# Danfoss Turbocor: Compressor Inlet Sting Apparatus for Dynamic Real-time Monitoring and Recording of Compressor Inlet Guide Vane Operations

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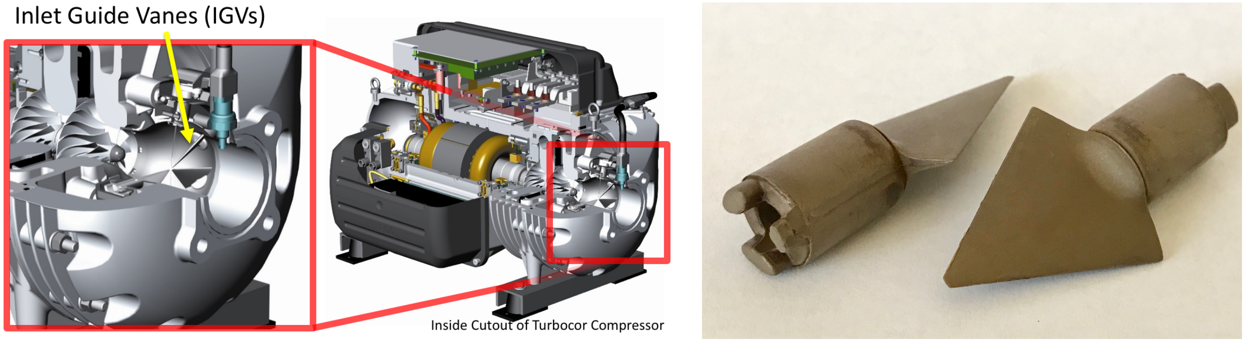
**The Danfoss IGV Senior Design Team is engineering a monitoring device for the Danfoss testing lab. The compressors Danfoss makes use blades at the entrance to help channel the incoming gas which help control the performance of the compressor. These blades can break due to high pressure zones and vibrations caused by the gas. Danfoss Turbocor does not currently have a method to inspect the blades while the compressor is running. The device we built uses a small camera inside the pipe that feeds the gas, aimed at the entrance to provide live video of the blades directly to the test lab. With this, the test lab can see if the blades are working properly. A computer program also uses the live video feed to analyze a set of QR code stickers placed on the blades. This program provides more detailed information about the blades, like if they are broken or moving in unplanned ways. The program inspects the video feed and automatically determines if all of the stickers on the blades are present and estimates the angle of the blades based on the tilt of the stickers. With this computer program our system alerts the Danfoss testing lab technicians if the system detects any problems with the blades. Our team designed the housing for the camera and the lighting system used inside the pipe. We also developed the program to analyze the stickers on the blades. With the device, Danfoss engineers and designers can see the blades during operation for the first time, and they can learn about the conditions that the blades undergo during operation. This paper gives an overview of the project background, the methods used in designing and testing the device and outlines the final results of the project**

## Nomenclature

$IGV$ = Inlet Guide Vane

# I. Introduction

Danfoss Turbocor designs and manufactures industry leading compressors for a variety of HVAC applications. These compressors use magnetically levitating bearings to hold the central axle of the impellers allowing for a completely oil free design. The inlet guide vanes (IGVs) at the inlet of the compressors regulate the incoming flow of refrigerant. The compressor can modify the inlet mass flow rate by changing the angle of the IGVs to change the performance characteristics and to increase the overall efficiency. The IGVs also introduce swirl into the inlet flow, leading to a better incident angle with the compressor's impeller, reducing the induced turbulence after the first stage. Figure 1)a shows the IGV locations at the front of the compressor and figure 1)b better outlines what the geometry of the IGVs looks like.



a) Cross-Sectioned Compressor Showing IGVs

b) Sample IGVs removed from compressor

**Figure 1. Overview of IGV location and geometry**

While developing new compressor models, Danfoss Turbocor testing facilities install compressor prototypes including IGVs in refrigerant testing loops and run a series of tests to measure the performance of the compressor. These testing rigs often run for weeks at a time. However, sometimes one of the IGVs breaks while the compressor is running, invalidating all measured data because broken IGVs are not identified until after the testing rig is deconstructed. Therefore, Danfoss needs to have a reliable real-time visual inspection method that they can use to monitor the integrity of the IGVs without having a large impact on the incoming refrigerant flow into the compressor so that the overall performance is not impacted. This is the device that our team constructed.

