

Characterization and Performance Testing of Natural Gas Compressors for Residential and Commercial Applications

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Abstract. Relatively little information is available in the literature with respect to the performance of compressors used during the dynamic charging process of a tank. Therefore, work presented in this paper shows the measurement results of performance testing of a natural gas compressor and analyses the compressor characterization based on the experimental data. Initial tests were conducted using air and carbon dioxide given the thermodynamic similarities between these fluids and natural gas. Finally, a new test stand was specifically designed and built for compressor dynamic testing using pipeline natural gas (NG) and the compressor reliability has been evaluated inside an explosion-proof engine test cell. Reliability tests at standard operating conditions monitored the performance consistency of the compressors over the testing period and the testing consisted of a series of tank charges aimed at evaluating the maximum operating temperature as well as the mass flow rate in the system.

1. Introduction

Limited studies have been conducted with respect to experiments and simulation models to monitor and predict the dynamic process of reciprocating compressor. The dynamic testing of a two-stage reciprocating air compressor with inter- and after-cooling during steady and transient state operation has been reported by Nakagawa et al. [1]. The application of micro-thermocouples for measuring the instant temperatures and pressures in cylinders was mainly discussed. A specific dynamic model for a small refrigerating cycle was presented by Janssen et al. [2]. Experiments and simulations for the start-up and pull-down phase of a freezer were reported as well. However, in these papers, the working fluids were conventional refrigerants or ambient air, and the experimental considerations were not comparable to the dynamic testing with natural gas, which has more safety regulations. Kim and Lee [3] conducted several dynamic tests to verify the reliability of high cycle fatigue of a gas compressor blade, and analyzed the fatigue testing results. Norman Shade [4] presented several cases of existing reciprocating compression assets and especially showed optimization of the testing rigs using pipeline natural gas. Moreover, many simulation models have been developed and analyzed. Chi and Didion [5] as well as Rajendran and Pate [6] both came up with transient simulation models for a heat pump and vapor compression cycle, respectively, but the experimental validations were not discussed in these two papers. Considering the combustible property of natural gas and safety aspects necessary, little work has been found in the open literature relative to the experimental testing of the dynamic charging process with natural gas. This paper focuses on reporting experimental data to evaluate the dynamic performance of a natural gas compressor during the charging process of a tank. In addition, reliability tests of the compressor system are also discussed.



2. Description of systems

2.1 Overview of all testing systems

To evaluate the efficiency, performance, and safety characteristics of natural gas compressors used in residential and commercial applications, a three-step sequence of testing was conducted and three test stands were built or modified for experimental performance testing of a two-stage reciprocating compressor system. The compressor performance tests were conducted using a combination of open loop and closed loop test setups with different working fluids that have thermodynamic similarities with natural gas. Initial open loop tests were conducted using air as a working fluid, because air is readily available, nontoxic, and nonflammable and carbon dioxide was chosen as the working fluid for the closed loop system, because the ratio of specific heat is very similar to that of natural gas. The open loop system was used to investigate the dynamic compressor performance when the discharge pressure increases due to pressurizing ambient air into a tank. The closed loop system was used to evaluate the compressor performance at specific discharge pressures that the compressor encountered during steady-state operation using carbon dioxide as the working fluid. Fig. 1 shows two test stands for the first two stages of testing: the left side shows the open loop test stand and the right side shows the closed loop hot-gas load stand. Detailed experimental results obtained with both test stands have been discussed in Xinye et al. [7] and [8].



Figure 1. Open loop and closed loop system test stand setups

In the next step, a new test stand was specifically designed based on the experiences gained during the first two stages of testing and was built for compressor dynamic testing using pipeline natural gas (NG). In addition, the compressor reliability has been evaluated in this stage of testing. Furthermore, some improvements were made to the final design of the NG compressor box for safety purposes and better performance based on the test results from the first two test stands.

