Development of the New Design Two-Stage Semi-Hermetic Single Screw Compressor for Heat Pump

Yoshiyuki IMAMURA*, Takashi INOUE, Kazuhei TAKAHASHI, Yoshiyuki UEMURA, Harunori MIYAMURA

Technology and Innovation Center, DAIKIN INDUSTRIES, LTD.
1-1, Nishi-Hitotsuya, Settsu, Osaka 566-8585, Japan

yoshiyuki.imamura@daikin.co.jp, takashi.inoue@daikin.co.jp,
kazuhei.takahashi@daikin.co.jp, yoshiyuki1.uemura@daikin.co.jp,
harunori.miyamura@daikin.co.jp

* Corresponding Author

ABSTRACT

Recently, due to climate crisis and to reduce the dependency of fossil fuel, legislators in both Europe and North America are implementing policies to phase out fossil fuels for heating. This has resulted to a rapid expansion of demand for heat pumps. Even in low outdoor temperature regions such as Northern Europe, the replacement fossil fuel heating with heat pump heating is required, which necessitates a high-pressure ratio compressor that significantly exceeds traditional air conditioning compressor operating conditions.

Although a two-stage compression process is generally more efficient than single-stage compression one at high pressure ratio, a compressor configuration that requires multiple compressor units to achieve the necessary compression increases production costs. Specifically, such traditional configurations include compressors arranged in series or two-stage compressors with two series compression mechanisms within a single casing.

Therefore, a compressor capable of achieving two-stage compression with the same number of parts as a traditional single screw compressor, thus leveraging the unique characteristics of the single screw compressor that forms independent upper and lower compression chambers with one screw rotor and meshing two gate rotors. A prototype compressor consisting of a two-stage semi-hermetic single screw compressor has been operated and tested. This paper reports the results of characteristics and challenges extracted from this investigation.

1. INTRODUCTION

1.1 Background

In recent years, more and more countries are banning or planning to ban fossil fuels in heating. From France which is banning gas boilers in new buildings from 2023 to Denmark which wants all buildings connected to district heating or heat pumps by 2029. These announcements are strengthening and fast, across Europe. The same can be said in United States where New York became the first state to ban natural gas and other fossil fuels in most new buildings, passing a law earlier this year requiring most new buildings to be zero-emissions starting in 2026, with larger buildings coming into compliance in 2029. In California and Washington States, measures have been enacted encouraging increased electrification in homes and buildings through local building codes. While in 2015, combustion heating systems such as gas and oil boilers accounted for about 80% of the heating-related market, by 2050, boilers using gas, oil, and biomass as fuel are expected to disappear. Instead, it is projected that air-source heat pumps will constitute approximately 33%, ground-source heat pumps about 25%, gas heat pumps about 22%, and district heating around 20%. Heat pumps for residential use have been adapting to not only heating needs but also hot water requirements. However, large-capacity heat pumps have not been proposed for commercial air conditioning applications, and in order to comply with the banning fossil fuels in heating, it is necessary to develop compressors for heat pumps application as soon as possible.

1.2 Challenges of screw compressor for heat pump application

During the development of the compressor for heat pump application, to replace combustion heating with fossil fuel, it is assumed that they will be used in low outdoor environments, possibly below -20°C. Therefore, the performance aspects and the need for operating at pressure ratios exceeding 20 is paramount. Figure 1 depicts an example of a two-stage compressor assembly with at least two compressors mounted on series. This type of structure is widely used for industrial process applications in our company. Such configuration consists of multiple components and does not make it attractive for a cost effective because parts number is increased. To address this cost issue, a novel two-stage compressor which utilizing the distinctive and unique geometry of a single-screw compressor has been developed.

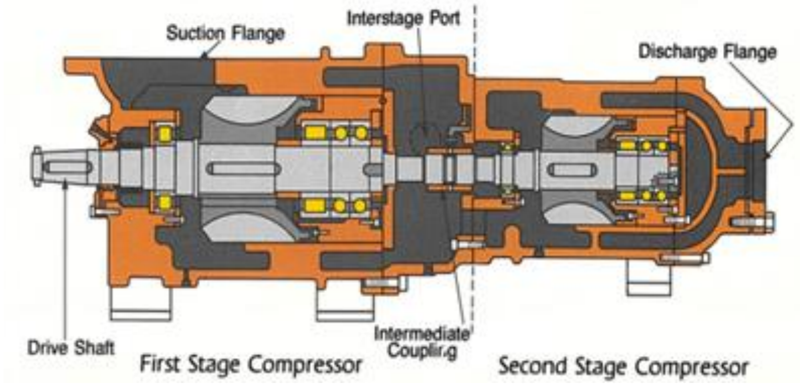

Figure 1: Cross-sectional view of a two-stage screw compressor for industrial process applications