In order to build a functioning device that met the needs of our sponsor, our team first needed to determine the main failure modes for the IGVs to see which we could address. We identified a total of 3 IGV failures types. The first failure occurs when the IGVs flutter or vibrate due to pressure differences in the flow. This causes the performance of the IGVs to decrease and can lead to long term failures due to material cyclic stresses. The second failure mode occurs when one of the IGVs breaks off due to large pressure forces acting on the front of the vane. This causes pieces of the IGV to enter refrigerant loop, decreasing the ability of the compressor to make adjustments to the mass flow rate of the refrigerant. The final failure mode occurs when one or more of the IGVs gets stuck while turning. While this doesn't cause pieces of the IGV to enter the loop, it does still decrease the ability to adjust the mass flow rate.

Due to budget and time constraints, our team decided to focus on the latter two failure modes. Monitoring both of those failure modes could be accomplished with easily accessible equipment wile monitoring for flutter would have required highly modified specialized equipment like a laser vibrometer. With the failure modes of focus clearly defined, our team could determine the main goals that the device needs to accomplish. Some targets were also defined with the goals which can be tested at the end to determine if the project was successful. Table 1 outlines the goals of the project and table 2 lists some of the notable targets our project set out to achieve.

| # | Project Goals |
|---|---|
| 1 | Produce a system to reliably measure the angle of the IGVs |
| 2 | Provide detailed visual monitoring of IGV failures |
| 3 | Minimize impact on the fluid flow |

**Table 1. Project Goals**

| Target | Value |
|---|---|
| Minimum Sample Rate for Monitoring Vanes | $1Hz$ |
| Minimum Angle Sensor Accuracy (in terms of percent open) | $\pm 10\%$ |
| Pressure Needed to Withstand | 300psi |
| Maximum Allowable Length | 50 cm |

**Table 2. Project Targets**

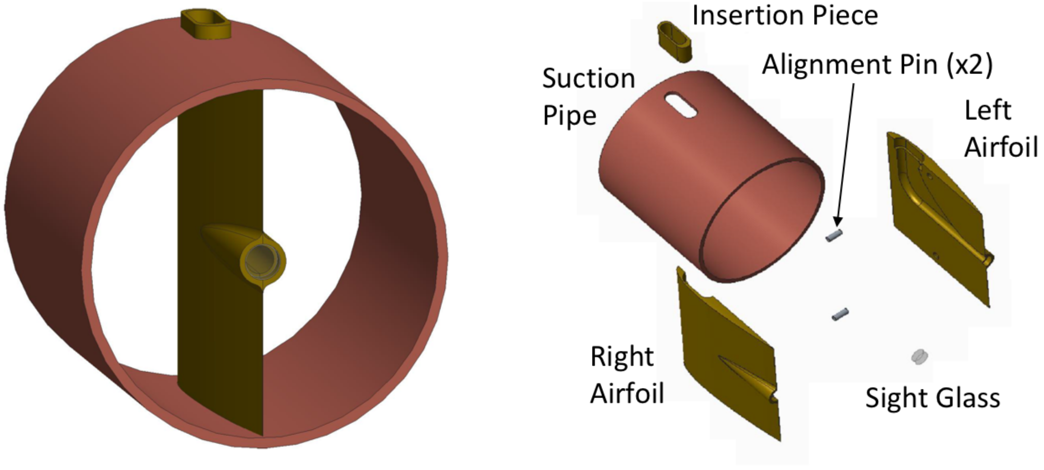
With the goals and targets defined, our team started working on brainstorming and generating different concepts for the sting apparatus. We identified 3 main subsystems that we needed to construct in order to fulfill all of the needs for the project. The first subsystem identified was the visual monitoring subsystem for the IGVs to give the test lab a video feed of the inside of the compressor. The second was an angle monitoring subsystem so that our system can determine the angle of each individual IGV and provide it to the test lab to verify that all the angles match. Finally, we identified the need for a lighting subsystem. This is because the camera used for the visual monitoring is placed inside the inlet pipe which is completely dark, therefore internal lighting inside the pipe is needed so that the camera can pick up the IGVs at the compressor inlet. After some brainstorming and research, we analyzed different concepts for each of the subsystems. Table 3 gives a general overview of the subsystem concepts our group came up with.

