2021

Horizontal Scroll Compressor for Refrigeration Applications

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ABSTRACT

New efficiency regulations, as well as trends in applications of new low GWP refrigerants, force compressors to be re-designed, especially for A3 refrigerants, because of the regulatory limitations of the refrigerant charge. The paper addresses compressor design allowing for more efficient use of the refrigerant charge.

An oil sump retains significant amount of refrigerant diluted in the oil. Elimination of the oil sump allows to use the limited refrigerant charge more effectively. Furthermore, it reduces the size of the compressor and simplifies the compressor structure. Another benefit of this type of compressor is its orientation flexibility- the same compressor can be installed vertically or horizontally. These design features are beneficial in close-coupled systems, as well as transport (truck/trailer) refrigeration systems.

The sump-less design requires a revision of friction pairs in the compressor: radial bearings, thrust bearings, tip-to-base contact and others. Existing refrigeration compressors rely on the continuous oil flow for journal bearing lubrication, while the lubrication mechanism in the sump-less compressor relies on the oil mist. This design leverages the approach utilized in the automotive scroll compressors, but the requirements and conditions for the compressor operation and reliability are different. The paper discusses the major design steps and results of preliminary reliability and system tests with an experimental determination of the optimal oil charge.

1. INTRODUCTION

HFC (hydrofluorocarbon) refrigerants are to be phased out soon because of their high GWP (Global Warming Potential). Most of their replacements are A2 or A3 refrigerants. Application of those usually restricts the refrigerant charge of the systems, since flammable fluid possess safety risk. For instance, the maximum charge of the system with A3 refrigerant is 150 grams, according to level specified by ASHRAE-15. The problem of minimization of the refrigerant charge was considered previously, for example, in Padilla et al., (2014), Poggi et al., (2008), Fernando et al., (2004), Bamigbetan et al., (2018). Most of the refrigerant is in the heat exchangers during the system operation (Hoehne and Hrnjak, (2004)). Thus, the approach was usually in optimization of the heat exchangers and their replacement with micro-channel heat exchangers (Padilla et al., (2014), Fernando et al., (2004) and Butrymowicz et al., (2016)). However, a large portion of the refrigerant is also staying in the compressor sump being dissolved in the oil (Hoehne and Hrnjak, (2004), Padilla et al., (2014)). Reduction of the oil charge will be beneficial for the reduction of the refrigerant charge (Fernando et al., (2004)).

In the refrigeration system, the oil is required for lubrication of the friction pairs inside the compressor. In a scroll compressor, the oil is pumped from the oil sump via the hole through the shaft. The oil charge in the oil sump is optimized for each compressor for sufficient lubrication of friction pair and to minimize the oil circulation rate in the system. Thus, the problem of oil charge reduction becomes a problem of the oil sump elimination and revision of the oil management in the compressor and in the whole system. Elimination of the oil sump results in a significant re-design of a compressor. The friction pairs of this compressor should still be lubricated, but all this oil continuously travels with the refrigerant through the system. Oil mist lubrication is used as a lubrication method. These changes lead to compressor designs similar to compressors in automotive AC systems.

2. COMPRESSOR DESIGN

A successful sumpless design must be both cost effective and efficient compared to existing compressors. Utilizing radial and dual-force axial compliance will help to achieve this challenge.

Axial compliance: Design of axial compliance mechanism was chosen as a first step in the compressor design in this work. Floating fixed scroll design used in production scroll compressors includes thrust bearing requiring hydro-dynamic lubrication which functions with continuous oil supply to the friction pairs. Even though it was demonstrated that thrust surface is viable if the oil mist with the suction gas is directed to the thrust surface, a floating orbit scroll design was chosen for this application.

Shell pressure: Both high side and low side shell options were considered and tested. Finally, a high side design was chosen because of the simpler construction, easier variable volume ratio valves application, discharge pulse and shell oil entrapment mitigation.

The cross-section of the designed compressor was described in Perevozchikov et al. (2020) and Ignatiev et al. (2020). It is shown in Figure 1. The compressor has direct suction. The oil moves with the suction flow through the compression mechanism. The compressor can have both horizontal and vertical orientation.

Bearings: The journal bearings, typically used in the scroll compressors, require continuous oil supply and cannot rely on an oil mist lubrication. Therefore, rolling element bearings are selected in proposed sump-less compressor design.

The rolling element bearings must be sized properly in dependence on the application that the compressor is designed for. Each application can be represented as a set of weighted compressor conditions, where weight is a time period while the compressor is operating at this condition. The forces acting on the bearings are calculated and are used in equation (1) to calculate the minimum required load rating of the bearing for a given life requirement:

$$C_{r\,min} = \sqrt[p]{\frac{60L_{10}\sum t_i n_i F_i^p}{10^6}} \tag{1}$$

where C_r is the dynamic load rating, i denotes different load conditions defined by t_i as the weight of the condition, n_i as the speed (rpm), F_i as the load, L_{10} is the required bearing life (hours), p is 3 for ball bearings and 10/3 for roller bearings.

