Numerical Analysis Scheme for Predicting the Oil Level Variation in Horizontal Rotary Compressor

Joonhyung Kim[1*], Munseong Kwon[1], Jongwon Choi[1], Sedong Lee[1], Sunghyuk Park[1]

[1] Advanced C&M Development Lab., SAMSUNG ELECTRONICS Co., Ltd.
Suwon-si, Gyeonggi-do, Republic of Korea
E-mail: joonh82.kim@samsung.com

* Corresponding Author

ABSTRACT

Rotary compressors are categorized into vertical and horizontal types based on the installation direction. Unlike vertical rotary compressors in which the compression part is submerged in oil, in horizontal rotary compressors, only a part of the compression unit is submerged, which may result in reduced oil supply performance and potential issues. For this reason, it is necessary to accurately predict oil level variations inside horizontal compressors. However, the hermetic design of rotary compressors makes it challenging to observe the internal oil level during operation. This study developed a numerical analysis approach for predicting oil level variation in horizontal rotary compressors. A multi-phase flow analysis technique for two-phase flow of refrigerant and oil was chosen and the influences of critical parameters were assessed. Using the numerical analysis technique, the oil level variations were predicted under various oil amounts and operation speed conditions, and the results were validated through the actual visualization tests using a bolted type compressor equipped with a sight glass. The predicted results such as refrigerant inflow through the oil flow path agreed well with the observation from the tests and the errors between the numerical predictions and the measurements obtained from the tests were within 6.8%. The outcomes of the validation tests clearly demonstrate the numerical methodology developed in this study successfully predicts the characteristics of oil level variations inside horizontal rotary compressors.

1. INTRODUCTION

Due to the critical importance of lubrication in rotary compressors, numerous studies have been conducted to assess and enhance this aspect [1-5]. As shown in Fig. 1, rotary compressors are typically mounted vertically, allowing their compression units to be immersed in lubricant oil. This configuration simplifies the structure of the oil supply system, ensuring consistent oil distribution during the compressor operation. However, in horizontal rotary compressors, used in applications with spatial limitations, only a portion of the compression unit is submerged in oil owing to the different orientation of installation. Therefore, various problems may occur due to poor oil supply, requiring the integration of an additional oil supply module. When developing a horizontal rotary compressor, designing an oil supply system specially designed to the specific model is crucial.

When a rotary compressor operates, the discharged refrigerant and the rotation of the motor create pressure differences within various regions inside the compressor. In the case of horizontal rotary compressor as shown in Fig. 2, the stored oil is widely distributed across the compression and the motor sections. Due to the pressure differences, the oil level varies across different areas. Among the forces circulating lubricating oil inside the compressor, the influence of head force due to oil level is the most significant. Therefore, in designing the oil supply system for horizontal rotary compressors, the characteristics of oil level fluctuation need to be taken into account. However, due to the hermetic nature of rotary compressors, observing the internal oil level during operation requires time-consuming and instrumental-intensive experiments. The improvement of computing power and resources has enabled numerous studies on the lubrication characteristics of hermetic compressors. [6-10]. However, as most of these studies have focused on vertical rotary compressors, additional research is needed to verify the oil characteristics inside the horizontal rotary compressors.

