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SUPERSONIC EJECTORS FOR HYDROCARBON EMISSIONS CAPTURE

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ABSTRACT

Supersonic ejectors can be applied to capture low-pressure leakage gas from the gas seal vents of a centrifugal compressor. This captured gas can be re-injected into the fuel gas line of the gas turbine driver or the captured gas can be used as a fuel for gas fired utility heaters. By capturing the gas that is normally emitted to the atmosphere the operator can reduce operating cost and enjoy a reduction in hydrocarbon foot print. Because the supersonic ejector does not have moving parts, the system operating and maintenance costs are lower than functionally comparable traditional systems.

In this study, a prototype of a supersonic ejector system was developed and tested at a pipeline compressor station. The obtained test data were used for developing and tuning a mean-line aerodynamic analysis tool, which predicts the ejector's operating map. A family of three ejectors was designed to cover a range of operating conditions associated with gas turbine driven pipeline compressors. These ejectors were built, installed on a specially designed panel, described as the ejector system, and tested on inert gas at the original equipment manufacturer's (OEM's) facility. A comparison of predicted and as-tested supersonic ejector performance maps is discussed and conclusions are made about the system operating range.

INTRODUCTION

For over 100 years, ejectors have been used to inject fluids into processes. Ejectors have no moving parts and are known for their rugged durability and low cost. Ejectors continue to be utilized in many industrial applications such as refrigeration and heat pump systems and in gas-vapor recovery from hydrocarbon storage tanks, to name a few. These applications operate on a design that is sub-sonic or marginally supersonic. For this reason, traditional ejectors have limited application due to their fundamental performance with a low pressure ratio.

To overcome the pressure rise limitation, a supersonic ejector (SSE) was developed by a major pipeline operator that allows for a higher compression ratio [1]. This technology was created over the past eight years in an effort to capture fugitive emissions from gas seal vents in pipeline compressors and then re-inject the gas into fuel lines for the gas turbine drivers. In addition to reducing greenhouse gas emissions, this system would help to offset fuel costs.

To inject seal emissions into a turbine fuel supply, the seal gas pressure must be increased from a reasonable vent pressure, usually less than 700 kPa, to the fuel gas pressure, thus requiring a pressure ratio of over 4:1. Since a single-stage SSE can only produce a pressure ratio of about 3:1, most applications require a two-stage system, with the ejectors are placed in series, as shown in Figure 1.

Because the motive gas demand increases exponentially with each stage, anything larger than a two stage system may not be economical. A prototype of a two-stage supersonic ejector concept was developed and successfully tested at the pipeline station by Botros et al. [2].

Each of the two ejectors in a tandem arrangement operates supersonically to allow for a high expansion ratio of motive gas. Gas velocity at the exit of the first stage nozzle is well in excess of Mach number value of 2 resulting in a very low static pressure. This allows for the low pressure suction flow to be drafted and mixed into the stream. The gas exiting the first stage flows into the suction of the second stage where the Mach number ranges from 1.5 to 2.0. The second stage was designed with a lower Mach number since the higher pressure suction flow requires less expansion of the motive gas.

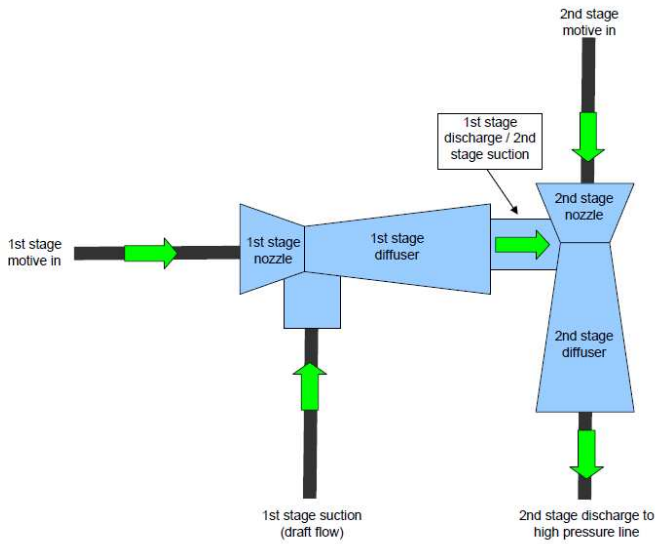

Figure 1. Schematic of Tandem Supersonic Ejector on a Natural Gas Pipeline Compressor.

An ejector is a unique piece of equipment that can be utilized in the gas transportation industry, as well as applications where there is a high-pressure gas stream available and there is a benefit in elevating the pressure of a low-pressure gas. This opportunity does exist in compressor stations, refineries, gas processing plants and pipeline systems all over the world.