Ball bearings are chosen as the main and lower bearings and needle bearing as a drive bearing.

Flow management: The scroll set may have discharge ports on both fixed and orbit scrolls. If a discharge valve is required for efficiency of high-pressure ratio conditions, then it can be installed on both scrolls (see Ignatiev et al. (2020)).

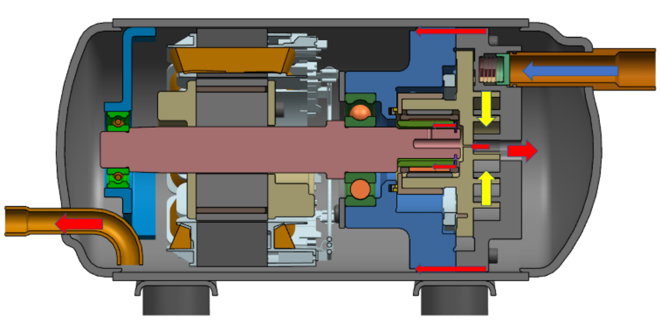

Figure 1: Refrigerant flow in the sump-less compressor.

One of the tested 3-ton sump-less compressor had a discharge port in the orbit scroll only. The cross-section of this compressor is shown in Figure 2. Total flow of the compressed refrigerant together with the oil mist passes through the radial compliance mechanism and drive bearing, providing the best lubrication to the friction pairs.

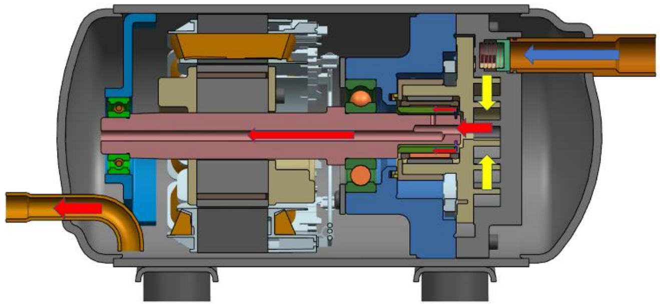

Figure 2: Sump-less compressor with discharge port in the orbit scroll

Radial compliance mechanism: A mechanism comprising unloader and eccentric shaft pin with flat surfaces was chosen as a primary radial compliance mechanism (see Caillat et al., (1993)).

3. COMPRESSOR PERFORMANCE

The performance of the compressor was measured within the operating envelope of a typical AC compressor including rating points according to ASHRAE Standard 540-2019 and at the rating conditions corresponding to the system test points according to AHRI Standard 210/240-2017. The tests were taken in calorimeter. The compressor efficiency was equivalent to the efficiency of 3-ton production scroll compressor. Its volumetric efficiency was slightly higher because of the direct suction. However, the mechanical losses were higher resulting in overall efficiency equivalent to the efficiency of the production scroll compressor. The test results at specific point are presented in Table 1.

Table 1: Test results for a compressor prototype

Tevap F (C)	Tcond F (C)	Speed RPM	Efficiency %
45 (7.2)	130 (54.4)	3600	70
50 (10)	115 (46.1)	Nominal	71

4. RELIABILITY TESTS

For the preliminary assessment of the new design reliability, we chose three reliability tests that allow to conduct accelerated preliminary tests with an emphasis on the compressor components that may have major reliability concerns. The tested prototypes passed these tests without any major failure modes.

4.1 High-Load Test

High-load test was performed to demonstrate the ability of the bearings to operate for the required life of the compressor. This test was performed for both horizontal and vertical compressor orientations. The compressor ran at the condition in the top-right corner of the envelope at the maximum designed speed. We assumed that the test was successfully passed if the compressor could operate with about the same efficiency in a predefined time period and the bearing did not have signs of failure.

Two sump-less compressors were tested at high-load conditions. Both compressors successfully passed the minimum predefined test period and did not show bearing failure modes in the extended tests.

4.2 Defrost Test

The compressor is designed for refrigeration application. In this application, the compressor can operate at a condition when the liquid refrigerant from the evaporator returns to the compressor suction in defrost cycles. Reliability of the sump-less compressor at this condition was assessed. The focus in this test was on the drive bearing and scroll set. The liquid refrigerant could wash the oil from the surfaces of the scroll resulting in accelerated wear of the scroll surfaces. The compressor prototype with the cross-section shown in Figure 2 was chosen for this test because it was less favorable for the drive bearing lubrication. The refrigerant was discharged through the port in the orbit scroll onto the drive bearing, the liquid refrigerant might not be fully evaporated in the scroll and might reach the drive bearing washing the oil. It might take some time for oil to relubricate the compressor components. The drive bearing would be starving during this time.

