A Prediction Method for Slug Limit of Scroll Compressor using CFD Two-Phases Flow Simulation

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ABSTRACT

Slug test is used to simulate a real application work condition in lab. During operation, a compressor eventually gets to endure dynamic slugging which is characterized by the arrival of a liquid refrigerant at the suction side when the compressor is already running. Because of this dynamic, the liquid is able to reach the compression side. The presence of incompressible liquid in the scrolls (volumetric compression) involves mechanical strength quickly becoming unbearable for the compressor involute breakage or Oldham coupling breakage are the consequences suffered by the compressor following a severe slugging.

In this paper, a prediction method of slug limit is introduced which is based on simulation result numerical fitting to experimental result. In laboratory, engineers use dynamometer to monitor the image of compressor current intensity which shows a steep peak when more and more liquid refrigerant injected. Once the current peak ratio exceeds our goals, we would take the corresponding liquid quantity as slug limit of the compressor.

And this liquid injection process is transient simulated by CFD method using two-phases flow model – Eulerian multiphases model which allows for the modeling of multiple separate yet interacting phases. The phases can be liquids, gases, or solids in nearly any combination. Liquid refrigerant is thought as granular phase and calculated. Mass flow rate of each phase at outlets is recorded during calculation process and divided by normal mass flow rate (only gas suction). The maximum ratio of mass flow rate is used to predict slug limit comparing to experimental criterion. Using this method, it's easier to comparing with different parts structure which one is better for slug performance and which one is worse, saving time and cost and more and more helpful for engineering design.

1. INTRODUCTION

As we know, test can tell the slug limitation of compressor, but it cost too much, for example machining and assembling samples. It costs not only a lot of money but also quite a few of time. Using simulation tool is a reasonable solution to save many traditional tests. Following detailed introduces why we need slug test and how we did it in lab. We use current peak ratio as a criterion to judge the slug limitation of compressor rather than mass flow rate or pressure or temperature which are used in CFD code.

In this paper, we use CFD tool to simulate mass flow rate of liquid flow into scroll, which has similar changing tendency with current peak ratio. In other words, the current fluctuation happens when there is slug flow into compressor because motor load raises up suddenly which is also the result of a big mass flow into scroll. But we have to make some assumptions, for example the liquid mass particles are rigid body other than phase changeable liquid refrigerant particles. We must balance the calculation time and model complexity. If the calculation model was over-complex and cost too much time, it violates our original intension.

From our experience, the criterion of current peak ratio of the max load and no load of slug is set down for different type of compressors. But it is a different number for mass flow rate ratio. We simulate many types of Danfoss compressors and get a simulation judgement method by curve fitting to test result. Using this method, engineer gets many conveniences when design or modify a part which is related to slug performance, improve flooded start ability, application of different manifolding system and so on. The aim of slug simulation is not necessarily getting a specific number. To quantized judge the improvement level is more important for engineers.

2. TEST PROCEDURE AND RESULT ANALYSIS

2.1 Test Procedure

At the beginning of every test cycle, the system insures there is enough liquid refrigerant as test standard in a tank. Then open the valve inject the liquid into compressor in a very short time and record the current fluctuation during the injection process. As the current peak get the standard value, we think it get the limitation of this type of compressor.

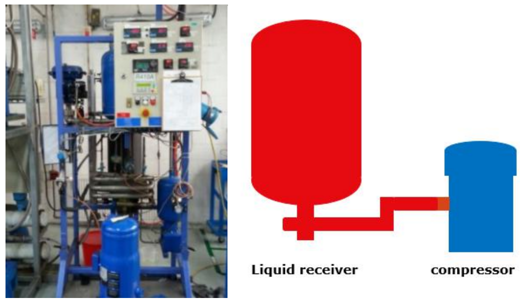

Figure 1. Test platform

2.2 Test Result Analysis

After each cycle, laboratory technician saves the screen shot of amperemeter, and calculates the ratio of max current peak and normal current value. There is an example of test result analysis shown as figure 2. The title is different quantity of liquid injection each time. When the liquid quantity is increasing, the current of compressor is also increasing at the same time. We set a standard of evaluation in advance, to judge the performance of compressor facing to this slug phenomenon in lab.