The supersonic ejector employs a convergent-divergent nozzle to increase the velocity of a motive gas, thus reducing the static pressure allowing the low pressure gas to be mixed. As the motive gas flows through the first stage nozzle, the velocity increases and reaches sonic conditions at the nozzle's throat. The nozzle then diverges to further accelerate the sonic flow. At the exit of the nozzle, the gas is highly supersonic resulting in a very low static pressure. At this point, the suction flow is mixed into the motive gas. The motive-suction gas mixture then enters the supersonic diffuser and converges to a throat where a shock wave occurs as the flow transitions to subsonic, resulting in a static pressure increase. This gas then becomes the suction flow of the second stage where the same process occurs, further boosting the suction pressure to a level high enough to inject into another fluid, such as a fuel supply line or the compressor station inlet.

More background information on the applications and major pipeline operator experience can be found in [1] and [2].

DESIGN AND SIZING

The turbomachinery OEM and the pipeline operator have been working together since 2008 to implement a new process system for recovering and compressing hydrocarbon gas leaked from dry gas seals in centrifugal compressors.

The OEM licensed the supersonic ejector technology from the original developer with intent to apply it as an environmentally beneficial solution for the industry. The OEM employed VAVE (Value Analysis / Value Engineering) processes [3] to develop a proprietary design of the supersonic ejector and associated system that reduce parts, simplified construction, and minimized the cost while also providing a compact systematized solution for easy retrofit to existing compressor stations.

In addition to cost reduction the VAVE project's objective was to create a design that could accommodate variations in nozzle and diffuser geometry. The design solution incorporated the nozzles and diffusers into a single stainless steel housing thus eliminating the need for complicated fittings, as shown in Figures 2 and 3. Assembly of the unit consists of simply sliding the nozzles and diffusers into their respective bores within the block. The internal parts are held in place by SAE four-bolt flanges with threaded connections allowing for piping to be connected without the need for welding. The O-rings on each of the internal parts seal the block and eliminate the need for gaskets.

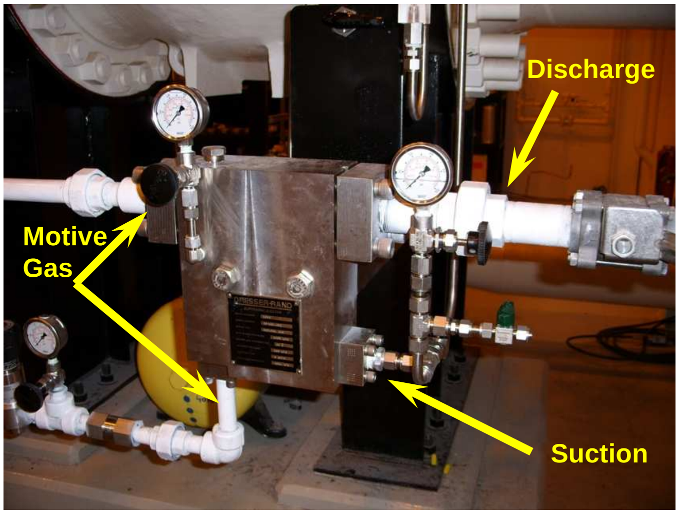

Figure 2. OEM's Design for the Supersonic Ejector.

The supersonic ejector components are selected by using the required pressure ratio and site specific process gas conditions. Knowing the mass flow of the fugitive gas that needs to be captured, the first stage motive gas mass flow rate can be estimated. The required mass flow of the motive gas determines the diameter of the nozzle throat. The desired suction pressure is equivalent to the motive gas static pressure at the nozzle exit, which sets the exit diameter of the nozzle.

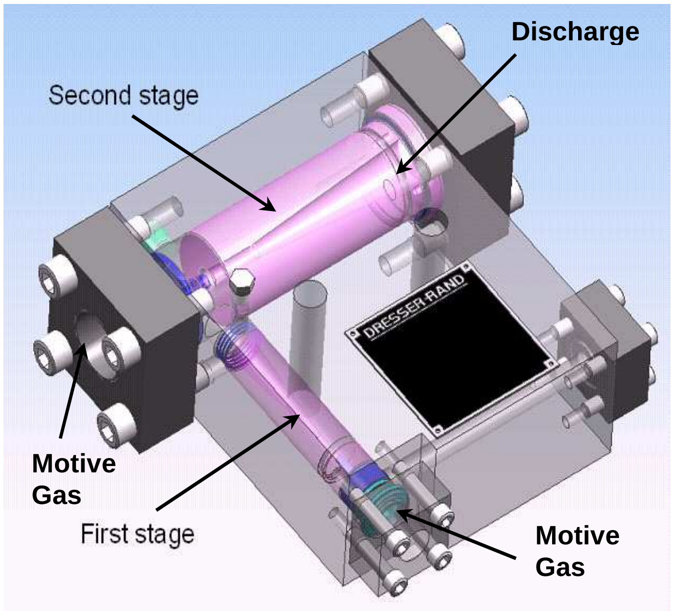

Figure 3. Computer Model Of VAVE Design Showing Internal Components Installed Within Stainless Steel Housing.

