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Study of High-Performance Engineering Polymers Applied in Reciprocating Hermetic Refrigeration Compressors – Part 2: Extension to New Components & Experimental Validation

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ABSTRACT

Energy efficiency of hermetic refrigeration compressors has been of tremendous importance in both domestic and commercial applications, leading to significant focus on innovations in not only product design and manufacturing processes but also materials. This paper is a continuation of a previous study by the authors that investigated energy efficiency gain by comparing low conduction heat transfer plastic materials to incumbent metallic materials. In this work, suitability of high performance polymeric materials for metal replacement has been evaluated for three components of a commercial compressor: cylinder head, valve plate and discharge tube. Considering functional requirements of each component, suitable polymeric materials were selected to replace the current metallic part. Equivalent plastic designs were developed for each part without altering any other component and functionality of the compressor assembly. Finite element-based simulations were performed to verify and optimize the plastic designs. Also, injection molding process simulations were conducted to verify the feasibility of the molding process. Physical prototypes were developed for experimental tests. The objective was not only to validate the efficiency gain predicted at system level simulation in the previous study but also to evaluate durability of each of the plastic components. Short-term test findings included in this paper are compressor operational performance, internal refrigerant leakage, and calorimeter performance measurements. The variability of the calorimeter results was substantial compared to the expected differences estimated by numerical simulation. With the first round of tests, we estimated the sample size using the averages and standard deviations and concluded that the sample size should be increased in order to detect the effect of interest. Calorimeter tests indicated a COP gain of 1.16% to 2.91% at specific conditions. The plastic parts survived and were intact after short term testing. The refrigeration leakage of the plastic components was similar to the metal counterparts and no loss in the bolt torque retention was detected. This work provides grounds for durability and performance stability evaluations of plastic components in the future work.
Keywords: Compressor; Metal Replacement; Advanced Polymers; COP Improvement; Finite Element Analysis

1. INTRODUCTION

In order to improve the refrigeration system performance, researchers from academia and industry have been focusing on increasing the efficiency and reducing the losses of the system. Since the compressor is the main driving element in the refrigeration cycle, its performance has significant effect on the effectiveness of a refrigerator. Among several factors, performance of a compressor is affected by superheating inside the compressor leading to lower energy efficiency. One of the main heat sources inside the compressor is the energy transfer from the high temperature compressed refrigerant through the internal metal components i.e., cylinder block, cylinder head, valve plate, discharge muffler, and discharge tube. The authors of the current paper previously investigated improving the compressor performance by decreasing the energy transfer between the hot high-pressure refrigerant and internal components thus reducing heat losses within the compressor, [1]. It was proposed that decreasing the thermal conductivity of the internal components like the cylinder head, valve plate and the discharge tube would increase thermal insulation. Using a full three-dimensional heat transfer model, the work studied the efficiency variation if the thermal conductivity is decreased by replacing the current metallic components by polymeric parts using the commercial code GT-SUITEmp [1, 2, 3, 4]. Based on these thermal predictions, efficiency gains in a compressor by replacing metal components with polymeric materials were predicted.

Building on this previous work, the current paper continues the metal-to-plastic (M2P) replacement of the previously identified cylinder head component as well as two additional components: the valve plate and discharge tube.

Figure 1 shows the original metal components replaced with plastics. For each of the three components, an equivalent plastic design was developed in an attempt to achieve the same or better COP performance than existing metal parts without altering any other component and functionality of the compressor assembly. To optimize and verify the plastic designs as well as the feasibility of the manufacturing process, computational simulations were performed. Using the optimized design, physical prototypes were developed with identified materials for experimental testing. Furthermore, to investigate the short-term performance, three tests were conducted: leakage, torque and calorimeter. The objective was not only to validate the COP gain predicted at system level simulation in the previous study, but also to evaluate reliability of each of the plastic components.

(a) (b) (c)

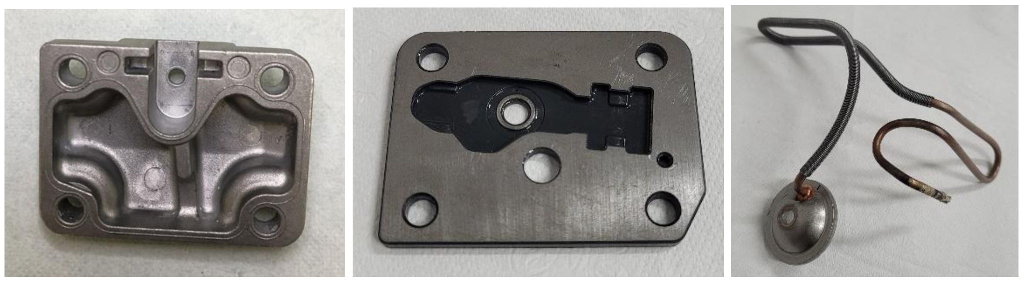


Figure 1: Original metal parts: (a) Cylinder head (b) Valve plate (c) Discharge tube