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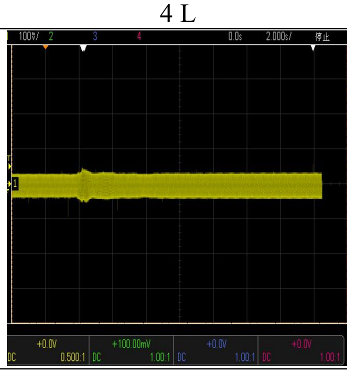	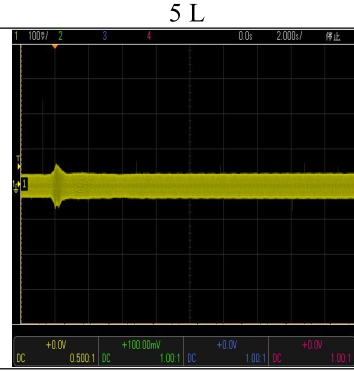
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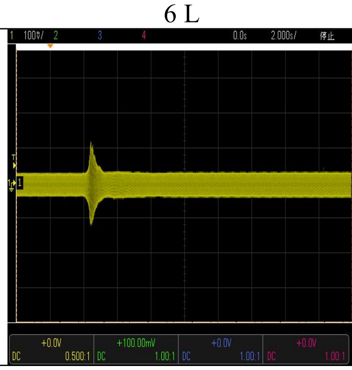
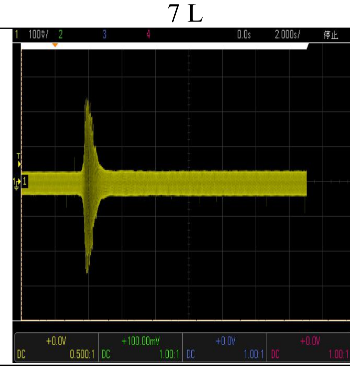
	

Figure 2. Amperemeter screen shots

In figure 2, injection quantity is varying from 4 to 7 liters. The current peak is getting steeper as the increasing liquid. Meanwhile, it can be record numerically as following figure 3.

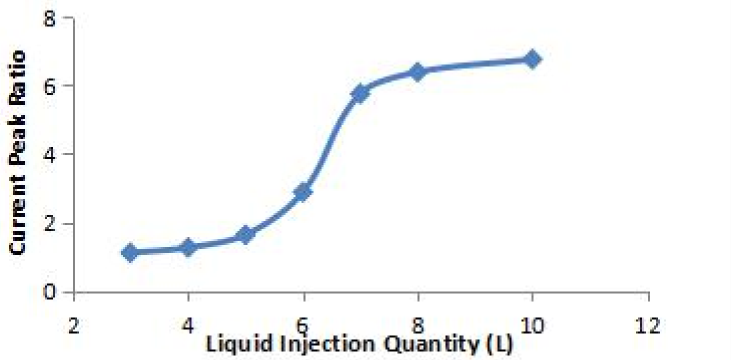


Figure 3. Current peak ratio by test

3. NUMERICAL SIMULATION

3.1 Calculation model

The calculation model is only about tested compressor and doesn't take the test system into account which is shown in figure 4. The inlet is compressor suction fitting and outlet is close to the scroll involute shown in figure 5. Although the area should be moving when it was running but we assumed a fixed vent as the calculation outlet. The whole domain is called low pressure side where pressure is close to suction pressure.