| # | **Visual Monitoring Concepts** | **Angle Monitoring Concepts** | **Lighting Concepts** |
|---|---|---|---|
| 1 | Camera in pipe elbow to monitor IGVs from center | Accelerometer to measure position based on change in gravity | Individual lights in pipe close to the IGV to light IGV |
| 2 | Camera placed in central body to see from center of pipe | AprilTags used with a camera to calculate angle based | Ring light around camera to evenly light IGVs |
| 3 | Multiple cameras on pipe side used to construct a composite image | Light sensitive paper to easily see and approximate angle of each IGV | Clear pipe which allows ambient lighting |
| 4 | Mirror on central body with external camera to center of pipe | Digital Image Correlation | |

**Table 3. Project Subsystem Concepts**

After researching each option for the subsystems and long discussions with our project sponsor, our team selected to use a camera placed in a central body for the visual monitoring. For the angle monitoring we selected to use April-Tags placed on each IGV which can be read by the camera and analyzed by computers located in the test lab. Finally, we chose do develop individual lights to light the IGVs.

With the concepts selected, our team designed the monitoring apparatus. We used an airfoil spanning the diameter of the inlet pipe as our central body. This airfoil has a channel on the inside where we can feed our camera through to position it in place for the monitoring of the IGVs. Figure 2 gives a schematic of our final design.



a) Assembly View of Final Design

b) Exploded View of Final Design

**Figure 2. Finalized Design of Monitoring Apparatus**

# II. Methods

With the design of the device finalized and constructed, we ran a series of tests to make sure that everything operates as expected and that the device will not fail. These tests fell into two categories. The first set of tests validated that our system can withstand the conditions in the test lab while the compressor is running. We identified the areas of concern for this category of tests using a risk assessment procedure. The second category of tests validated that our system works as expected and can properly provide the needed monitoring data to the Danfoss Turbocor test lab. Table 4 shows the first set of tests and shows what the passing conditions were for each.

| Test | Passing Conditions |
|---|---|
| AprilTag Paint Refrigerant Compatibility | Material used to paint the AprilTags on the IGV does not corrode or dissolve in the presence of refrigerant |
| Sightglass Epoxy Refrigerant Compatibility | Epoxy used to insert the sight glass into the airfoil housing does not corrode or dissolve in the presence of refrigerant |
| Final Assembly Pressure Test | Epoxy seals withstand the pressures inside the refrigerant loop |
| Final Assembly Seal Test | Epoxy seals prevent refrigerant leaks into ambient environment |

**Table 4. Tests run to validate that the system withstands compressor conditions**

We tested for refrigerant compatibility by exposing a piece of brass coated in our selected paint to the refrigerant for a total of one week. After exposure, we removed the piece of brass to inspect the paint and see if any corrosion had occurred or if the paint dissolved in the environment. We conducted the same test to check the compatibility of the epoxy with the refrigerant where a brass piece containing the epoxy was exposed to refrigerant for one week and inspected to see if there was any corrosion. For the remaining 2 tests, we constructed a separate testing device. This testing device is shown in figure 3.

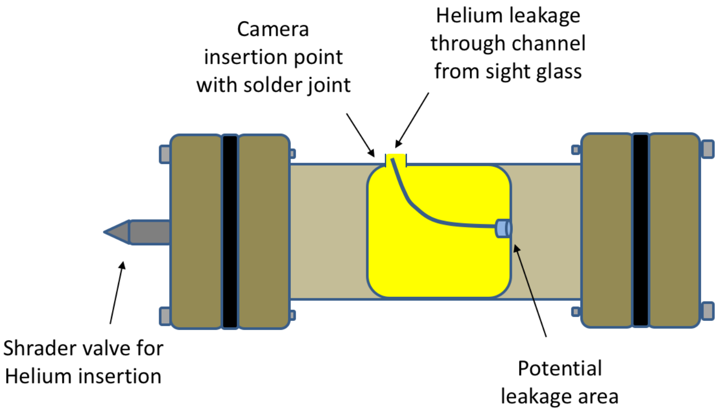


**Figure 3. Testing device for leakage and pressure tests**

Since our testing device has flange connections on either end, we used two flange caps to create a sealed environment separate from the compressor refrigerant loop. We modified one of these caps with a Schrader Valve and inserted helium into the assembly for the leak test and water for the pressure test. We inserted helium into the assembly to check if all of the epoxy seals functioned properly and to ensure that no refrigerant would leak. We used the water to test how much pressure the assembly could withstand. We used water instead of gas because the water is incompressible, so if the assembly were to burst, it would not cause an explosion. The results for all of these tests for environment compatibility are in terms of pass/fail. Table 5 below shows the second set of tests that our team ran to make sure that the system works as expected after we verify the environment compatibility.