During all tests, the following compressor measurements were recorded: compressor mass flow rate, suction and discharge temperatures, suction and discharge pressures, intermediate pressure and temperature, and compressor power consumption. Using these measurements, the compressor performance was evaluated. An overview of the completed tests is shown in Table 1.

2.2 Natural gas testing system

The schematic of the natural gas test stand is shown in Fig. 2. All tests with natural gas were conducted inside an explosion-proof engine test cell. The test stand was designed to withstand pressures of up to 14 MPa by using stainless steel piping. A strainer, filled with desiccant, is used at

the inlet of the test stand and installed before the compressor to collect moisture and dust contamination inside the pipeline natural gas. Three solenoid valves, located in the NG supply line (SV100), the suction line (SV01) and the discharge line (SV02), respectively, are controlled from the control room remotely for safety purpose. One manual ball valve is located after the strainer to shut off the natural gas flowing into the compressor. A check valve is also used to prevent any natural gas backflow from the pressurized tank. Furthermore, a mass flow meter is installed to measure the mass flow rate of natural gas after the compressor. At the end of the test stand, two pressure vessels, equipped with one pressure gauge, one pressure relief valve, one manual valve and one flexible hose, are connected to the test stand by two three-way valves.

Table 1. Overview of the full completed tests

Test Type	System	Working Fluid	Number of Tests	Comments
Dynamic charging	Open loop	Air	10	New test stand was built
Steady-state			5	
Steady-state	Closed loop	CO ₂	5	Hot-gas load stand was modified
Dynamic charging	NG test system	Natural gas	300	New test stand was built

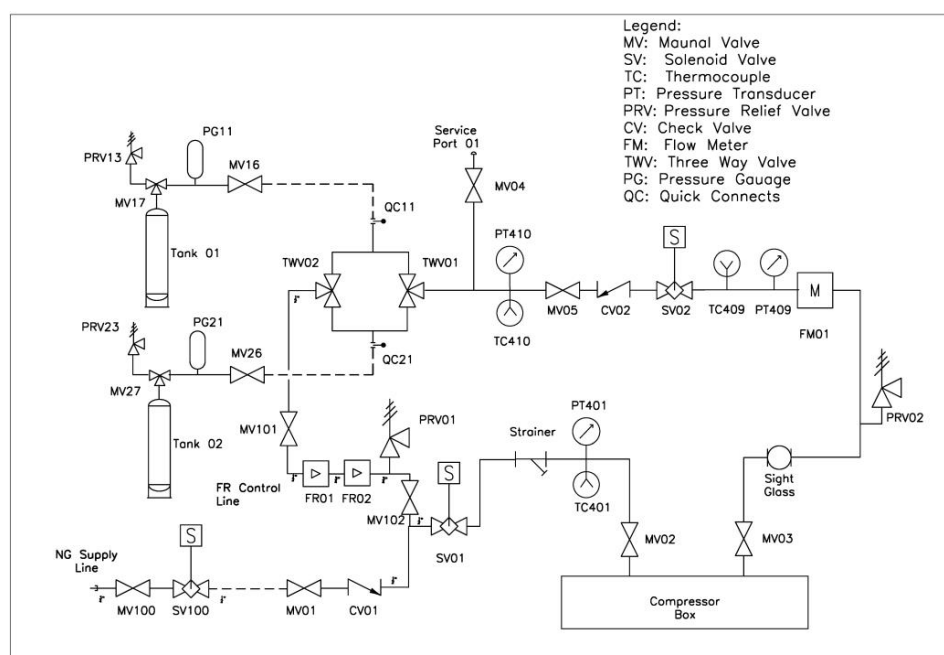


Figure 2. Schematic of the natural gas system

With this configuration of three-way valves, two methods were used during the natural gas testing: pipeline charging and tank-to-tank charging. Using the pipeline charging method, natural gas passes through TWV01 to either of two tanks when TWV02 is closed. Pipeline natural gas is used to charge the empty tank until the target pressure was reached. In this case, MV101 is closed and TWV01 is opened to fill the target tank (Tank01 or Tank02). The tank-to-tank charging method was utilized to charge an empty Tank02 from a full Tank01 or vice versa. In this case, the pressurized gas passes through two flow regulators, FR01 and FR02, to throttle the compressed natural gas to the compressor suction pressure. The benefit of this approach is to significantly expedite the testing time, as there is no need to empty the natural gas after two tests as is the case with pipeline charging.