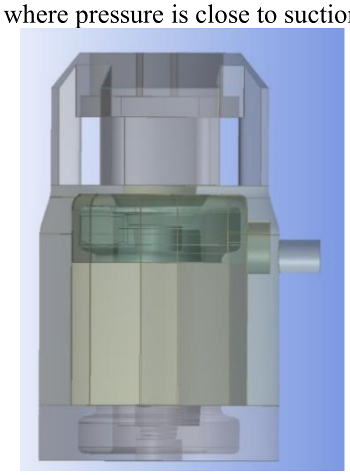


Figure 4. Calculation model

The calculation is to check the flow path of liquid refrigerant and velocity at the suction port of involute in transient process. Here are some hypotheses:

- Not considered geometry moving. We simulated dynamic process, but the model didn't move at all. Only boundary was related to time;
- Considered two phases flow. Used Eulerian multiphase model;
- Not considered heat transfer. The properties (density, viscosity) of material were constant.

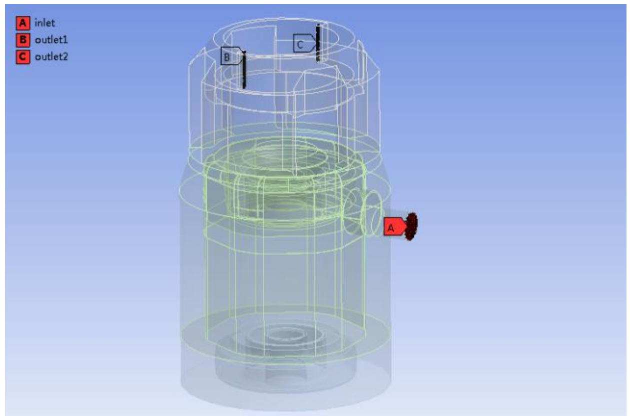
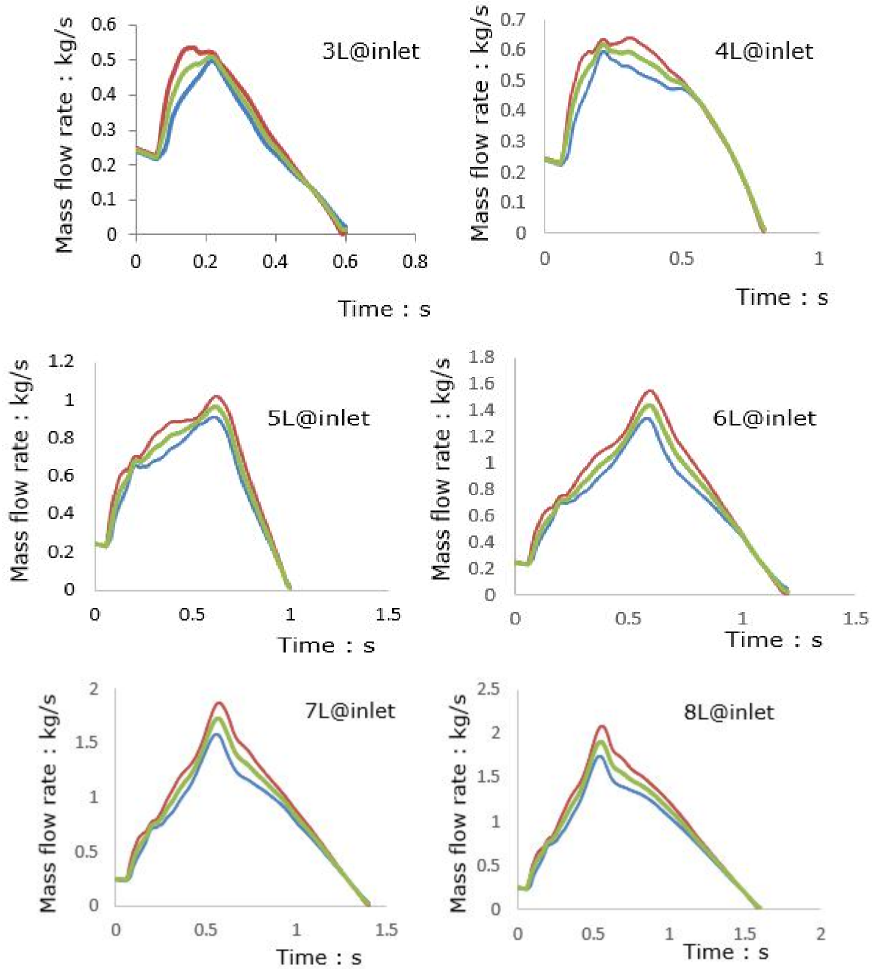