The total mass flow through the first stage becomes the second stage suction flow. As in the calculation for the first stage, this determines the second stage nozzle throat diameter. Compressible flow equations can predict the discharge pressure from the second stage diffuser. The second stage nozzle exit diameter is sized to produce a static pressure lower than the discharge pressure from the first stage, so that flow is driven into the second stage.

To simplify the sizing process, a sizing tool was created that would automatically solve the one-dimensional, adiabatic inviscid compressible flow equations. The tool determines the necessary motive gas pressure and flow rate, and then calculates the nozzle and diffuser geometry.

Part of the VAVE design was to allow for a limited number of standard designs utilizing common parts such as the ejector block.

After completion of basic market research three standard ejector sizes were selected that would cover a significant range of operating conditions. The fuel pressure for most turbines ranges from about 1700 kPa to 4200 kPa, depending on the size and manufacturer. Thus, the three standard sizes were designed with discharge pressures of 2000, 3100, and 4200 kPa. The sizing tool is used to determine the optimal nozzle and diffuser geometry based on a motive fluid of natural gas and a seal leakage for each application.

FIELD TESTING

In 2006 a prototype SSE system was built and tested at the pipeline operator's test facility with great success. Field trials at the compressor station continued in 2007. The ejector was installed on a centrifugal compressor driven by 23 MW LM2500 gas turbine. This unit was chosen, in part, due to its high utilization hours allowing performance testing of the ejector system on a wide range of operating conditions and fluctuating loads. The technology implementation at this station was a success, as described in detail by Botros et al. in [2], and the supersonic ejector continues to operate at this site to this day.

The second SSE prototype, as shown in Figure 4, was designed by the OEM [4] and prepared in 2009 for another pipeline compressor station, on the unit driven by 14MW LM1600 gas turbine. The ejector was installed on a barrel compressor with tandem dry gas seals with intermediate labyrinth seals. The ejector suction was connected to a common vent line for the primary seal leakage of both dry gas seals on the unit. The primary vent line was equipped with a pressure relief valve for the event of a seal failure. Additionally, a backpressure relief valve was installed on the ejector suction line to limit backpressure. If the ejector failed to maintain a suction pressure below the backpressure relief valve set point, the regulator would allow the seal emissions to bypass the ejector and travel to the original atmospheric vent. A flow meter located just before the ejector suction measured all emissions captured by the ejector while flow meters on both individual dry gas seal vent measured total seal emissions.

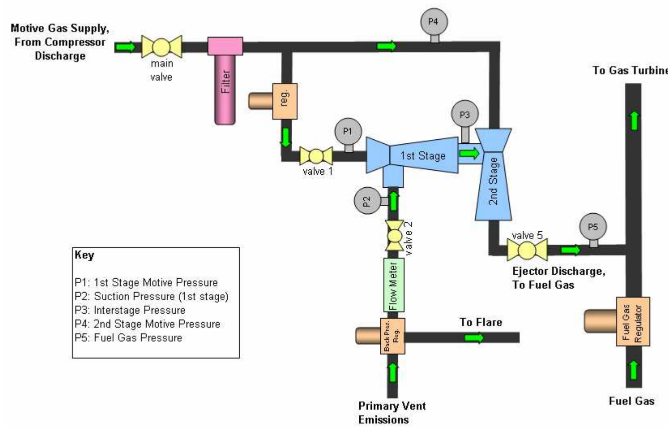

Figure 4. Schematic of SSE Installation at the Pipeline Station.

Motive gas for the ejector was provided by the compressor discharge. A ball valve on the motive gas line allowed for overall motive pressure adjustment for both stages, and a pressure regulator just upstream of the first stage allowed for independent adjustment. Motive gas was filtered upstream of the ejector and regulators by a high-flow simplex filter equipped with a differential pressure measurement.

The ejector discharge was connected to the gas turbine fuel supply downstream of the fuel pressure regulator. A PLC-controlled valve on the ejector discharge allowed for automated isolation of the ejector when turbine speed was below 5450 RPM. This was necessary to avoid supplying the gas turbine with excess fuel while operating at low speeds. Pressure gauges were installed at various locations and a handheld infrared temperature gun was used to monitor the gas temperatures.

Initial testing at the second station was conducted in 2009. Subsequent testing focused on determining the operating range. The ejector was left connected to the compressor for long-term testing. Eventually the ejector stopped drafting the seal gas emissions, as indicated by the suction flow meter. Numerous inspections and tests were conducted to troubleshoot the ejector and determine the cause of the unit falling out of service.