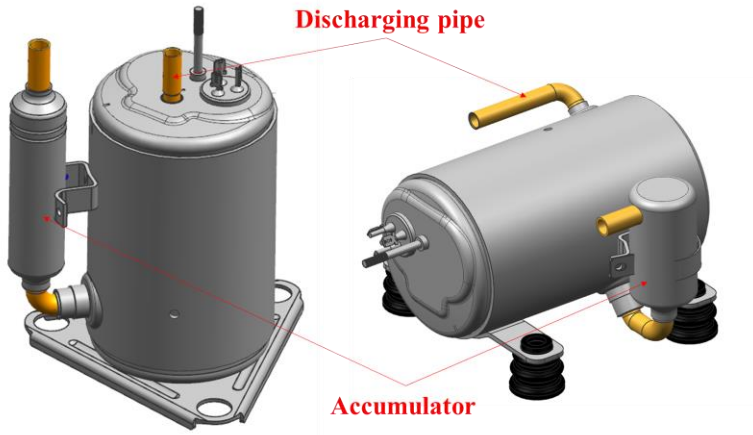


Figure 1: Vertical and horizontal rotary compressors

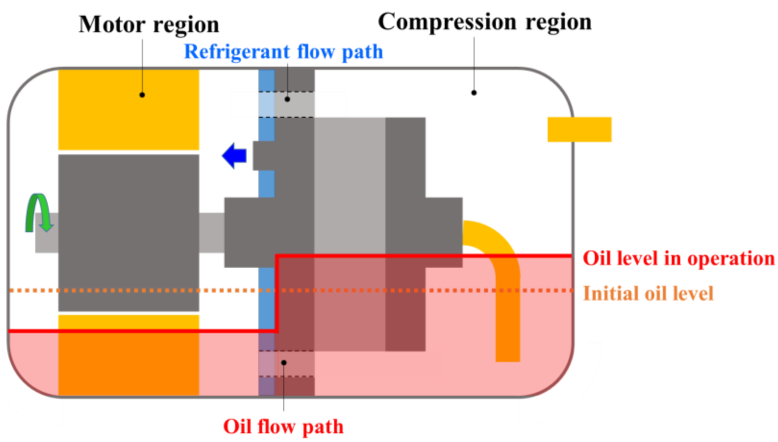


Figure 2: Oil level variation in horizontal rotary compressor

This study developed a numerical analysis methodology to simulate the oil level variations inside horizontal rotary compressors. A multi-phase flow analysis technique suitable for two-phase flow of refrigerant and oil was selected, and key design parameters were identified and their influence assessed. The oil level variations of the actual development model were numerically predicted over a range of operating conditions and validated by actual oil level visualization tests.

2. NUMERICAL ANALYSIS METHODS

The multi-phase models for simulating the correlation between each phase are categorized into homogeneous and inhomogeneous models. The inhomogeneous model allows for different velocity fields in each phase due to the presence of slips at phase interfaces. In contrast, the homogeneous model, lacking slips, assumes the same velocity field for all phases. In horizontal rotary compressors, the slip is negligible since the flow is governed by rotor rotation and refrigerant discharge. In addition, the interface needs to be maintained to accurately simulate the oil level variation. Therefore, in this study, a free surface model based on the homogeneous model was selected as the multi-phase flow analysis model.

The homogenous model assumes that the transported quantity is the same for all phases, allowing the use of a single bulk transport equation. The governing equation is defined as follows [11, 12].

(Mass Conservation) $$\frac{\partial(\rho_n f_n)}{\partial t} + \frac{\partial(\rho_n f_n u^i)}{\partial x^i} = 0 \quad (1)$$

, where ρ_n is the density for each phase, f_n is the volume fraction and u^i is velocity field.

(Momentum Conservation) $$\frac{\partial(\rho_m u^i)}{\partial t} + \frac{\partial(\rho_m u^j u^i)}{\partial x^j} = -\frac{\partial P}{\partial x^i} + \frac{\partial \tau_m^{ji}}{\partial x^j} + \rho_m g^i \quad (2)$$

ρ_m is the mixture density: $$\rho_m = \sum \rho_n f_n \quad (3)$$

τ_m^{ji} is the mixture stress tensor: $$\tau_m^{ji} = \mu_m \left(\frac{\partial u^i}{\partial x^j} + \frac{\partial u^j}{\partial x^i}\right) \quad (4)$$

μ_m is the mixture viscosity: $$\mu_m = \sum \mu_n f_n \quad (5)$$

, where f_n is the volume fraction, where the sum of all volume fractions is equal to 1.

Numerical simulations of the oil level variation were conducted using a commercial CFD solver, ANSYS CFX 2020 R1. The flow domain was extracted from the compressor and a grid system was generated using the ANSYS mesh tool as shown in Fig. 3. The unstructured grids were created to ensure that at least 5 grids were arranged in narrow flow paths such as an air gap. The standard k-ε model was applied for the turbulence model, and R134a refrigerant and POE oil for working fluids. The mass flow rate condition was set at the inlet and the pressure condition at the outlet, respectively, and the rotor rotation was simulated using a rotating wall method.