Figure 5. Boundary set

In initialization, whole domain is refrigerant gas and boundary condition for inlet is mass flow rate with all liquid. We monitored pressure changing during liquid injection process in test, and then record mass flow rate changing process, for instance 2 liters liquid injected into compressor in 2 seconds. We assumed the mass flow rate is linear decreasing as calculation input. Meanwhile we monitored mass flow rate at the outlets as the simulation output comparing with current ratio by test and got a simulated slug limit which could save many tests.

3.2 Calculation result

The calculation is unsteady and monitored result is varying with time shown in figure 6.



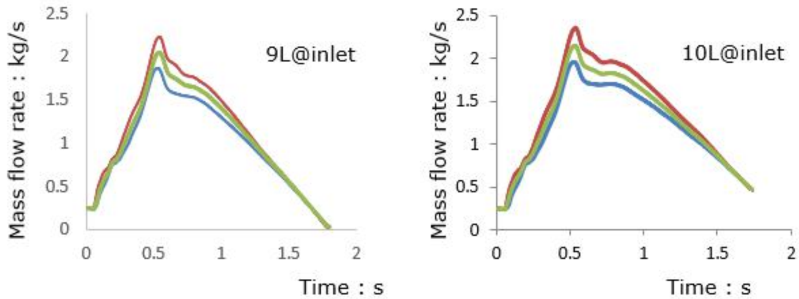


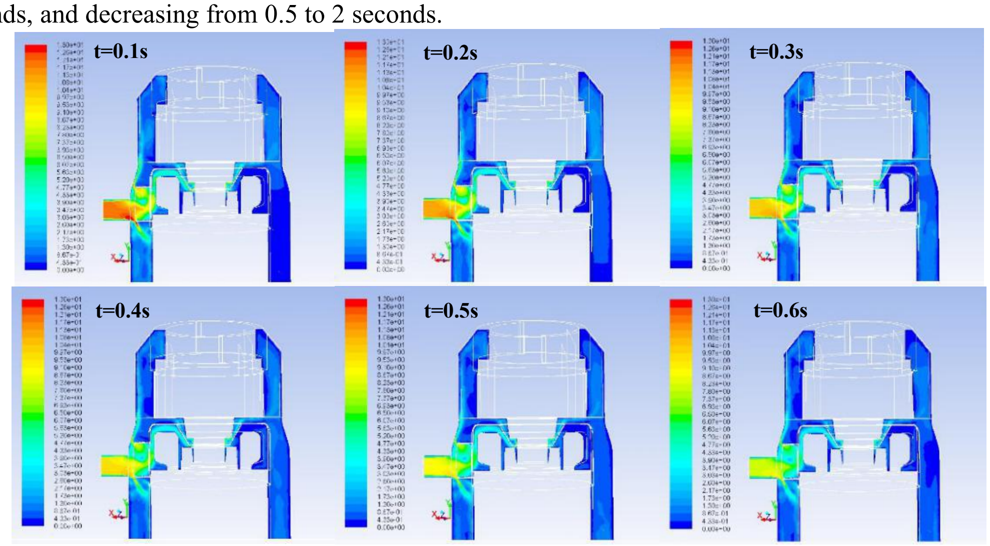
Figure 6. Mass flow rate at outlets with different liquid quantity

The figure 6 is liquid mass flow rate at two outlets (red line is outlet1, blue line is outlet2 and green line is the average of two outlets). We simulate different liquid quantity as input and record the max number during the procedure. The trends are very close which is half rising and half declining. But they are different time when the max mass flow rate come. When we use 3 liters liquid injection, it come to max at 0.25 seconds. When we use 4 liters liquid injection, it is almost 0.4 seconds. However, when injection liquid is bigger than 5 liters, the max happen over 0.5 seconds (around 0.6s). Then we also record the total max number (both liquid and gas) which is shown below.