2. STRUCTURE OF COMPRESSOR

2.1 Single Screw Compressor

Screw compressors have become increasingly popular for air conditioning and refrigeration applications. They are broadly divided into two types. Twin screw compressor and on the other hand is single screw compressor. Single screw compressor was invented by Bernard Zimmern in 1960s. It has a unique compression mechanism, comprising one main rotor with two meshing gate rotors one on each side as shown in Figure 2. The low-pressure refrigerant sucked in from the compressor inlet is supplied to the grooves provided in the screw rotors. The higher and lower compression chambers take in the refrigerant at the same pressure, and as the volume decreases due to the rotation of the screw rotors, the refrigerant is compressed. Generally, the timing at which the compressed refrigerant is discharged does not change between the higher and lower compression chambers. This means that the compression loads occurring in each of the higher and lower compression chambers are equivalent. However, the compression loads occurring in the higher and lower compression chambers are in opposite phase, and therefore the compressive loads on the screw rotors and the main shaft balance out, theoretically resulting in no compressive load on the main shaft.

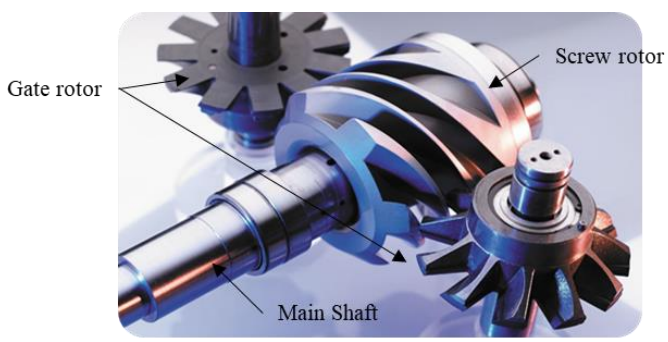

Figure 2: Single screw compressor

2.2 In The Development of New Design Two-Stage Compressor

In this development project, we have proposed two new designs for a two-stage compression mechanism. Each design has its own unique features. The first proposed design consists of three gate rotors for one screw, while the second design consists of two gate rotors for one screw rotor. Prototypes were built and evaluated for both designs, but this paper focuses on the second proposed design. However, a brief overview of the first proposed design is provided below. The most distinctive feature of the first propose design two-stage screw compressor is its incorporation of three gate rotors for a single screw rotor. This concept allows two-stage compression with low-stage suction, intermediate and a high-stage discharge pressure all contained in one single rotor and rotor housing. While the addition of a gate rotor from the traditional compressor structure increases the number of components, it also leads to a reduction in the impact of leaks from the high-stage compression chamber, as the behind of the high-stage compression chamber serves as an intermediate pressure chamber.

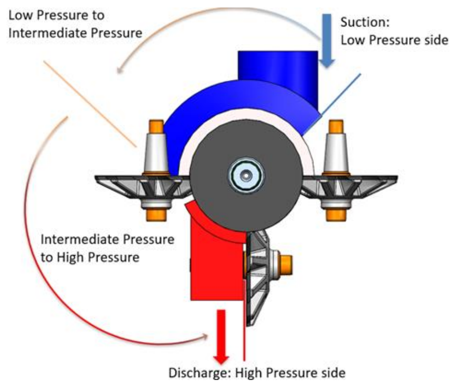

Figure 3: Outline diagram of new design two-stage compressor with three gate rotors

2.3 New Design Two-Stage Compressor with Two Gate and A Screw rotor

The proposed new design for two-stage compression leverages the characteristics of a single-screw compressor. This is achieved by re-evaluating the screw rotor shape and casing in the conventional compressor design to fully isolate the higher and lower compression chambers. As shown in Figure 4, a modification in the refrigerant flow path of the compressor is necessary to supply the refrigerant compressed in the low-stage compression chamber to the high-stage compression chamber. Although the number of compression chambers is reduced from the conventional two to one due to the structural changes, leading to a decrease in volumetric flow rate, The technical challenges and strategies related to achieving two-stage compression using one screw rotor and two gate rotors are outlined below.