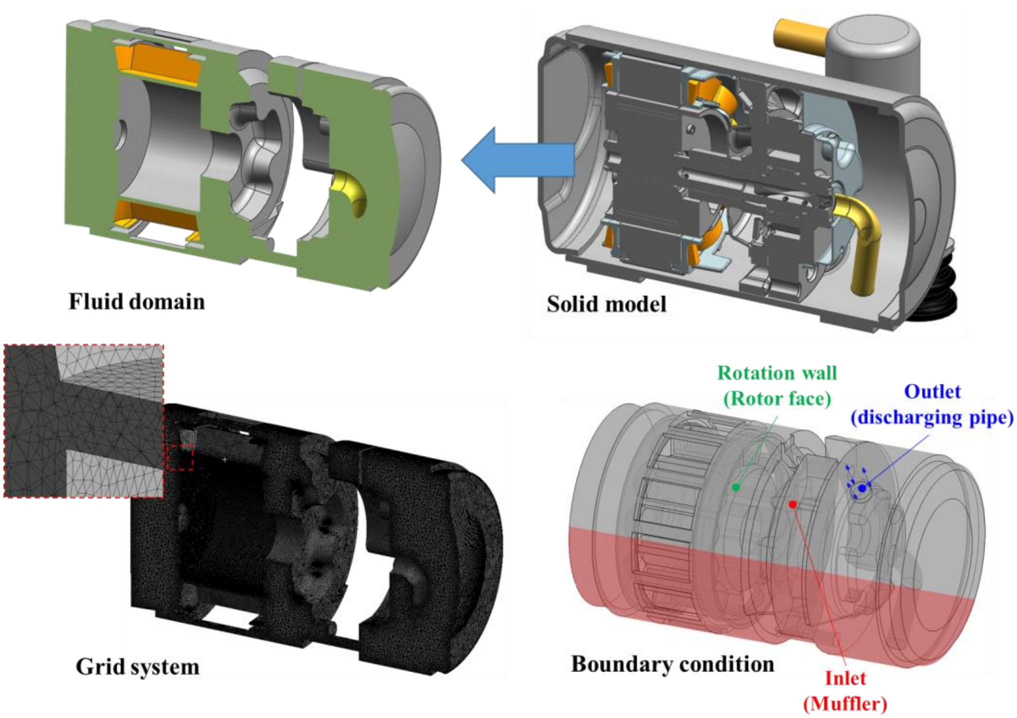


Figure 3: Numerical analysis methods to evaluate the oil level variation

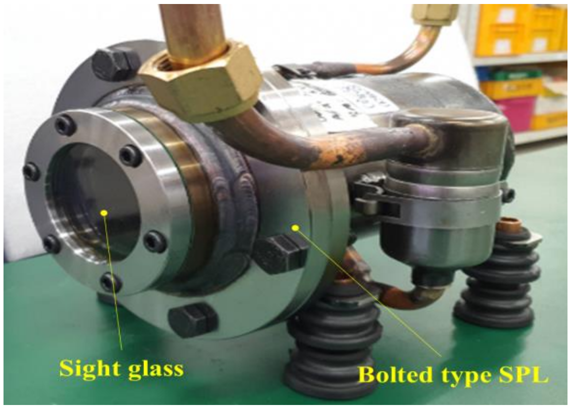


Figure 4: Sample for oil level visualization test

3. EXPERIMENTAL METHODS

Oil level visualization tests were conducted to validate the numerical methodology [13]. Figure 4 presents the actual sample used in the experiments. A bolted-type compressor was constructed, identical in specifications to the model used in the numerical analysis, facilitating adjustments to the oil amount and modifications to the part design. A sight glass was configured to make visible the oil level variation around the compression part where the oil supply pipe is located.

The sample thus fabricated was operated in a calorimeter with the same oil amount and operating conditions as the numerical analysis. The oil level was then measured after the calorimeter had reached a stable state, and compared with the numerical prediction.