Considering functional requirements of each component, suitable polymeric materials were selected to replace the current metallic parts. High temperature engineering polymers like polyphthalamides (PPA) and polyphenylene sulfide (PPS) are attractive for these applications due to their two orders of magnitude lower thermal conductivity than aluminum. In addition, they are typically compatible to the compressor environment and retain their mechanical properties at high temperatures and dimensional stability with low creep and high fatigue resistance. These properties must be maintained when exposed to the various refrigerants encountered in a compressor, so chemical resistance is required. Pai-Paranjape [5] has demonstrated that these filled engineering thermoplastics have good chemical compatibility with R-134A and R-410A compressor environments. Another characteristic of PPA and PPS is the ability to be easily injection molded into complex components and maintain tight dimensional tolerances. These suggested polymers are not overpriced to exclude their use. The polymer material selection for metal replacement of each of the three components is described in the methodology section.

2. METHODOLGY

2.1 Metal-to-Plastic Design Development and Prototyping

For this work, after-market compressors were purchased. The selected model is a variable speed reciprocating compressor whose speed ranges between 1620 and 4800 RPM. This is a high efficiency household freezer/refrigerator system based on the Brazilian energy efficiency rating program and operating with R800A refrigerant [6]. To develop equivalent plastic designs, CAD models of existing metal parts were generated through reverse engineering optical and tomography methods. To verify and optimize the plastic designs, finite element-based simulations were performed. Also, injection molding process simulations were conducted to verify the feasibility of the molding process. The effects of processing and gating were taken into account considering the fiber orientation and weld line effects on performance of the plastic parts. Multi-scale material modeling was employed. Physical prototypes were developed through machining injection molded stock shapes. This helped expedite the experimental short-term testing without developing an injection molding tool. The objective was to evaluate the feasibility of each of the plastic components and to validate the efficiency gain predicted previously.

2.1.1 Cylinder Head

The cylinder head component is meant for enclosing the compressed high-pressure high temperature refrigerant from the cylinder block and providing a passageway for the compressed refrigerant to the discharge tube. Two key requirements of this component are to ensure gas-sealing and minimize the heat transfer which are related to the efficiency of the compressor. This requires materials possessing properties compatible with the compressor environment as discussed above. Another material characteristic is the ability to be easily injection molded into complex components and maintain tight dimensional tolerances. The fiber reinforced semi-crystalline aromatic polymers selected for this application are polyphenylene sulfide (PPS) and polyphthalamide (PPA). Table 1 shows the relevant mechanical and physical properties [7].

The plastic design presented in the previous paper [1] was developed through successive iterative analyses. The design progression is shown in Figure 2(a). Since the original publication, the optimized plastic design was further analyzed.

Table 1: Properties relevant to proposed materials for cylinder head and valve plate

Material	Cylinder Head			Valve Plate		
	PPA Amodel® AS-1145	PPA Amodel® AS-1566	PPS Ryton® R-240	PEEK Ketaspire® KT-880 GF30	PAI Torlon® 5030	PPA Amodel® AS-9933
Thermal Conductivity (W/m.K)	0.33	0.45	0.29	0.30	0.36	0.35
Mold shrinkage (Flow / Cross flow) (%)	0.2 / 0.6	0.3 / 0.5	0.2 / 0.5	0.2 / 0.6	0.15 / -	0.2 / 0.9
Density (g/cc)	1.56	1.84	1.66	1.53	1.61	1.46
Tensile Modulus (GPa) @ 23°C	16	22	14	11	14	11.4
Tensile Modulus (GPa) @ 75°C	13	21	13	11.0	12.5	10.6
Tensile Modulus (GPa) @ 120°C	10.5	16.0	8.0	10	11	9.5
Tensile strength break (MPa) @ 23°C	263	200	185	200	250	198
Tensile strength break (MPa) @ 75°C	185	140	131	166	220	182
Tensile strength break (MPa) @ 120°C	125	85	84	130	195	132
Poisson's ratio	0.40	0.40	0.38	0.39	0.40	0.38
Fatigue strength at 23°C 10E6 cycles (MPa)	82	-	92	105	-	-

(a) (b)