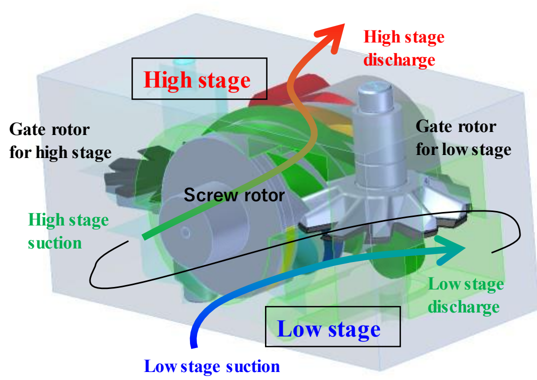

Figure 4: Conceptual drawing of new design two-stage compressor with two gate rotors

2.3.1 Isolation of high and low compression chambers: As illustrated in Figure 5, conventional screw rotors have notches at the ends to allow the intake of refrigerant, known as suction cuts. These are designed to facilitate the intake of refrigerant from the axial direction. However, in the proposed two-stage machine, where separation of the high and low compression chambers is necessary, it was decided to modify the screw rotor shape by eliminating the suction cuts (refer to Figure 6).

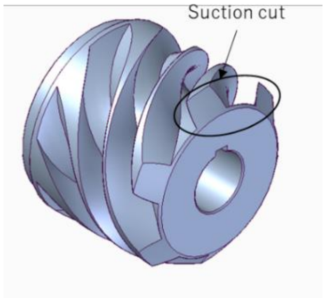

Figure 5: Conventional Shape (with Suction Cut)

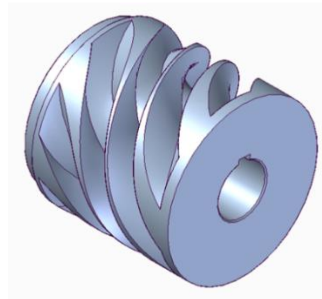

Figure 6: New Shape (Suction Cut less)

2.3.2 Improvement of reverse pressure on the gate rotor: The metal gate rotor support located on the back of the gate rotor in the single-screw compressor bears the compressive load generated within the compression chamber. However, in the structure of a new two-stage compressor, the back of the gate rotor forming the low-stage compression chamber becomes an intermediate pressure point, resulting in lower pressure within the compression chamber. This leads to a pressure differential towards the compression chamber from the gate rotor support side, which did not occur in the traditional single-screw compressor.

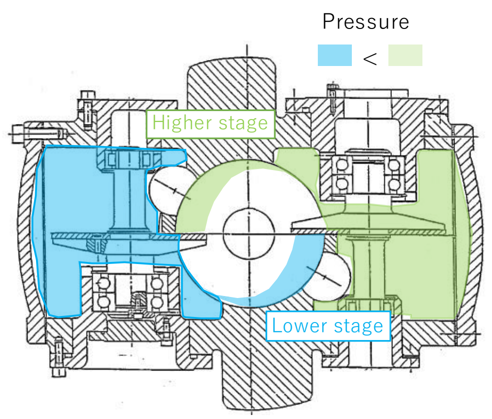

Figure 7: Pressure distribution during closing of compression chamber

There is a risk that this pressure differential may cause the gate rotor on the low stage to bend towards the compression chamber, potentially resulting in damage. To prevent this bending of the gate rotor, it was decided to adopt a structure in which all teeth of the gate rotor are bolted to the gate rotor support.

Figure 8: External View of bolt fixing of gate rotor

2.3.3 Volume optimization for low and high compression chambers: In the case of a two-stage compressor, the high-stage compression chamber draws in refrigerant compressed in the low-stage compression chamber, necessitating an adjustment of the cylinder volume ratio between the two chambers. Whereas in the conventional design, the gate rotors were positioned 180 degrees opposed to each other, it was decided to adjust the opposing angle of the gate rotors as illustrated in Figure 9 to modify the cylinder volume ratio between the low and high compression chambers. However, by changing the ratio of the low-stage and high-stage volumes, the load on each compression chamber becomes unbalanced. As a result, the load on the shaft and bearings becomes consistently acts in one direction, and it is excessively larger compared to conventional compressors where the load was balanced, requiring a significant redesign of the shaft and bearings.