4. RESULTS AND DISCUSSION

4.1 Influence Assessment of Numerical Analysis Factors

As oil level changes within the complicated interior of the compressor need to be predicted, numerical analysis using multiphase flow methodology must take into account factors such as the impact of gravity and collisions between internal components and the oil surface. To investigate the effects of such factors, an unsteady-state analysis was performed under the operation condition of HPD (Heat Pump Drying) and 60rps.

Figure 5 shows the numerical results of oil level variation over time, obtained using a compressor model equipped with a weight balancer on its rotor. As the rotor rotated, the collapse of the oil level due to the collision between the weight balancer and the oil surface was observed. The collapsed oil surface did not recover and most of the oil, divided into lumps, was discharged through the discharge pipe. For this reason, a larger amount of oil discharge was predicted than the actual phenomenon. To address this issue, the weight balancer was subsequently removed from the analysis model.

Figure 6 shows the prediction results of the oil level variation with and without the integration of the effect of gravity. By removing the weight balancer, the severe collapse of the oil surface due to its rotor rotation was suppressed. Without considering the gravity effect, the oil surface near the rotor was predicted to be pushed and split due to the rotational force. This resulted in a large amount of oil being discharged through the discharge pipe. On the other hand, with considering the gravity effect, the pushing of the oil surface due to the rotor rotation was suppressed, and severe oil discharge did not occur. In addition, after several rotations of the rotor, it was also observed that the oil surface stabilized as the oil moved due to the pressure difference between the motor and compression parts. Table 1 presents the numerical analysis conditions determined through the effect evaluations conducted so far.

Table 1: Parameters and components of numerical analysis model

Analysis type	Multiphase model	Rotation Type	Gravity	Design change
Unsteady	Homogeneous model (Free surface)	Rotating wall	O	WB removal

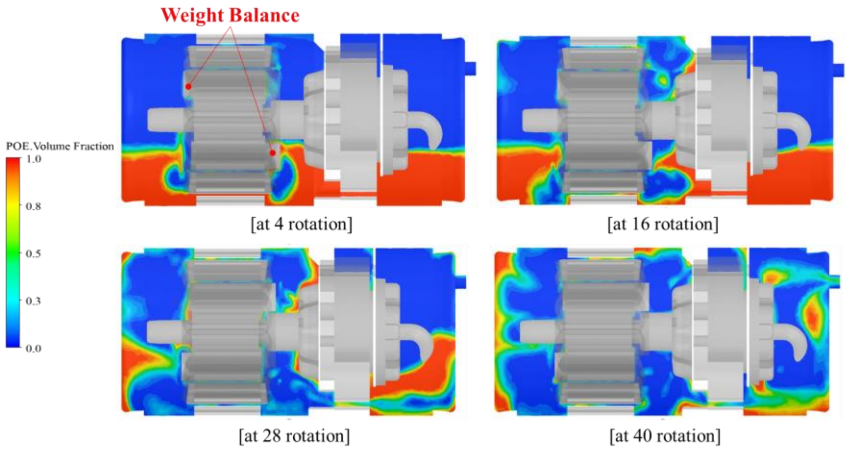
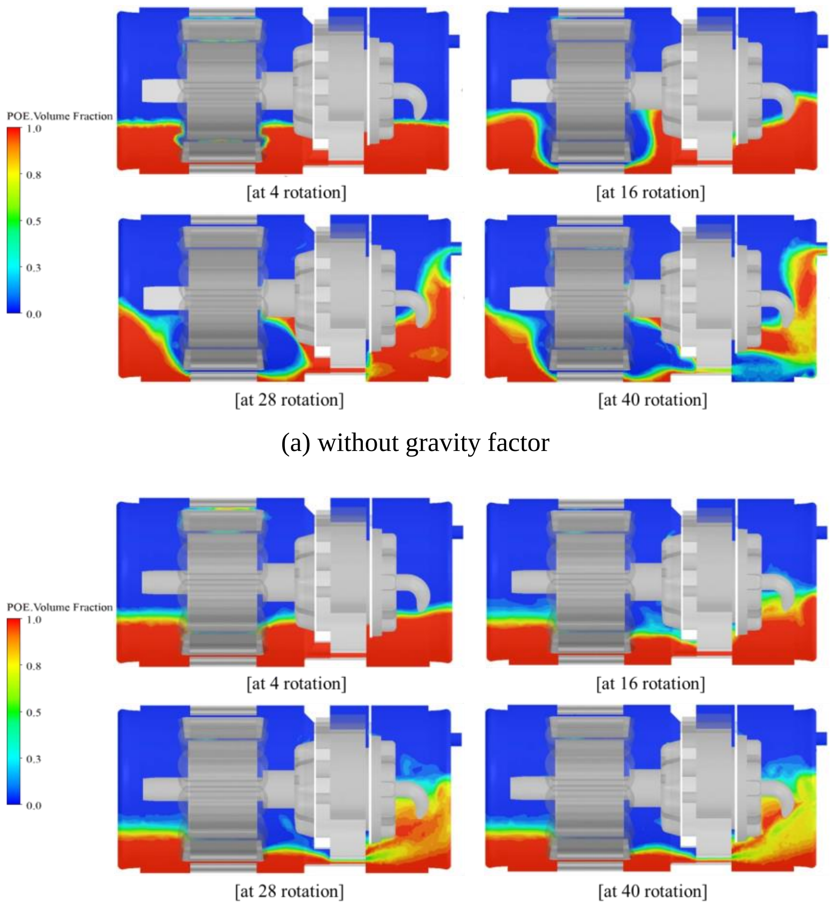