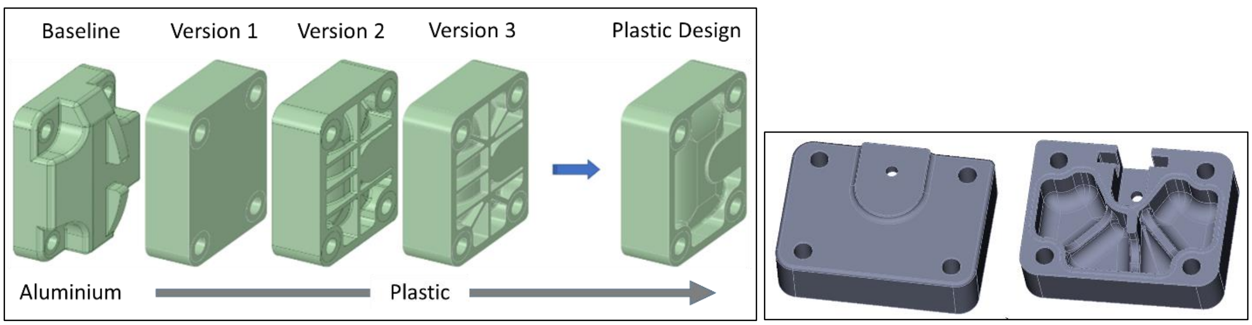


Figure 2: (a) Original design progression from aluminum baseline to a plastic version (b) Redesigned plastic head

The process involved conducting an injection molding simulation, transferring the resulting fiber orientations (thus anisotropic stiffness throughout the part) to the structural analysis, and calculating the resulting deflections and stresses. The results showed considerable deflection in the area of the seal. Because of this, the part was redesigned to increase overall rigidity. For this study, the resulting final part configuration is shown in Figure 2(b).

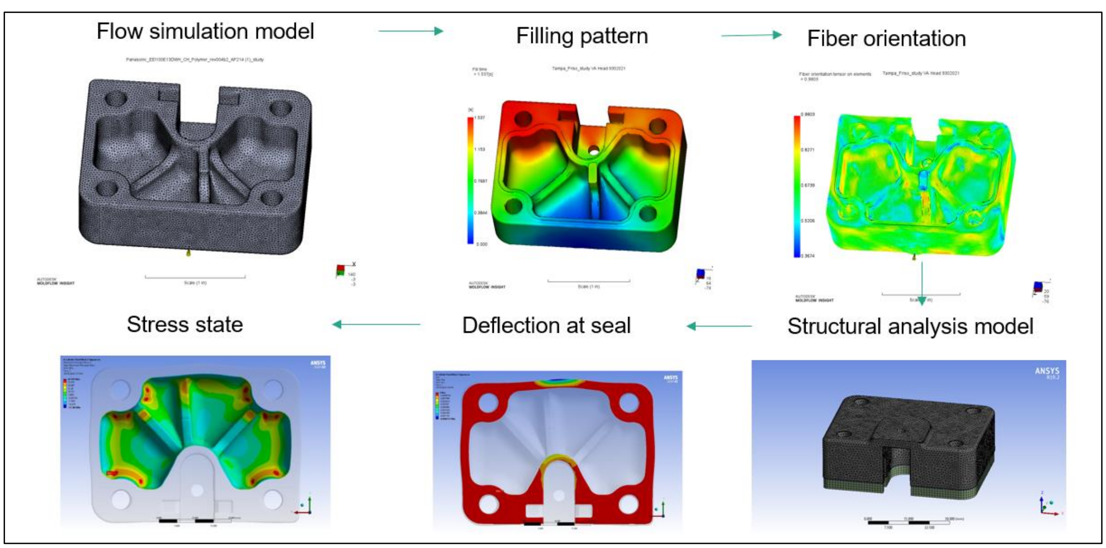


Figure 3: Cylinder head design analyses sequence

This stiffer design was subject to the same analysis sequence as the original design: Injection molding simulation, fiber property transfer, and subsequent structural analysis. The process is shown in Figure 3 and the results indicate the redesigned cylinder head meets the structural requirements and is acceptable for the injection molding procedure. The peak stress shown above is 42 MPa, which when compared to the tensile strength of the material at elevated tempearture ensures a generous safety factor, even if a flow weld line is present. Figure 4 shows the prototype of the final design obtained by machining extruded cylindrical blanks.

Figure 4: Cylinder head prototype

2.1.2 Valve Plate

The valve plate retains the metal suction and discharge reed valves. The mating surfaces of the reed valve and the valve plate must maintain an extremely accurate fit and dimensional configuration to provide sealing during the compressor operation. The sealing characteristics of these valves determines the efficiency of the suction and discharge processes and strongly influences the Energy Efficiency Ratio Rating of the compressor. The operating requirements for the valve plate dictate materials with enhanced properties while still possessing low thermal conductivity and good chemical resistance. The valve plate temperature is locally higher than the cylinder head requiring a more robust polymer with increased thermal, wear and toughness properties. Three attractive candidates for this component include a 30% glass reinforced PEEK, a 30% glass filled PAI, and a 33% glass filled “ultra” high temperature PPA. Relevant properties of the chosen materials are listed in Table 1.