A photo of the natural gas test stand located in the explosion-proof engine test cell is shown in Fig. 3. A flammable gas detector is installed close to the ceiling and the power would be shut off once a gas leak is detected. All tests were conducted by the operator in the control room, shown in Fig. 5, from where the solenoid valves and compressor box were controlled by a remote-control panel. All measured data was obtained and displayed using an appropriate data acquisition system. An emergency stop was used to shut down the entire system in case of any unexpected issues.

To dispose of the compressed natural gas, a natural gas heater setup, consisting of two flow regulators and a patio-comfort heater, was used to burn the compressed natural gas. The movable tank as well as the heater setup were moved outside of the engine cell and connected to the heater setup to complete the natural gas burning process. A photo of the heater setup can be seen in Fig. 4.



Figure 3. Natural gas system test stand setup (engine cell)



Figure 4. Natural gas system heater setup

An NG compressor box, as shown in Fig. 6, consisting of a two-stage reciprocating compressor to achieve the system target pressure in the storage tank, was connected to the test stand. An electronic box is installed inside the compressor box, which contains an ON/OFF switch, status indicator lights, and a remote-control button. Another flammable gas detector with a lower gas concentration setting, then the test cell, was installed inside the compressor box to shut-off the compressor in case of gas leaks. Built-in thermal protection has been included in the compressor control program to set the limits of compressor shell temperature as well as gas discharge temperature.



Figure 5. Natural gas system test stand setup (control room)



Figure 6. Natural gas compact compressor box

A schematic of the compressor box is shown in Fig. 7. The compressor is fitted with an oil management system, cooling fans, and an electronic control system. In addition, the compressor box includes both pressure switches and a pressure relief valve to ensure that a safe operating pressure is maintained. The target tank charging pressure of the compressor is 4500 kPa. When the compressor discharge pressure reaches 4500 kPa, the compressor electronics automatically shut down the compressor. The compressor is fitted with numerous thermocouples and pressure transducers to collect operational and reliability data.

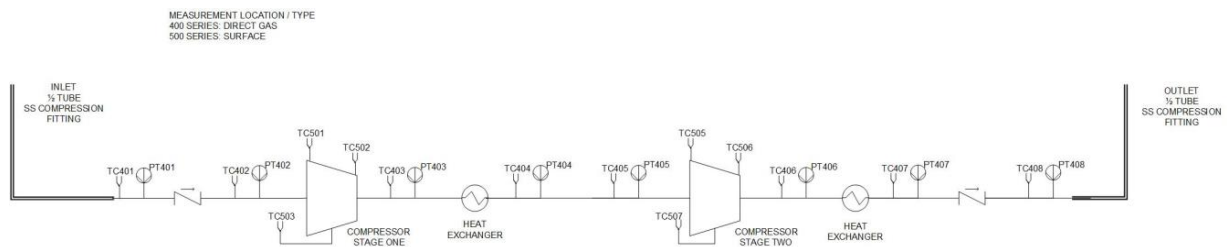


Figure 7. Schematic of the compressor box

2.3 Test stand instrumentation

All measuring instrumentation is indicated in the schematics shown in Fig. 2 and Fig. 7. All temperatures are measured with T-type thermocouples with $\pm 0.25^\circ\text{C}$ accuracy. The inlet pressure is measured with an absolute pressure sensor having an accuracy of $\pm 0.25\%$ of the reading. Other pressures are measured with gauge pressure sensors having an accuracy of $\pm 0.13\%$ of full scale. A micro-motion mass flow meter with accuracy of $\pm 0.1\%$ of the reading is installed after the compressor box to measure the gas mass flow rate. The electrical power consumption of the compressor box is measured with power meters that have an accuracy of $\pm 0.04\%$. A data acquisition system is used to convert the incoming voltages from the measuring instrumentation to digital signals and then to transfer the signals to a personal computer. The computer uses a proper data reduction program for further data analysis.

