th>
<th>Bend angle ($^\circ$)</th>
<th>No. of bends</th>
<th>No. of channels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wave plates A</td>
<td>8</td>
<td>1.2</td>
<td>80</td>
<td>11</td>
</tr>
<tr>
<td>Wave plates B</td>
<td>8</td>
<td>2.1</td>
<td>80</td>
<td>7</td>
</tr>
<tr>
<td>Wave plates C</td>
<td>8</td>
<td>3.0</td>
<td>80</td>
<td>3</td>
</tr>
</tbody>
</table>

Figure 4: Geometry specification and actual prototype of the wave plates

3. FLOW VISUALIZATION

3.1 Qualitative observation of separation
Oil droplets injected by the compressor discharge valve are entrained by the refrigerant vapor flow and enter into the discharge pipe. The job of impinging oil separator is to block some of the oil mist and drain the oil down to the bottom. Figure 5 shows the video frame at four different locations of an array of wave plates: in the middle of the 1st bend, in the middle of the 5th bend, at the bottom of the 1st bend, at the bottom of the 5th bend. Figure 6 shows the corresponding oil mass flow crossing the wave plates.

Oil droplets enter the array (ṁ_in) and many of them hit the bend wall because of inertia. Some oil droplets are swift enough to follow the streamline of vapor flow and pass through the separation structure, as marked as ṁ_pass. Captured oil droplets (ṁ_capture) form the oil film and part of the oil film drains to the bottom (ṁ_drain) of the separator chamber, as it is shown in the bottom two video frames. However, not all the captured oil will stick to the solid surface and drain easily. High-velocity vapor flow shear makes the oil film on the wave-plate wall to form oil droplets, which is called re-entrainment (ṁ_entrain). Also, at the bottom of the oil separator, drained oil droplets or ligaments can also be brought back to the vapor flow. The dynamic balance between all these mass flow decides the performance of the wave plates oil separator.

When comparing the video in the middle of the 1st bend and that in the middle of the 5th bend, it can be concluded that more oil droplets need separation in the bend closer to the oil flow inlet. This means the first bend faces a heavier burden to separate the droplets than the bend after it. Therefore, adding volume to the separator can increase the separation efficiency.

**Figure 5:** Qualitative observation of oil mist passing though the wave plates

**Figure 6:** Mass flow of oil mist around a wave-plate separator
3.2 Oil mist before and after the separator

The videos of oil entering or leaving separator are captured and provides more detailed parameters of the oil mist. As shown in Figure 7, less oil droplets appear in the video of oil mist leaving separator than that in the video of oil mist entering separator. The comparison between oil mist videos shows that a large portion of oil droplets are separated and drained. Furthermore, the droplet size histogram indicates that larger oil droplets are easier to separate while smaller oil droplets tend to follow the vapor flow and pass through between the gaps of wave plates.

![Figure 7: Video samples and corresponding oil droplet size distribution before/after the separator](image)

4. CFD SIMULATION

4.1 CFD setup

Discrete phase model (DPM) is commonly used to simulate one fluid or solid particle dispersed in another continuous fluid phase in a Lagrangian frame of reference. An important preliminary assumption made in the discrete phase model is that the dispersed phase occupies a low volume fraction. In oil separator case, the oil volume ratio of the oil-refrigerant mixture in the discharge pipe is estimated to be less than 5%. Therefore, the condition of oil mist at the compressor discharge pipe satisfies the assumption of the discrete phase model.

To simulate the movement of oil droplets, we use the Euler-Lagrange approach. The vapor phase is treated as a continuum by solving the time-averaged Navier-Stokes equations, while the dispersed phase is solved by tracking many droplets through the calculated flow field. The dispersed phase can exchange momentum with the fluid phase. Mesh independence is also carried out to achieve a balance between discretization error and calculation time.

Discrete phase is introduced in the simulation by defining an injection at the inlet of the test section. As shown in Figure 8, the internal volume of the test section is extracted as the flow region for the refrigerant-oil mixture. The injection is set as a group of droplets with the particular sizes flowing at the same velocity. The droplet size distribution is given by video processing results and the vapor velocity is given by the superficial vapor velocity in the inlet pipe of the test section.

The boundary condition for the vapor phase at the inlet is set as the velocity inlet, using the superficial vapor velocity calculated by system mass flow rate as the reference. For the discrete phase, boundary conditions are categorized into four types: trap, escape, reflect and wall film. Trap condition means that the droplet will be absorbed by the wall while escape condition allows the droplets to pass through when they hit the boundary. A reflect wall will give an opposite velocity vector to the incoming droplet based on momentum balance. Wall-film model is the most realistic case, which allows a single component liquid droplet to impinge upon a boundary surface and form a thin film. For the CFD simulation carried out in this study, the boundary condition of the bottom surface of the geometry is set as "trap". All other surfaces, including the surface of the wave plates, are set as wall film.