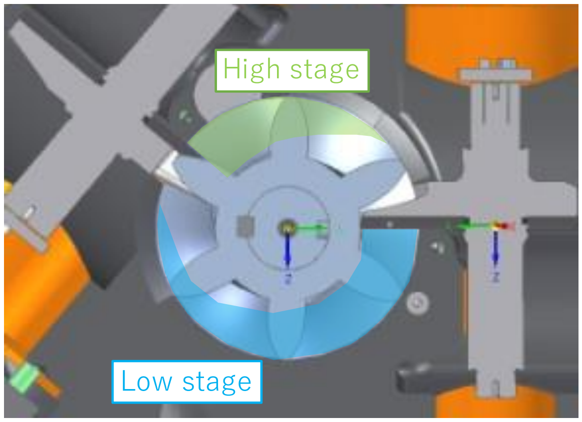

Figure 9: Volume ratio adjusting structure

2.3.4 Improve performance during low pressure ratio operation: Due to the potential use of the compressor for air conditioning, it is conceivable that air conditioning may be required during summer months in certain regions. Unlike heating conditions, cooling conditions can lead to pressure ratios of approximately 3-5, resulting in a performance decrease due to over-compression in a two-stage compressor. To maintain efficiency throughout the year, it becomes necessary to switch between two-stage and single-stage compression operations based on the operational conditions. In the proposed compressor, a mechanism was employed by moving the slide valve responsible for closing the high-stage compression chamber from the compression chamber, thus preventing the formation of the high-stage compression chamber. Consequently, the refrigerant discharged from the low-stage compression chamber flows out of the compressor without undergoing further compression in the high-stage compression chamber, allowing for single-stage compression.

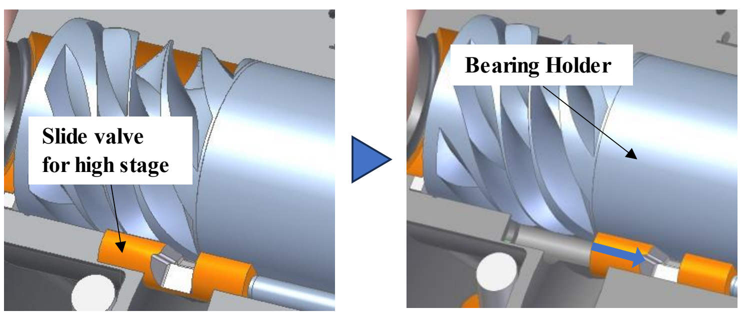

Figure 10: Switching structure of two-stage compression and single-stage compression

3. Experiment verification

3.1 Verification of the New Design Two-Stage Compressor Operation

A prototype two-stage compressor with the above-mentioned features was built and tested on a hot gas bypass test rig. While the compressor was designed for primarily R32 refrigerant, the performance evaluation was conducted using R410A due to equipment constraints of that test rig. Figure 11 illustrates the compressor assembly on the test rig. The test rig is not described in detail, but the piping design adjusts the temperature of the intermediate refrigerant by blending the refrigerant discharged from the low-stage with the liquid refrigerant in the receiver.

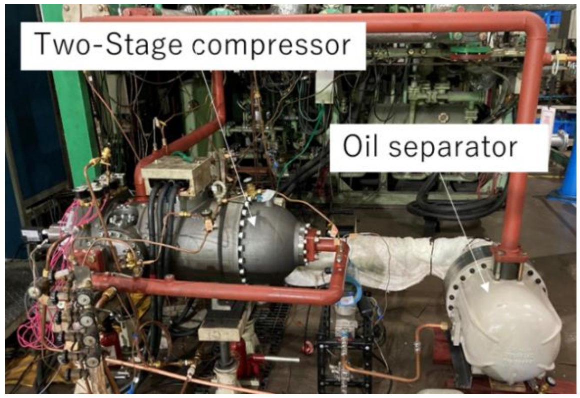

Figure 11: Appearance at the time of the test

Firstly, to verify that the two-stage compression process is functioning correctly due to the adoption of a novel structure, pressure measurements were conducted in both the low and high compression chambers. For this pressure sensors were attached at multiple points from the exterior of the casing towards the screw rotor bore to measure the internal pressures in each chamber and to analyze the pressure behavior by integrating the collected data. Figure 12 illustrates the relationship between the rotation angle of the screw rotor and the pressure measured within the grooves, confirming the distinct pressure behaviors in each compression chamber. Additionally, the approximate consistency between the refrigerant pressures after passing through the low-stage compression chamber and at the inlet of the high-stage compression chamber demonstrates that the refrigerant compressed in the low-stage chamber is supplied to the high-stage chamber and undergoes further compression in the high-stage chamber. Based on these observations, it was determined that the compressor is effectively established for two-stage compression using one screw rotor and two gate rotors.