2.4 Test matrix

A test matrix outlining the operating conditions for the natural gas system testing is shown in Table 2. The natural gas compressor testing consisted of a series of tank charges aimed at evaluating compressor performance and reliability. The following compressor measurements were recorded for each single dynamic test: compressor mass flow rate, temperature and pressure of all significant points and power consumption.

Table 2. Test matrix of natural gas system tests

Suction Pressure [kPa]	Target Pressure [kPa]	Method	Number of Tests [-]	Recorded Data
105	4500	Pipeline charging	20	Temperature, pressure, power, mass flow rate
105	4500	Tank to tank	280	

3. Experimental results

3.1 Experimental results

A dynamic test with 4500 kPa target pressure was conducted using the tank-to-tank charging method. Fig. 8 shows the variation of natural gas pressures as a function of time for test No.1, which means the first test in the sequence of test during the day.

Due to the nature of the charging process, it can be noticed that the intermediate pressure, PT_{405} , shows gradual rise during the start-up phase. This rate of pressure increase becomes smaller after the system has been running for 3 minutes. The discharge pressure of the compressor box, PT_{407} , increases significantly until it reaches the target pressure. Also, it is found that the intermediate pressure has a marked increase to an equilibrium pressure at compressor shutdown, which is due to the backflow through the second compressor stage.

By contrast, Fig. 9 shows the variation of natural gas pressures as a function of time for test No.10 which is the 10th test on the same day. It is observed that there have been distinct differences of pressure variation between test No.1 and No.10 during the start-up phase. Unlike the first test, it only takes approximately 1 minute in test No.10 for the rate of intermediate pressure (PT_{405}) rise to stabilize. The shape of the discharge pressure (PT_{408}) curve remains markedly similar from test No.1 to No. 10.

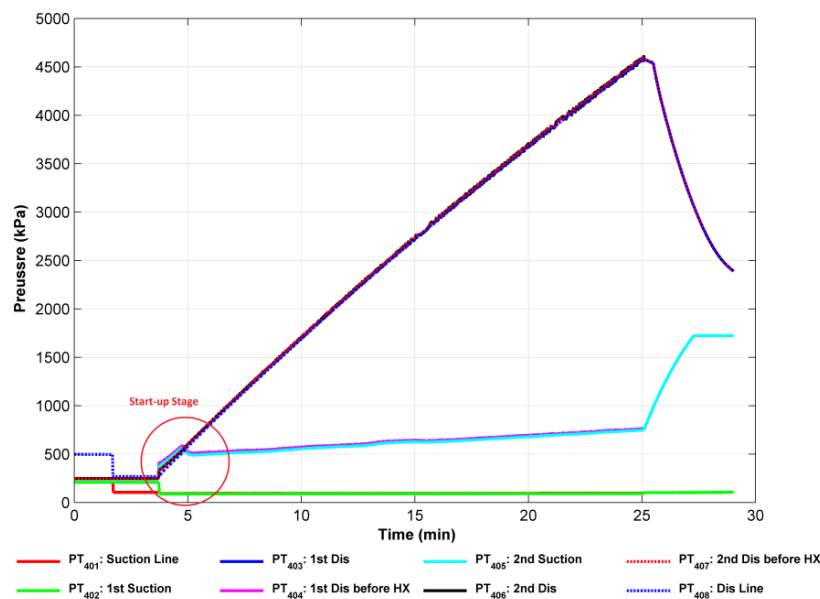


Figure 8. Pressure inside the compressor box (test No.1)