The compressor was running at the condition simulating an ice maker. The liquid refrigerant was dumped into the compressor suction line periodically.

Figure 3 shows suction gas temperature and the gas temperature measured just below the drive bearing. The latter temperature represents the discharge gas temperature. This temperature drops close to the suction temperature and remains almost constant for the period of liquid refrigerant dumping. This shows that some liquid refrigerant might reach the drive bearing for several second during each cycle.

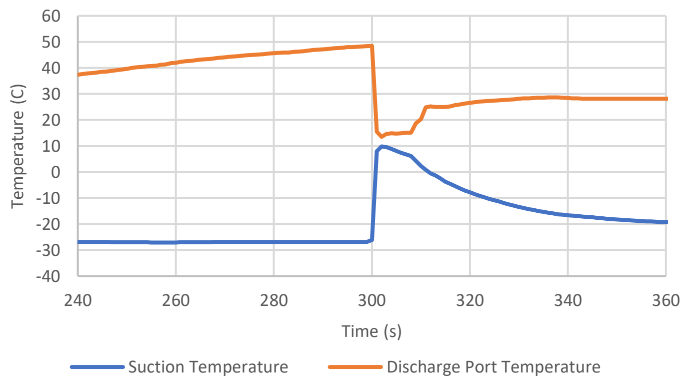

Figure 3: Suction gas temperature and temperature of the gas next to the discharge port.

After the test, the bearings did not have signs of damage due to the oil starvation.

4.3 Start/Stop Test

Another compressor failure mode can relate to compressor start moment. When the bearing suddenly starts spinning, hydrodynamic layer may be not formed resulting in boundary lubrication between rolling elements and races and the rolling elements may skid along the bearing races.

Start/stop test was done with a sump-less compressor. The compressor was cycled with running and idle periods. The condition was set to be close to ARI condition. The compressor passed through the number of cycles equivalent to the compressor life period.

No significant wear was observed on the bearings after the test.

5. SYSTEM TESTS WITH SUMP-LESS COMPRESSOR

The sump-less compressor was tested in refrigeration and air-conditioning systems: bottle cooler, two-door freezer and AC split system.

At first, a sump-less compressor was tested in a bottle cooler with R290 and R513A as refrigerants. It was demonstrated that the system with a sump-less compressor ran efficiently with only a 2-oz oil charge which corresponded to less than 1% oil circulation rate. This allowed to reduce by several times the refrigerant amount dissolved in the oil.

Air-conditioning split system performance was evaluated at different oil charge to determine the optimal oil charge. The original compressor in an off-the-shelf system was replaced with a sump-less compressor. A weighted average system efficiency was measured with using A_2, B_2, B_1 and F_1 conditions in AHRI Standard 210/240-2017. The dependence of the system efficiency on the oil charge is shown in Figure 4. The efficiency increased in the beginning, when the oil charge was increased from minimum amount, because the friction losses in the compressor were decreasing when we added oil, but the efficiency of heat exchangers did not change. Then, when we continued increasing the oil charge, the efficiency of the heat exchangers dropped resulting in higher pressure ratio condition and, as a result, in lower system efficiency.

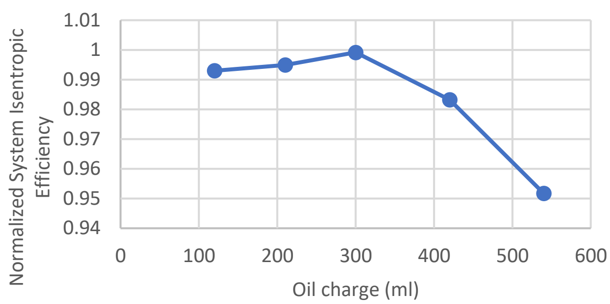

Figure 4: Normalized weighted average **s**ystem isentropic efficiency in dependence on the oil charge.

As the result from the series of tests, an initial relation of oil to refrigerant charge of air-conditioning split system has been established.

6. CONCLUSIONS

Sump-less design reduces amount of oil needed in the system and thus can make even larger systems capable to run with 150g of flammable refrigerant

Use of rolling element bearings instead of journal bearings allows to simplify the compressor envelope and to minimize the effect of speed on the oil circulation rate.

Sump-less compressor passed preliminary reliability tests. There were no major failure modes after the tests.

Optimal oil charge was determined for stand-alone refrigeration units charged with propane and a residential AC split system charged with R410A refrigerant.

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ACKNOWLEDGEMENT

The authors would like to acknowledge the support of management of the Emerson Commercial and Residential solutions for their support of the research project and preparation of paper.