Table1: Max total mass flow rate at different liquid injection

Liquid Injection Quantity Unit: L	Max total mass flow rate Unit: kg/s
3	1.04
4	1.35
5	2.03
6	2.93
7	3.66
8	4.01
9	4.28
10	4.48

Based on the 10 liters liquid injection case, the velocity distribution at different moments are visualized in figure 7 by contour of velocity magnitude located on center section surface. At the outlets, velocity keeps increasing from 0 to 0.5 seconds, and decreasing from 0.5 to 2 seconds.



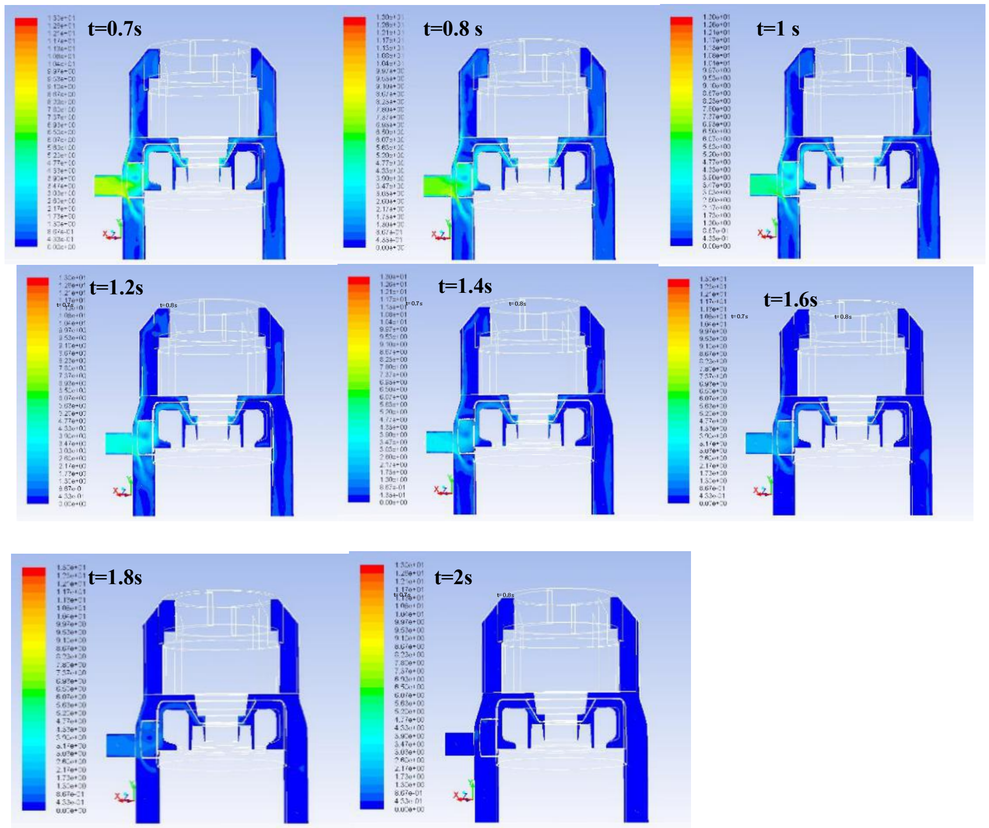


Figure 7. Velocity contour of 10 liter liquid injection

3.3 Result analysis and discussion

Use max total mass flow rate divided by theoretical mass flow rate only suction gas to get a ratio of mass flow rate:

$$\lambda = \frac{Q_t}{Q_g}$$

λ : Ratio of mass flow rate.