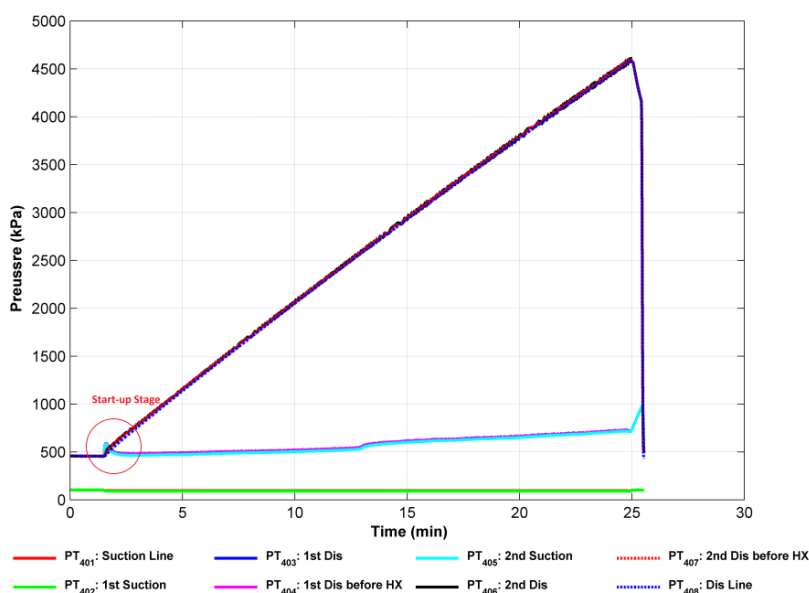


Figure 9. Pressure inside the compressor box (test No.10)

Fig. 10 shows the variation of natural gas temperatures as a function of time for test No.1. After the compressor system starts, it is found that the first-stage discharge temperature shows notable rise at the beginning. The second-stage discharge temperature (TC_{406}) has a delay, through the compressor start-up phase, before the temperature increases significantly until it reaches to a final value of 90°C.

Another obvious conclusion that can be drawn from Fig. 10 is that the each stage discharge temperatures show large jumps when the stage contribute to the system pressure rise. However, the rate at which the temperature of the second-stage gas temperature rises is larger than the rate at which the first-stage temperature rises. In addition, the second-stage temperature exceeds the first-stage temperature after the system is running for approximately 7 minutes. During this test, the maximum attainable temperature for the second stage is up to 90°C and for the first stage is 70°C. Also, it can be noticed that the temperature variations after the heat exchanger in both stages are relatively small, which are close to the ambient temperature during the entire testing. In addition, a small jump of the second-stage discharge temperature and oil return temperature can be seen in the right corner, which is due to the cooling fans being shut off with heat remaining in the compressor system after shut-down.

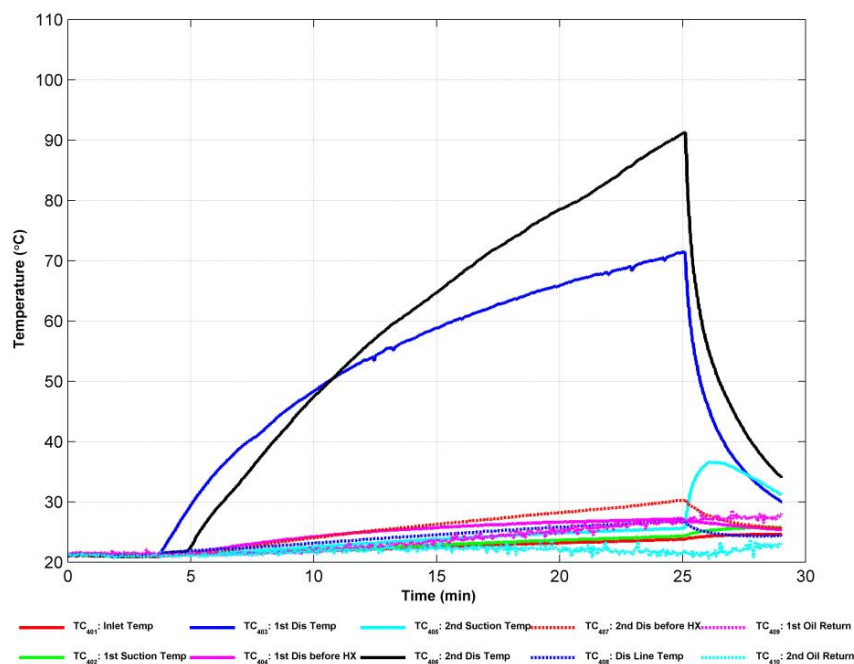


Figure 10. Temperature inside the compressor box (test No.1)