| Component Tested | Passing Conditions |
|---|---|
| Camera Visual System | Camera is centered in pipe and each vane is shown in the video |
| Angle Measuring System | AprilTags are identified and each angle is calculated to ±10° |
| Lighting System | Lighting is bright enough so that each of the vanes is easily identified by the camera |

**Table 5. Tests run to validate that the system works as expected**

We tested all of these systems together since they all rely on each other to properly function. The first step in establishing if the system satisfies the passing conditions was to see if the lighting system properly lights the inside of the pipe enough so that each of the vanes is visible. We then tested the camera placement to see if each of the vanes are visible in the camera view. Then we tested the camera and computer software required for reading the AprilTags together to check that the image is sharp enough to pick up the AprilTags. Finally, we tested the accuracy of the tags by comparing the output reading of the computer program with the actual angle of the vanes. We repeated this series of tests for a range of IGV angles while the compressor was running, to validate that the functionality of the device does not change with the angle of the IGVs. Testing the vane visibility and the AprilTag identification occurred on a pass/fail scale while the angle measurement results were in terms of the angle error.

## III. Results and Discussion

We got the results from the refrigerant exposure testing first since we needed this information first before constructing our final assembly. As previously mentioned, we exposed a piece of brass with the spray paint for the AprilTags and two different epoxies. After examining the brass piece, our team - in conjunction with experts at Danfoss - concluded that the spray paint and one epoxy passed the refrigerant exposure test. The other epoxy did not pass the test because it showed signs of discoloration. Therefore our team decided to only use the epoxy that passed the refrigeration test for the final assembly.

Our team then conduced the pressure and leak tests once we constructed our final assembly. We started with the water burst test by filling the assembly with water in a burst chamber and then rapidly raising the pressure. Since we could not precisely control the pressure inside the assembly, the pressure rose rapidly to 375 psi, well above the intended pressure test of 300 psi. However, the assembly survived and 12 minutes passed before we decided to pressurized the assembly. From this test, our team determined that the assembly is strong enough to withstand the test conditions in the refrigerant loop. Figure 4 shows some pictures of the burst test setup with the pressure gages showing that our assembly holds 375 psi.

**Figure 4. Pressure Burst Test Setup**

Our team then conducted a helium leak test by filling the assembly with helium and checking the leak rate out of the assembly. From this test, we determined that the helium leak rate out of the assembly was $4.67x10^{-7}atm\frac{cc}{s}$. This means that our assembly leaks about one cubic centimeter of helium at atmospheric pressure every 26 days. This rate is very much in the range of acceptable leak rates and likely means that no refrigerant will leak into the environment because the refrigerant molecules are much larger than the helium molecules. Based on the results of these tests, our device can withstand the conditions present in the refirgerant loop. Table 6 gives a summary of these test results.

| Test | Result |
|---|---|
| AprilTag Paint Refrigerant Compatibility | Pass |
| Sightglass Epoxy Refrigerant Compatibility | Pass |
| Sightglass Epoxy Pressure Text | Pass |
| Sightglass Epoxy Seal Test | Pass |
| Vane Brazing Seal Test | Pass |

**Table 6. Test results to withstand compressor conditions**

While these test results verify that our device will work in the short term, we cannot draw any conclusions to indicate that there is a certain lifespan of the device. Our group could only conduct these tests for a short amount of time, so we do not know the long term effects of the environment on the materials used in our final assembly. Table 7 below gives the results of the tests conducted to test the function of the device.

| IGV Position (°) | Vanes can all be seen | AprilTags are picked up by computer | Angle Error (°) |
|---|---|---|---|
| 0 | Pass | Fail | N/A |
| 10 | Pass | Fail | N/A |
| 20 | Pass | Fail | N/A |
| 30 | Pass | Fail | N/A |
| 40 | Pass | Pass | 2 |
| 50 | Pass | Pass | 2 |
| 60 | Pass | Pass | 2 |
| 70 | Pass | Pass | 2 |
| 80 | Pass | Pass | 2 |
| 90 | Pass | Pass | 2 |