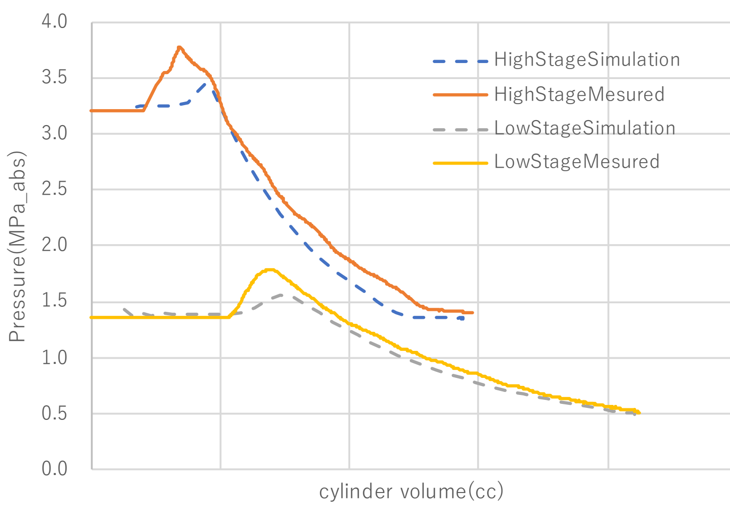

Figure 12: Pressure in the compression chamber

3.2 Performance Evaluation of the New Desing Two-Stage Compressor

As previously mentioned, this compressor is designed in view for heat pump application as an alternative to fossil fuel heating, to be employed in low outdoor temperatures below -20°C. To evaluate the performance trends of the prototype compressor, tests were conducted by varying the pressure ratio from 8 to 14. Figure 13 depicts the relationship between pressure ratio and volumetric efficiency, showing a similar trend of diminishing volumetric efficiency with increasing pressure ratios, as observed in traditional compressors. Furthermore, when comparing the simulation performance results with those obtained from the prototype, it was evident that the measured results were lower. This discrepancy is believed to be due to a lack of understanding of all the leakages and thermal losses occurring within the compressor's structure, recognizing that addressing these issues is a future challenge. On the other hand, Figure 14 illustrates the relationship between pressure ratio and compressor power, indicating a tendency for the measured compressor power to be higher than the calculated values. Upon examining the pressure within the compression chamber depicted in Figure 12, it was observed that the pressure rise on the high-stage compression side occurs earlier than the calculated compression start time. This suggests an increase in power. It signifies the necessity to identify the specific mechanism causing the compression chamber to commence earlier than the determined closing time based on the geometric shape. Additionally, the sustained pressure rise even after the discharge port opens suggests a significant over-compression and is also considered a factor contributing to the power increase.