(a) (b)

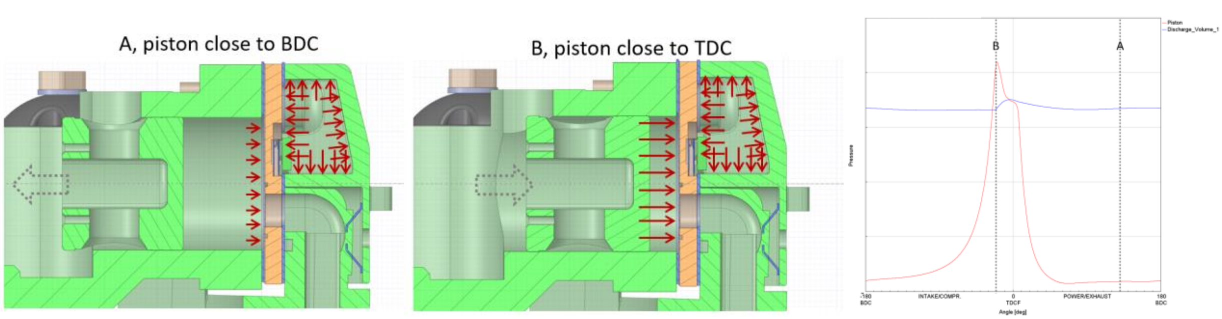


Figure 5: (a) Valve plate load conditions (b) Plot of cylinder pressure (red) and cylinder head pressure (blue)

These valve plate plastic designs were subjected to stress and deformation analysis for two load conditions, shown in Figure 5: A– when the piston is close to the bottom dead center and the pressure inside the cylinder head is significantly higher than the pressure inside the cylinder, and B – when the piston is close to the top dead center and the cylinder pressure is higher than the cylinder head pressure. Condition A is more critical because, if the valve plate isn’t stiff enough, significant leakage can occur between the cylinder head and valve plate.

As shown in Figure 6, the structural analysis indicates the stresses at the valve plate are lower than the failure criteria, and the relative deformation in the sealing area between the valve plate and the cylinder head is small enough to provide sufficient sealing with the existing gasket. For reference, the peak stress was 29 MPa.

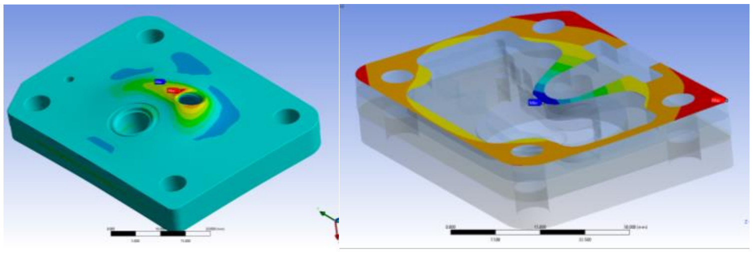


Figure 6: Valve plate stresses (left) and relative deformation between the valve plate and the cylinder head (right).

Figure 7 shows the plastic prototype of the selected design obtained by machining the injection molded plaques.

Figure 7: Valve plate prototype

2.1.3 Discharge Tube

The copper discharge tube is an ideal candidate for metal replacement. It conveys the high pressure high temperature gas to the external condenser line on the outside of the compressor. It also has to be designed to withstand the noise-vibrations-harshness (NVH) associated with the compressor operation and the momentum spurts of the starting and stopping of the compressor. A perfect candidate material for this part is an extruded PFA polymeric tube. PFA resins are a family of semi-crystalline melt processable perfluoropolymers with excellent mechanical properties, high and low temperature resistance, chemical inertness, inherent flame resistance, and inherent damping characteristics.

(a) (b) (c)

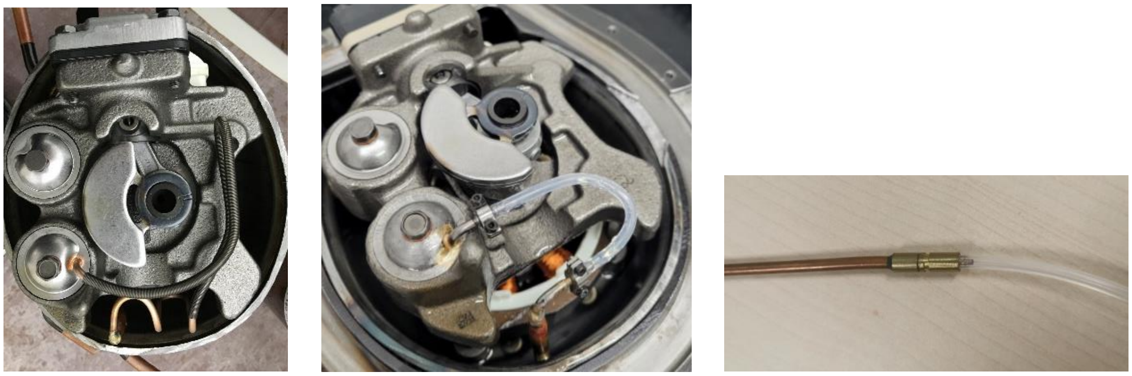


Figure 8: (a) baseline copper discharge tube assembly (b) polymer discharge tube assembly (c) polymer discharge tube connected to metal outlet