Q_t : Total mass flow rate including gas and liquid in slug work condition

Q_g : Mass flow rate only suction gas in normal work condition.

The aim of this calculation is to get a non-dimensional value to compare with test result which is also a non-dimensional ratio value of current peak. The figure 8 shows simulation result and test result tendency, blue line is tested current peak ratio and red line is simulated max mass flow rate ratio. The tendency has a good agreement. The liquid injection procedure basically can be divided into three stages. Firstly, little liquid injected (far less than slug limit, for instance less than 4 liters liquid), compressor managed to overcome the impact of liquid and wouldn't bring big current fluctuation. Secondly, more liquid injected (close to slug limit, beyond the limit, for instance in the range of 4 liters-8 liters), more and more liquid sucked into scroll brought a huge motor load and obvious current peak occurred. Thirdly, much more liquid injected (over 8 liters in this example), the scroll can not take more liquid away so mass flow rate basically got the limitation and the motor showed same phenomenon-the current peak wouldn't get larger anymore. If the quantity continued to be increased, the compressor could be broken down.

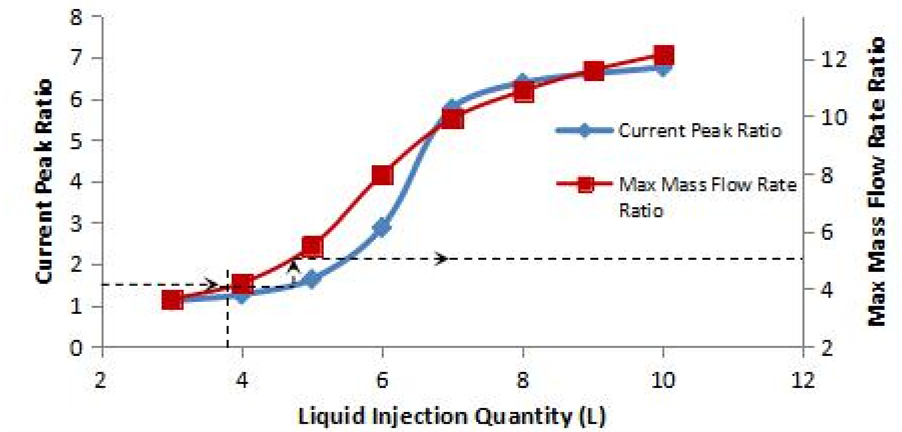


Figure 8. Comparison of test and simulation

Based on test criterion we get slug limit for a compressor and following along the vertical dotted line we get the relevant max mass flow rate ratio with same liquid injection quantity. We use the relevant value as the simulated slug limit. If a compressor from same platform has a larger ratio than the simulated slug limit, we think it take risk of failure when liquid flow back.

4. CONCLUSION

This paper shows a CFD approach to simulate a kind of scroll compressor reliability test – we called it slug limit test. For Danfoss scroll compressor, there are many different types and slug limit criteria. We choose a typical one as the research target, make a slug limit test, record the current peak ratio and get the quantity of limitation. Then we built a numerical model, make simplifications, assumptions, and calculations. From calculation result, we know max mass flow rate has increasing and decreasing process in one slugging cycle. The time of getting the peak is later and later until the total liquid injection is close to limit. After making a curve of different liquid injection quantity, we know the whole process can be divided into three stages which is including the first steady stage, the second sharp rising stage and the third relevant steady stage which is almost the compressor limitation of taking liquid ability. After that we use simulated result curve fit to test curve and get another criterion which is in same level with test criterion. The simulated max mass flow rate ratio has a very good agreement with tested current peak ratio. It has same tendency which help to set a series of criteria for other types of compressor. By this criterion, engineer can tell the difference of new design with the former one or other ideas when he just has simulation result. Based on the simulation accordance to experiment, a lot of time and money can be saved in the product development procedure.

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