The effect of turbulence is considered using Reynold-stress model. The simulation takes SIMPLE as the scheme and uses second order for pressure discretization and second-order upwind for momentum discretization.
4.2 Preliminary simulation results
Steady state simulation is carried out with three different geometries under two different mass flow rates. The preliminary CFD results are shown in Figure 9 and Figure 10. Figure 9 shows the trajectory of discrete phase colored by the droplet Sauter mean diameter in the corresponding cells. Figure 10 shows the trajectory of discrete phase colored by droplet velocity magnitude. Oil droplets enter the separator region together without too much interaction with each other. This can also be verified by our visualization results. Droplets start to deposit on the surface of wave plates and the mean diameter of the droplets gets larger after the impingement. From the side view, it can be seen that larger droplets tend to settle down and fall to the bottom due to gravity. The simulation results show more details of the oil mist flow and it is supported by our observation through high-speed videos.

Figure 8: CFD simulation setup on the fluid region of the test section

Figure 9: Droplet track in the visualization chamber colored by droplet Sauter mean diameter

Figure 10: Droplet track in the visualization chamber colored by velocity magnitude
5. RESULTS

5.1 Separation efficiency
Separation efficiency is the most important parameter of an oil separation structure. Figure 11 plots both experimental and CFD results of the separation efficiency of wave plates tested. Here vapor superficial velocity is used as the main variable. 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. The reason to use vapor superficial velocity instead of mass flow rate as the main variable is that mass flow rate is strongly affected by the system working condition 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 systems.

From Figure 11, it can be concluded that separation efficiency drops as the vapor superficial velocity increases. This can be explained by the re-entrainment effect. Refrigerant vapor with high velocity tends to entrain the oil film back to the vapor mainstream. Some oil ligaments break into smaller droplets due to the kinetic energy introduced by the vapor.

When comparing the separation performance of different wire mesh pads, wave plates A has a better separation efficiency than wave plates B and C. This is because wave plates A has smaller gap width and more bends. Also, CFD simulation was carried out for three geometries under two different vapor velocities. The simulation results agree well with the experimental measurement.

![Figure 11: Separation efficiency of three different wave plates by experimental results and CFD simulation](image)

5.2 Pressure drop
Pressure drop is the main cost of introducing an oil separator if we consider the effect on the performance of the whole vapor compression cycle. As shown in Figure 12, the pressure drop of three wave plates is plotted as the function of vapor superficial velocity. In general, it is intuitive to see the pressure drop goes up with the vapor velocity.

To compare the same separator at different flow conditions, the pressure drop increases as the velocity of vapor phase increases. When comparing different separators under the same flow condition, the pressure drop of a denser separator (wave plates A) is larger than that of a sparser separator (wave plates C).

If we put the pressure drop and corresponding separation efficiency together, we can conclude that a separator with higher separation efficiency usually cost more pressure drop. This indicates a trade-off between separation efficiency and pressure drop for the design of oil separators.
6. CONCLUSIONS

Oil separators are important for the oil management and system performance of air conditioners and refrigerators. Flow visualization and CFD simulation are applied to characterize the refrigerant-oil mixture in the oil separators. Flow visualization provides a qualitative observation of oil flow mass balance in the separation. Oil mist before and after the separator is further analyzed with more details like droplet size distribution and droplet mean diameters. CFD simulation based on discrete phase model is developed to predict the trajectories of oil droplets. The boundary of both vapor phase and discrete phase are specified to consider the interaction between oil droplet and oil film on the wall. The CFD simulation is later verified by separation efficiency and pressure drop measured by experiments.

The separation efficiency and pressure drop of the same oil separator are compared under different flow conditions. In general, higher vapor velocity causes lower separation efficiency due to the re-entrainment effect. Pressure drop introduced by the separation structure increases as the vapor velocity goes up. The effect brought by different geometry design is also included. For different impinging separators under the same flow condition, a structure with smaller gaps and more bends achieve higher separation efficiency. Correspondingly, a structure with a higher separation efficiency usually brings higher pressure drop. Furthermore, the total volume of the separation chamber influences the performance, too. Introducing the oil separator to the system always bring both gain and cost. The gain includes lower oil circulation ratio and better heat transfer performance of the heat exchangers. The cost includes the larger pressure drop and the extra volume brought by the structure. To design an oil separator fitting the requirement of compressor application, a trade-off between the three main aspects (separation efficiency, pressure drop and volume) must be balanced.

NOMENCLATURE

\[ \dot{m} \] mass flow rate \ (g/s)

OCR oil circulation rate \ (%)

\( \eta \) separation efficiency \ (%)

\( \omega \) mass fraction of refrigerant in refrigerant-oil mixture

Subscript

\( \text{drain} \) drained back to the compressor

\( \text{in} \) coming into the separator

\( \text{system} \) circulating in the system

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