Table 2: Properties relevant to proposed materials for discharge tube

Material	PFA Hyflon® P-450
Thermal Conductivity (W/m.K)	0.20
Density (g/cc)	2.18
Tensile Modulus (GPa) @ 23°C	0.6
Tensile strength break (MPa) @ 23°C	26

Relevant properties of the selected PFA material are listed in Table 2. One critical design detail is the hermetic connection of the extruded tube to the outlet of the discharge muffler and the refrigerant exit tube. Several design concepts were investigated. This process resulted in a robust interface that has proven to meet the compressor operating requirements. The extruded tube and interface details are shown in Figure 8(c).

2.2 Short-term Testing

The machined prototypes were subjected to short-term tests including refrigerant leakage, torque stress and calorimetry measurements. These tests were used to investigate the feasibility and reliability of each of the plastic components and to validate the efficiency gain predicted at system level simulation in the previous study. Different test setups were prepared for the short-term testing. Specific test setups, including semi-hermetic calorimeter testing, were performed on the baseline compressor (all metal parts) and the modified compressor containing all three plastic components. These setups are described in the sections below.

2.2.1 Leakage Test

Refrigerant leakages can occur between several parts in the compressor and can significantly reduce both cooling capacity and performance efficiency. Typical areas for possible refrigerant leakage are:

- Piston cylinder blow by (clearance between piston and piston cylinder)
- Valve Plates (sealing between reed valves and valve plate)
- Gaskets and mating surfaces (cylinder head and valve plate)
- Discharge tube connections. (PFA extruded tube connection between discharge muffler and exist tube)

As the cylinder head, valve plate and discharge tube, were replaced with polymer, it was important to check if the sealing characteristics of the polymer parts performed similar to the metal ones. The initial sealing between the metal reed valve and polymeric valve plate was imperfect due to the surface irregularities associated with the machining operation and assembly alignment. It is critical for the polymeric valve plate and the reed valve interface to be perfectly matched. For this to occur, the mating surface on the polymer valve plate had to be honed by hand to remove the surface anomalies associated with the machining operation. This modification provided the same sealing characteristics as the original metal counter parts.

(a) (b) (c)

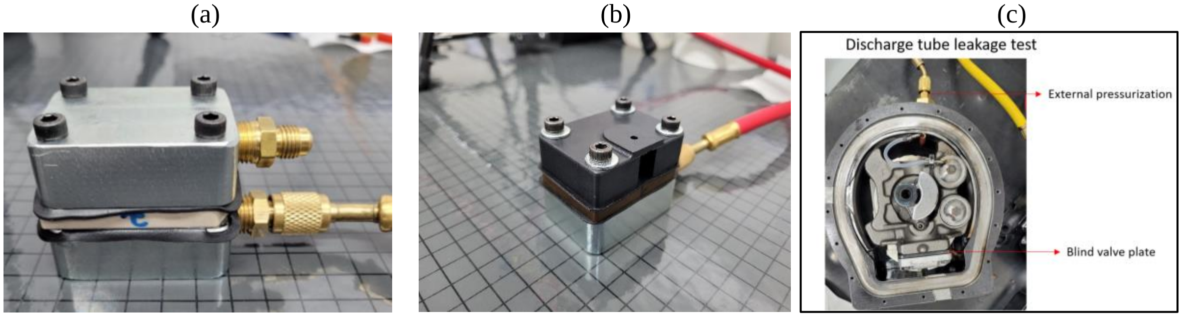


Figure 9: Leakage test: (a) Device to measure the valves and valve plate leakage (b) Device to measure the cylinder head leakage (c) Apparatus to measure the discharge tube leakage. The valve plate is assembled in the compressor and the discharge line is externally pressurized

The polymer cylinder head was obtained by machining a polymeric stock shape of PPS. The discharge tube was obtained by extruding a small diameter tube of PFA. No secondary processing operations were necessary to improve their sealing characteristics. A specific experimental apparatus was designed to measure the sealing/leakage characteristics of the polymeric components. The apparatus composed of a high-pressure gas reservoir and a pressure regular. The apparatus was connected to each subassembly. The subassembly was pressurized to a specific pressure and the inlet valve was closed. The subassemblies pressure was measured at specific time intervals. The test concluded when the pressure dropped to 87.5% of the original pressure. The working fluid was air. The leakage/sealing performance was defined as the elapsed time to decrease the reservoir pressure from 1 [pressure units] to 0.875 [pressure units]. Table 3 shows the time associated for each sub-assembly. Each sub-assembly was characterized with a specific leakage time. For this work we have five subassemblies, as shown in Figure 9**:**

- Suction valve and valve plate
- Discharge valve and valve plate
- Cylinder head
- Discharge tube and its connections
- Cylinder head, valve plate and valves, discharge tube, compressor shell and discharge volume

The leakage test showed good sealing for the polymeric components after minor modifications to the valve plate discharge and suction ports. The valve plate discharge and suction ports required an abrasive lapping finishing to improve the sealing between the reed valves and valve plate. The cylinder head and discharge tube yielded good sealing without any additional adjustments. The compressor assembly using polymeric components resulted in sealing properties equivalent to the metal baseline version. In summary, all leakage times of the polymer components were similar to the metal counterparts and met the approval criteria.