Similarly, a comparison of the system temperature is made between two tests on the same testing date. Fig. 11 shows the variation of the natural gas temperatures as a function of time for test No.10. A major difference between the No.1 and No.10 tests is the hike of the second-stage discharge temperature during the start-up phase, which jumps to 80°C immediately. There is only a very short time lag for the second-stage temperature rise, unlike 7 minutes in test No.1. Also, the rate at which the discharge temperature of the first stage rises is smaller than the previous test after 5 minutes of testing, the temperature increasing only from 88°C to 91°C. In addition, as shown in Fig. 11, the maximum attainable temperature of the second-stage is approximately up to 105°C, only 15°C higher compared with the temperature in test No.1. Moreover, except for the two discharge temperatures, all other system temperatures only show minor changes during the entire testing, in contrast to the gradual increase in test No.1. Furthermore, the variance is within 3°C, regardless of the ambient temperature change.

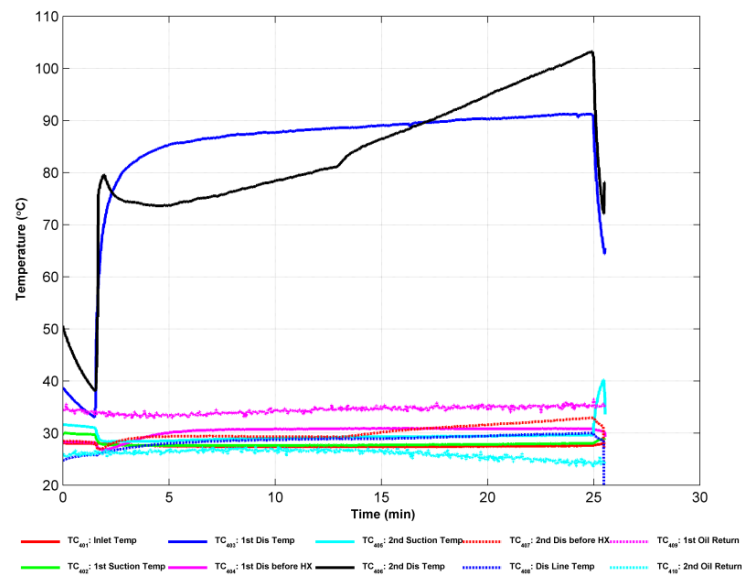


Figure 11. Temperature inside the compressor box (test No.10)

3.2 Reliability results analysis

Fig. 12 and Fig. 13 show that the variation of the measured compressed natural gas pressure and temperature is small in multiple dynamic charging tests with identical target pressure. This is significant given that there is only a two to five minutes pause between tests. The identical target pressure was set to 4500 kPa and suction pressure was kept stable at 105 kPa. The running time for each test is approximately 25 minutes. It can be seen that the variation of the measured compressed natural gas temperature in these continuous tests increases along with the testing time but the cooling fans worked efficiently to cool down the system. The maximum attainable temperature of the system was found to be 105°C, which is reached within six tests in series. Also, it is noted that the maximum temperature no longer increase after the third test in the continuous tests series when the system is under a periodic cycling.