Figure 5: Oil level prediction with a weight balancer



(b) with gravity factor

Figure 6: Oil level prediction with gravity effect

Table 2: Evaluation sets for oil level variation

Set No.	Operating condition	Storage oil [g]	Rotating speed [rps]
1	HPD (Heat Pump Drying)	200	30
2			45
3			60
4			75
5		350	30
6			45
7			60
8			75

4.2 Model Prediction and Validation

Based on the modeling methodology outlined in the previous section, numerical analyses were conducted under the conditions specified in Table 2. As shown in Fig. 7, a grid test was performed on the compressor model used in the analysis to generate an appropriate grid system. Each analysis was conducted under a steady-state assumption due to the computing resource limitations.

The predicted results of the oil level variation inside the horizontal compressor for each condition was presented in Fig. 8. As the compressor operated, a pressure difference between the motor part and the compression parts occurred, leading to variations in oil level height depending on the region. As the dynamic pressure increased in the motor section, the oil level there decreased, the oil from the motor section moved to the compression section, causing the oil level in the compression section to rise. These differences in oil level increased as the rotational speed increased. Especially at rotational speeds above 60rps, it was predicted that the oil level in the motor section dropped below the oil flow path, allowing refrigerant to flow through the path. This refrigerant inflow is one of the causes of compressor cooling capacity loss.

The effect of the oil amount on the oil level was also studied. With 350g of oil filled, the oil level rose above the mid-height of the compressor at a rotational speed of 30rps, and it appeared that the oil level rising close to the outer diameter of the rotor could hinder its rotation. Additionally, at speeds above 45rps, the oil level in the compression section was observed to be high, potentially resulting in excessive oil supply. Therefore, filling the compressor with 350g of oil was considered to be an overcharging specification. However, at speeds over 60rps, the refrigerant inflow through the oil path was similarly observed. To address this issue, it is necessary to change the position of the oil flow path and/or redesign the differential pressure structure.