Table 3: Leakage time results for each sample assembly

	Sample 1	Sample 2	Sample 3
Suction valve and valve plate	60 min	30 min	20 min
Discharge valve and valve plate	> 60 min	60 min	> 60 min
Discharge tube	~120 min	~120 min	~120 min
Cylinder head, discharge tube, compressor shell and discharge volume	> 60 min	> 60 min	> 60 min

2.2.2 Torque Test

Polymer parts are susceptible to creep and bolts used to retain components can loosen with time. To check torque retention, a torque test was developed with thermal cycling to guarantee a minimum residual tightening torque for the cylinder head bolts. Starting at room temperature, the assembled cylinder head and valve plate are heated up to 100°C (measured at the cylinder head) and kept at that temperature inside an oven as shown in Figure 10(a). After 1 hour, the compressor unit is removed from the oven and cooled to room temperature. The room temperature cylinder head residual tightening torque is measured. The residual tightening torque is defined as the torque needed to start the rotation of the bolt in the tightening direction.

(a) (b) (c)

Figure 10: Torque test: (a) Compressor inside the oven (b) Thermometer (c) Compressor inside the oven

Three torque test procedures were evaluated:
Test 1: Tightening torque up to 4 N-m, thermal cycle, retightening torque up to 4 N-m, thermal cycle, up to 5 cycles
Test 2: Tightening torque up to 6 N-m, thermal cycle, retightening torque up to 6 N-m, thermal cycle, up to 4 cycles
Test 3: Initial tightening torque of 6 N-m and residual torque verification performed after each thermal cycle. Retightening torque of 6 N-m after 1st thermal cycle. No retightening required after 1st thermal cycle, a total of 8 thermal cycles were used.

Torque testing was implemented to verify bolt torque values and did not diminish over time due to polymer creep. All cylinder heads assembles underwent thermal cycling until the minimum residual torque tightening value was maintained. As shown in Table 4, the torque test showed that after just a few thermal cycles it was possible to stabilize the assembly residual torque:

Test 1: Residual tightening torque stabilized around 4 N-m after thermal cycle 4.
Test 2: Residual tightening torque stabilized around 4 N-m after thermal cycle 2, around 6 N-m after thermal cycle 3.
Test 3: One retightening torque was needed after the first thermal cycle. No retightening torque for the following thermal cycles. The residual tightening torque stabilized above 4 N-m after the thermal cycle 3.
The samples for the calorimeter tests followed Test 3 procedure.

Table 4: Torque test results

		Bolt 1	Bolt 2	Bolt 3	Bolt 4
Test 1	Thermal cycle 1	1.5	2.0	1.8	1.3
	Thermal cycle 2	3.2	3.7	3.2	3.2
	Thermal cycle 3	2.7	3.0	2.8	2.7
	Thermal cycle 4	4.2	4.2	3.7	3.8
	Thermal cycle 5	4.0	4.5	4.0	4.0
Test 2	Thermal cycle 1	No recorded data	No recorded data	No recorded data	No recorded data
	Thermal cycle 2	4.7	4.5	4.5	4.0
	Thermal cycle 3	6.3	6.0	6.2	6.0
	Thermal cycle 4	7.0	6.5	6.5	6.5
Test 3	Thermal cycle 1	3.5	2.5	3.0	3.5
	Thermal cycle 2	5.4	4.5	5.0	5.4
	Thermal cycle 3	4.8	4.1	4.5	4.0
	Thermal cycle 4	4.9	4.1	3.8	4.5
	Thermal cycle 5	4.8	4.0	4.0	4.7
	Thermal cycle 6	4.7	4.2	4.6	4.5
	Thermal cycle 7	4.7	4.3	4.8	4.8
	Thermal cycle 8	4.8	4.3	4.7	4.7

2.2.3 Calorimeter Test

The calorimeter experimental test is a short (8~10 hours) test, and aims to quantify the cooling capacity and energy consumption of refrigeration compressors. The ratio between the cooling capacity and the energy consumption is the coefficient of performance, COP, which is a measure of the compressor efficiency.
The cooling capacity is related to the mass flow rate of the compressor. The energy consumption depends on the electrical losses (in the motor and the controller), the friction losses, and the thermodynamic power consumption ($P*\Delta V$). Figure 11 shows the schematic of calorimeter test setup. The calorimeter assemble usually contains:

- electrical power analyzer
- a mass flow meter
- a secondary fluid heat exchanger
- controllers, heaters, coolers to provide controlled evaporating and condensing refrigerant temperatures and pressures, and a controlled inlet refrigerant temperature, and a controlled surrounding air temperature

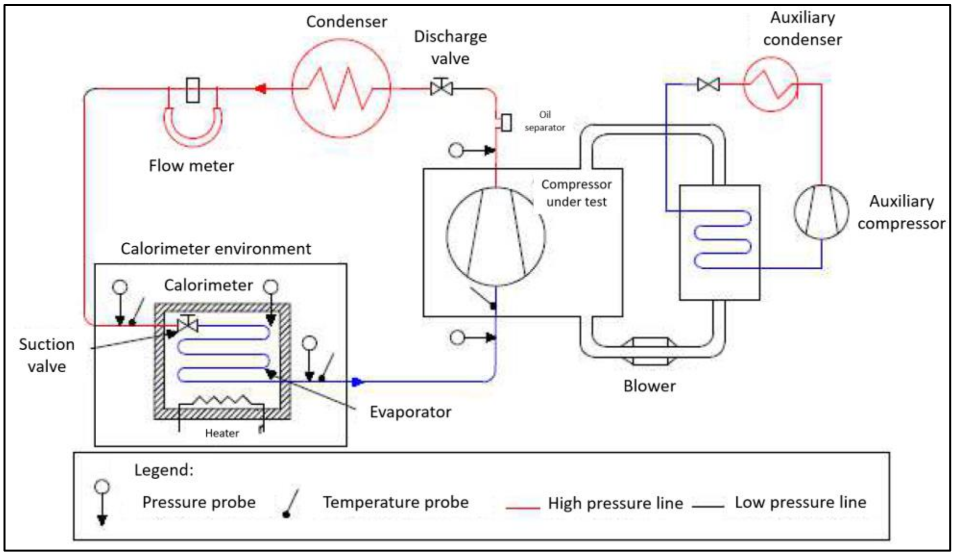
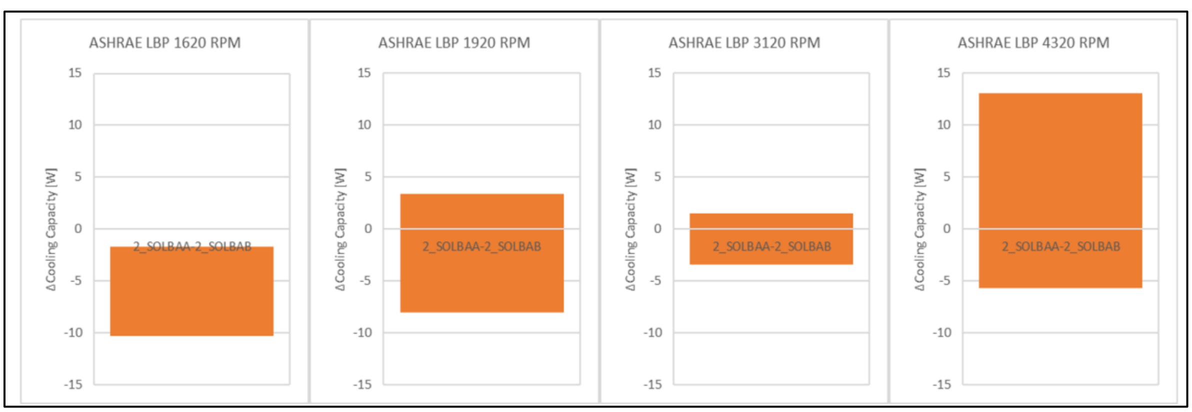


Figure 11: Schematic of calorimeter test setup [8]

Table 5: Two compressor configurations were assessed: all metal compressor and M2P compress using polymer cylinder head, valve plate and discharge tube. Three samples for each configuration were evaluated.

	All metal (Baseline, BL)	Polymer cylinder head, valve plate and discharge tube (Metal to polymer, M2P)
Sample 1	BL1	M2P1
Sample 2	BL2	M2P2
Sample 3	BL3	M2P3

The calorimeter results were analyzed using paired t-test methodology. The variability of the calorimeter results was substantial compared to the expected differences estimated by numerical simulation. It was not possible to statistically conclude whether the cooling capacity and COP was different, better, or worse, with the exception of two situations. Assuming that the cooling capacity and COP is normally distributed with a 95% confidence interval, the M2P cooling capacity changed at 1620 RPM by -8.2% to -4.2%, and COP changed at 3120 RPM by +1.16% to +2.91%. Figure 12 shows a 95% confidence interval change in cooling capacity and COP, respectively. Positive values means that the M2P version is higher than the baseline.