**Table 7. Tests run to validate that the system works as expected**

Our device was able to properly see the vanes and AprilTags for all angles greater than 30°. At 0° to 10° the AprilTags were not visible because the orientation of the vanes was parallel to the inlet flow and the the camera view, but the vanes were visible and we were able to verify their integrity. The AprilTags were visible in the view of the camera at IGV positions of 10° to 30°, but given the angle of the vane, the computer was not able to pick up the tags and provide a reading. Our device worked properly over the rest of the range of IGV positions and was able to provide angle readings for each of the IGVs. These angle reading were all within the allowable error range and had an error of roughly 2°. Figure 5 shows a picture of the inlet taken from behind the assembly and a picture of the camera view from the videoscope. Unfortunately, the AprilTaged vanes were not installed for these pictures.

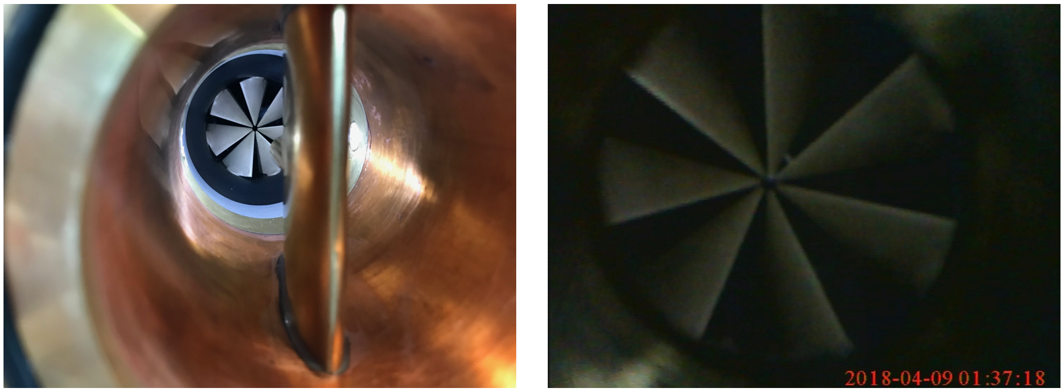


**Figure 5. Final assembly and sample image from videoscope**

## IV. Conclusion

Our senior design group was able to design and construct a monitoring device for Danfoss Turbocor that gives the test lab a live feed of the compressor inlet. With this monitoring device, the test lab is able to see the vanes in the camera view for all operating conditions and IGV positions to monitor if any of the vanes have broken off. Additionally, the device allows the test lab to check and verify the angle of the IGVs for all positions of the IGV greater than $30°$ with an accuracy of up to $\pm 2°$. With this device, the Danfoss Turbocor testing lab can run tests on their compressor prototypes for weeks at a time with the ability to monitor the IGVs so that there is no risk of corrupting weeks worth of test data due to an unidentified broken vane.

In addition to the advantages that this device provides to the Danfoss Turbocor test lab, our device shows that it is possible to develop a monitoring device that could be used in applications other than the test rig. For example, someone could use this device in the field for compressor installations in areas where regular checks of the IGV are not possible so that maintenance is only called out when there is a confirmation of an IGV breaking.

## V. Future Work

There are a few things that our group wants to do to make the design of this product even better. First, we would like to conduct more refrigerant compatibility testing on the materials that we used. These tests would focus on long term effects on the materials so that we have a better estimation of the product lifespan and so we can research and select better materials. We would also like to test more high end cameras. While we think that we picked the best possible camera for our price range, there are more expensive cameras available with larger resolutions and higher frame rates that could make the video sharper and make the AprilTags easier to read. We would like to put some focus on changing the design of the sightglass so that it is modular. This way, inserting the sighglass would not require epoxy and would be much easier to assemble. Additionally, we would like to implement a high cycle monitoring system. This system should measure the vibrations of the vanes to help the test lab identify any failures due to high cycle fatigue. Finally, we would like to further develop the AprilTag software to implement an alarm system so that we can immediately alert the test lab when one of the vanes breaks.