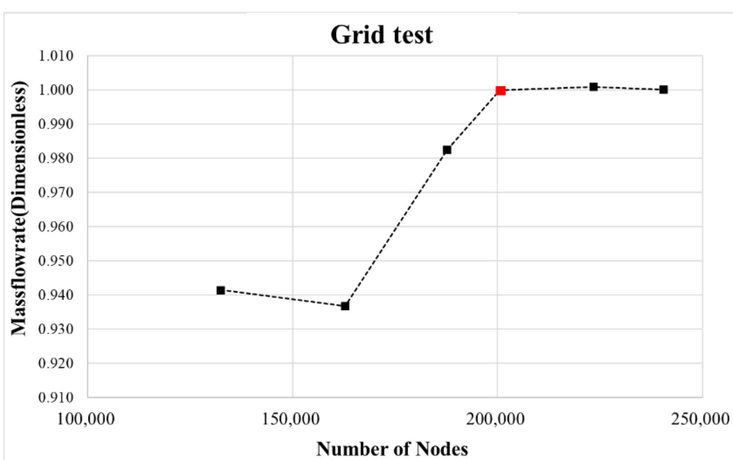
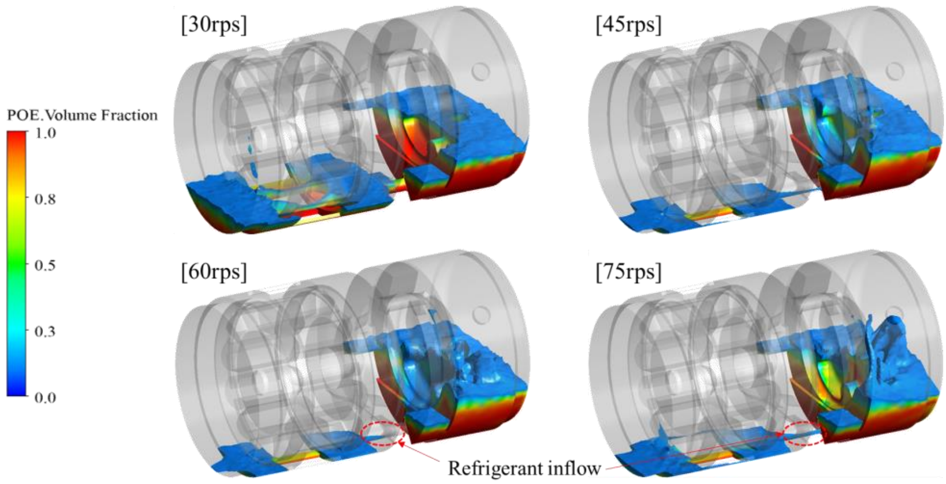


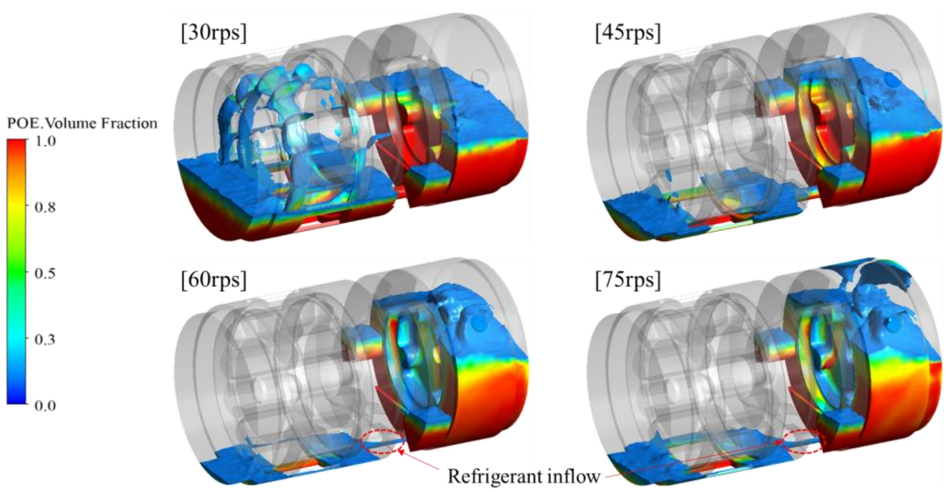
Figure 7: Grid independence test

To determine the effectiveness of the numerical analysis methodology, actual oil surface visualization tests were conducted under conditions identical to those used in the numerical simulations, and the comparison results are shown in Fig. 9. As previously discussed, since 350g of oil filling was considered to be an overcharging specification, the visualization test was only conducted with a 200g oil filling condition. The oil surface in numerical simulations was determined based on an oil volume fraction of 0.5 or higher.