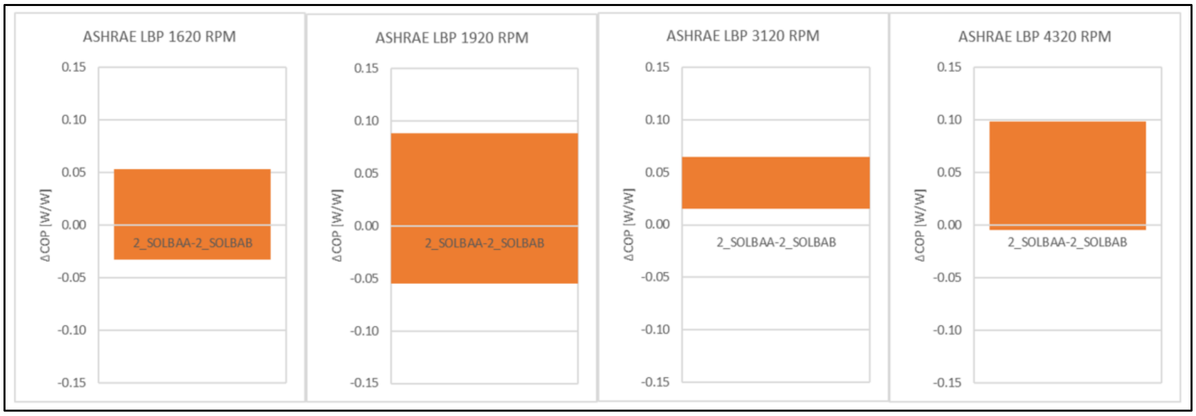


Figure 12: Calorimeter test results: Capacity difference vs RPM (top) COP difference vs RPM (bottom)

The decrease in the cooling capacity in unexpected and additional investigations must be done. There are several effects like leakage, backflow, etc. that can influence the cooling capacity at low RPM. Another way to validate the M2P and the metal baseline calorimeter data is the p-value. The p-value can determine if the test data has a real statistical difference. If the p-value is lower or equal to (1-conf.level=0.05), we can conclude that the difference between the two paired samples are significantly different. Table 6 presents the p-value for the change in the cooling capacity and the COP. As shown by the confidence interval, only the change in the cooling capacity at 1620 RPM and the COP at 3120 RPM are statistically conclusive. With that first round of tests, we also estimated the sample size to reasonably detect an effect and if it really is there. Table 6, also shows the sample size needed to capture the effect of the metal-to-plastic replacement on cooling capacity and COP for each RPM level. We considered 0.8 power as the effect size according to Cohen's formula, 0.05 significance level and paired t-test. It's clear that for cooling capacity the sample size was appropriate to conclude the effect at 1620 RPM. For the other RPM and COP values, the sample size should be increased but an effort size evaluation must be done to decrease the cooling capacity variability at 3120 RPM and 4320 RPM. These results indicate a COP gain at high RPM. At lower RPM, the results were statistically inconclusive. Additional testing is being conducted to further quantify the results. Other materials are also being investigated.

Table 6: p-value and the effect of the M2P on the change in the cooling capacity and the COP for each RPM

RPM	Δ Cooling capacity p-value	ΔCOP p-value	Sample size needed to detect the effect on cooling capacity	Sample size needed to detect the effect on COP
1620	0.03	0.42	3	25
1920	0.22	0.42	8	17
3120	0.23	0.02	189	5
4320	0.24	0.06	50	5

3. CONCLUSIONS

The testing discussed in this paper illustrate that specifically selected aromatic polymers are suitable for components in a compressor environment. The plastic components showed not adverse behavior in the 8-10 hour calorimeter test, were intact, and displayed no physical damage from the testing. Refrigerant leakage associated with the machined plastic components were similar to their metal counter parts. The bolt retention torque associated with the plastic components remained constant throughout the test, indicating that with the proper torque value, plastic creep will not be a significantly variant in maintaining the sealing properties of the plastic parts. Some initial torque retention was lost during thermal cycling, but straightforward solutions are available to maintain the desired torque levels. At high RPM, the results indicate the expected COP gain can be achieved. At lower RPM, the results were inconclusive. The variability of the calorimeter results was substantial compared to the expected differences estimated by numerical simulation. With the first round of tests, we estimated the sample for a paired t-test and concluded that the sample size should be increased to a number as high as 189 in order to detect the effect of interest. To reduce sample size, efforts must be made to decrease the variability of the tests. Even when using paired t-test methodology to statistically evaluate the calorimeter tests and assuming that the cooling capacity and COP is normally distributed with a 95% confidence interval, the M2P cooling capacity changed at 1620 RPM from -8.2% to -4.2%, and COP changed at 3120 RPM from +1.16% to +2.91%. Additional testing will be conducted to further refine those results. Building on the current work, the next step is to manufacture injection molded prototypes that will be used to evaluate durability and performance stability during long term testing.

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