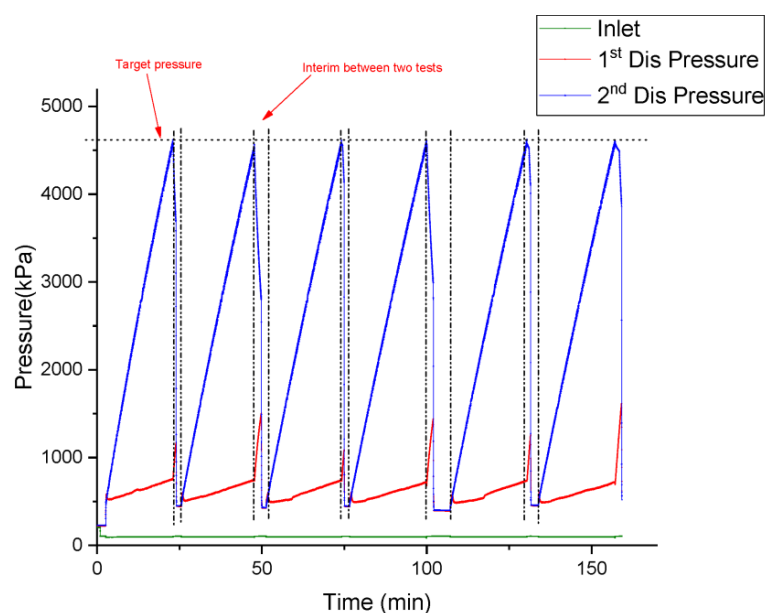


Figure 12. Variation of pressure in continuous dynamic charging test

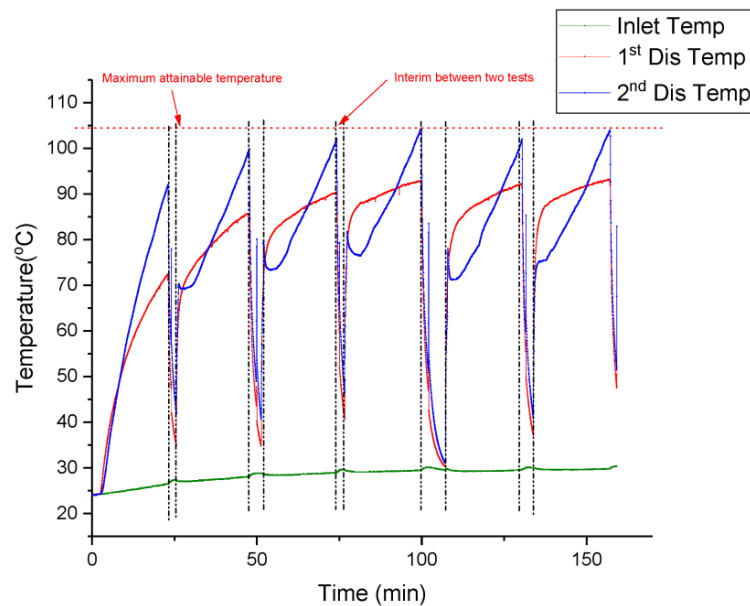


Figure 13. Variation of temperature in continuous dynamic charging test

In summary, 300 natural gas dynamic charging tests have been completed to evaluate the performance and safety characteristic of the compressor system. The differences between different continuous tests have been noticed and analyzed, which is instructive for the performance improvement and system design. The reliability analysis shows that the compressor system is robust and meets the discharge pressure and temperature design goals. Furthermore, the maximum operating temperatures are within allowable ranges and no thermal protection issues showed up. The operation of the NG compressor system was proven to be reliable and predictable.

4. Conclusions and future work

The paper demonstrates the measurement results of performance testing of a natural gas compressor and the compressor characterization are analyzed based on the experimental data. Following the previous two stages of testing, a new test stand was specially designed and built for compressor dynamic testing using pipeline natural gas (NG) and the compressor reliability has been evaluated. The results obtained from different tests appear to be plausible and significant to show the different performance of the compressor during a dynamic charging process. The development of the simulation model has recently been completed and the compressor dynamic performance will next be predicted and evaluated. Future development for this dynamic model will provide an accurate prediction of the intermediate pressure and the total charging time. Also, the mass flow rate and compressor characteristic will be calculated and validated by the experimental data in future work.

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