The errors between the numerical predictions and the data measured from the visualization tests were within 6.8%. Furthermore, the refrigerant inflow through the oil flow path was also predicted and agreed well with the observation from the tests. The results of the validation tests clearly demonstrate that the numerical methodology presented herein successfully predicts the oil level variation in horizontal compressors. The numerical methodology developed in this study is being applied to various research fields including designing a differential pressure structure to reduce the oil amount, optimizing the location of the oil flow path, and improving the oil supply system.



(a) Storage oil: 200g



(b) Storage oil: 350g

Figure 8: Influence of gravity factor

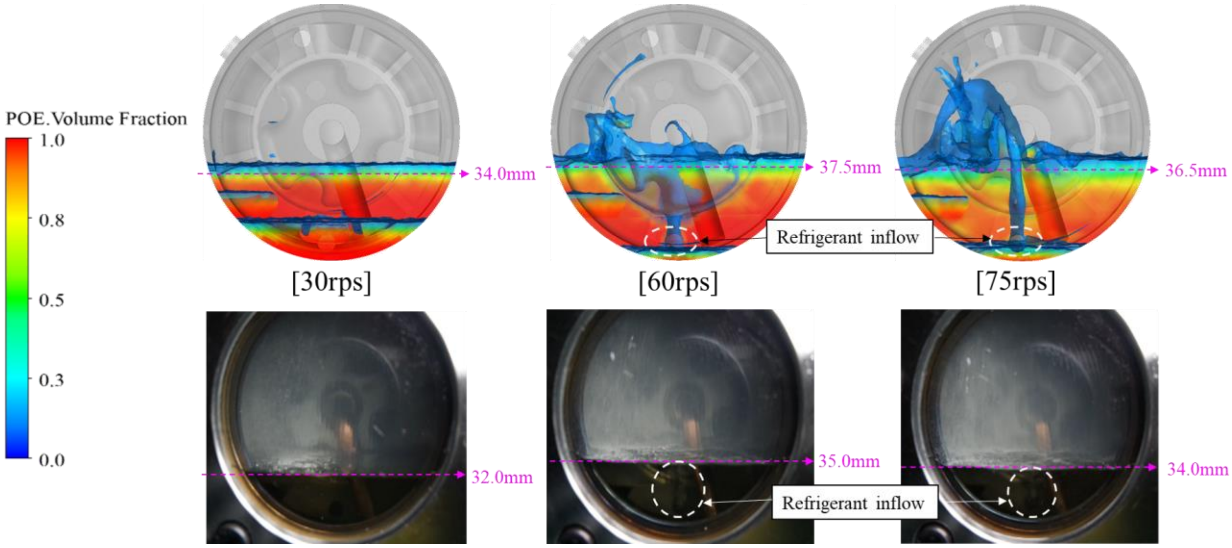


Figure 9: Comparison between numerical and actual visualization test results

5. CONCLUSION

A numerical methodology for prediction of the oil level variation in horizontal rotary compressors has been developed using a multiphase flow analysis approach. Using this method, the characteristics of the oil level variation are predictable according to operating conditions. The following specific conclusions can be made:

- A free surface model based on the homogeneous model was selected as the multi-phase flow analysis model, and the influence of the numerical factors was investigated. The weight balancer was removed from the analysis model in solve the problem of the weight balancer collapsing the oil surface. The effect of gravity was considered due to the oil level stabilization.

- The prediction of the oil level variation was validated by the visualization tests over various operating conditions. The errors between the numerical predictions and the data measured from the tests were within 6.8%. In addition, the simulation results, including the occurrence of the oil level differences between the motor and compression sections and the refrigerant inflow caused by excessive reduction in oil level in the motor section agreed well with the observation from the tests.

- The numerical methodology developed in this study is capable of predicting the oil level variation in horizontal compressors, and being applied to various fields such as designing a differential pressure structure and enhancing the oil supply system in horizontal rotary compressors.

NOMENCLATURE

f	volume fraction	(–)
N_p	total number of phases	(–)
P	pressure	(Pa)
t	time	(s)
u	velocity vector	(m/s)
V	flow velocity	(m/s)
μ	viscosity	(Pa·s)
ρ	density of the fluid	(kg/m^3)
τ	stress tensor	(N/m^2)

Subscript

m	mixture
n	phase of working fluid
o	oil

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