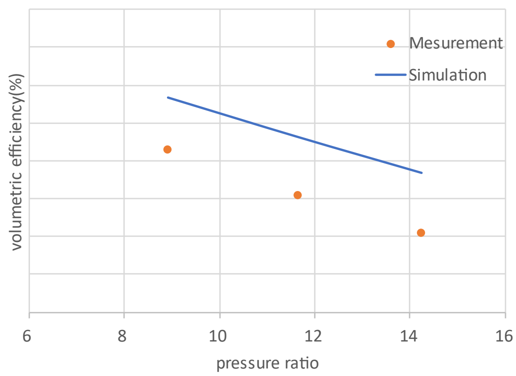

Figure 13:pressure ratio Curve with volume efficiency

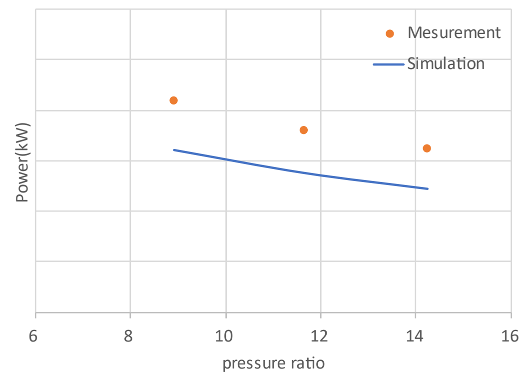

Figure 14: pressure ratio curve with Power

3.3 Switching Evaluation between Two-Stage and Single-Stage Compression Operations

As previously stated, owing to the intended use of the compressor for air conditioning, it was necessary to reassess the operation of the slide valve for the high-stage compression chamber to allow the compressor to adapt to general air conditioning conditions, such as a pressure ratio of 3-5. During the practical assessment, the operation state transition was verified by examining the pressure behavior before and after the first and second-stage compression chambers when transitioning from two-stage compression to single-stage compression. The measurement results are depicted in Figure 15. During two-stage operation, the refrigerant pressures at the inlet and outlet of the second-stage compression chamber did not match. However, by moving the slide valve for the high stage, the pressures aligned, confirming that the operational transition is proceeding as planned and functioning properly.

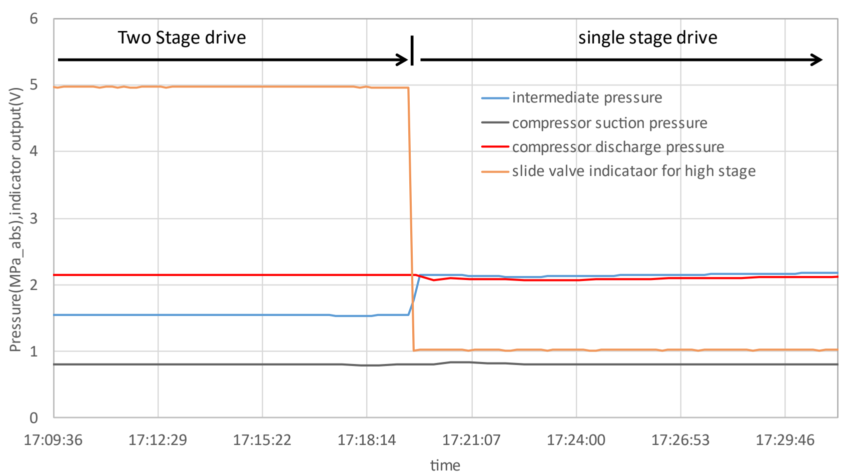

Figure 15: Measurement result when switching operation

4. CONCLUSIONS

Although problems remain, a new two-stage compressor has been successfully developed with the intention of reducing costs for application in heat pump chillers as an alternative to combustion heating. As outlined below:

- Through re-evaluation of the screw rotor shape and casing, it has been confirmed the actual machine can achieve a two-stage compression using one screw rotor and two gate rotors, without increasing the number of components from the conventional single-screw compressor.
- Discrepancies were found between the performance measurement results and the calculated values, indicating unidentified leak paths and factors leading to power increase.
- It has been verified the actual machine transition between two-stage and single-stage operation and this can be accomplished through the position control of the slide valve.

5. ACKNOWLEDGEMENTS

In the process of this development, we greatly appreciate the valuable advice given by Lafford, Dominic, Dhunput, Ashvin, Van der Poll, Maghmood, and Young, Terry, who are affiliated with J&E Hall, LTD. Furthermore, we would like to express our gratitude to Yoshimura Keiji, and Mori Kazuki from Daikin Industries, LTD. for their assistance in project management, as well as to Fukuda Daigo, Ueno Hiromichi and Goto Nozomi also from Daikin Industries, LTD. for formulating the fundamental concept of this development machine. We would like to take this opportunity to express our gratitude to them.

REFERENCES

C. Watanabe (2018) Trends in Heat Pump Technology in Europe Technological Trends in Heat Pump Conference 2017 and European Heat Pump Summit 2017. JSRAE Annual Conference Program In 2018

D. Fukuda, H. Ueno, T. Inoue, N. Goto 2021, Screw Compressor, and Refrigeration Device, WO2021/200858

EHPA: https://www.ehpa.org/news-and-resources/news/which-countries-are-ending-fossil-fuel-heaters

H. Ueno. (2013) History of Single Screw Compressors. In proceedings of the JSRAE Annual Conference, Japan (247-250)

Young T.W.T, Roll J.M, Dhunput A, Van Der Poll M, 2020, Screw Compressor, WO 2020/165561

Zimmern, B., and Patel, G.C. (1972) Design and Operating Characteristics of the Zimmern Single Screw Compressor. In proceedings of the 1972 Purdue Compressor technology Conference, West Lafayette, USA (96-99).