After compiling the data collected and analyzing the trends it became clear that the operating conditions at the second compressor station were not within the original design limits. It was determined that three key parameters lead to failure: insufficient motive gas pressure, excessive fuel gas pressure, and low set point of the suction backpressure regulator.

The combination of low motive gas pressure and high fuel gas pressure resulted in a pressure ratio outside the ejector's design limit. This limited the ability of the ejector to direct flow adequately into the fuel gas line.

To resolve the problem, the system was modified by installing larger motive gas line to reduce pressure loss between the compressor discharge and ejector skid. The fuel gas pressure was reduced and the backpressure regulator set point was increased. After these changes were made, the SSE successfully captured 100% of fugitive emissions, averaging 4.25 Nm3/h. This corresponds to captured gas amount of approximately 30 ton annually per compressor unit.

FACTORY TEST SETUP

A factory test was designed to evaluate the performance of the modified system under a wide variety of process conditions, including but not limited to the conditions at the stations where field tests were conducted. For the testing of the SSE at the OEM facility a special instrumentation panel was designed and manufactured, as shown in Figure 5.

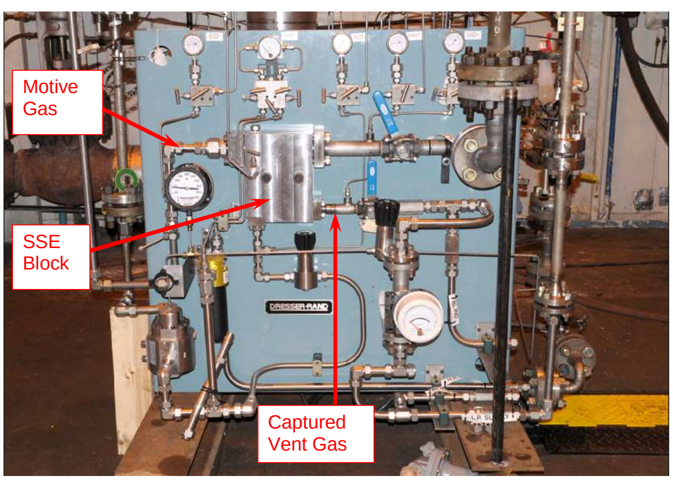

Figure 5. Fugitive Hydrocarbon Gas Capture System.

The test of the Supersonic Ejector system was conducted using nitrogen gas resulting in an improved accuracy of data. This would allow validating the performance prediction tool and increase confidence in using it for predicting SSE performance for natural gas. The test agenda included testing three ejectors of different sizes to validate the intended application of discharge pressure conditions ranging from 2000 to 4200 kPa.

Testing was conducted in four steps. During the first two steps one of two SSE stages was isolated to determine respective pressure values at suction and discharge. The set point range for the first stage was determined for the primary vent suction line while ensuring that discharge pressure would be sufficient in order to allow positive flow from the first stage to the second. During these two steps the discharge back-pressure was controlled by adjusting the discharge valve, as depicted in Figures 6 and 7. Motive pressure and suction pressure were the variables at each series of test runs. Motive pressure changed by increment 300 to 400 kPa while suction flow changed by increment from 1 to 2 Nm3/h.

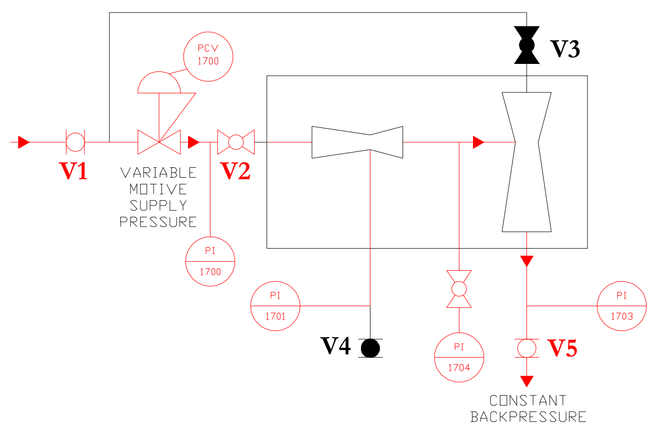

Figure 6. Factory Test Schematic Instrumentation Diagram, Step 1, Stage1 Isolated.

The next two steps were overall testing of the SSE, as shown in Figures 8 and 9. During the third step variable motive pressure was supplied to determine pressure values at the first stage suction line and suction flow rate at certain discharge back-pressure and suction supply pressure. Motive supply pressure and suction supply flow values were the variables. During the forth step the effect of discharge backpressure was investigated at constant motive supply pressure and constant suction supply pressure while varying suction supply flow. Motive and discharge pressure, and suction flow were varying by the same increments as in the first and second steps of the factory testing.

The above concept of testing in four steps allowed investigating the impact of individual parameters on ejector performance, which otherwise would be interdependent if test conducted for the two-stage SSE assembly only.

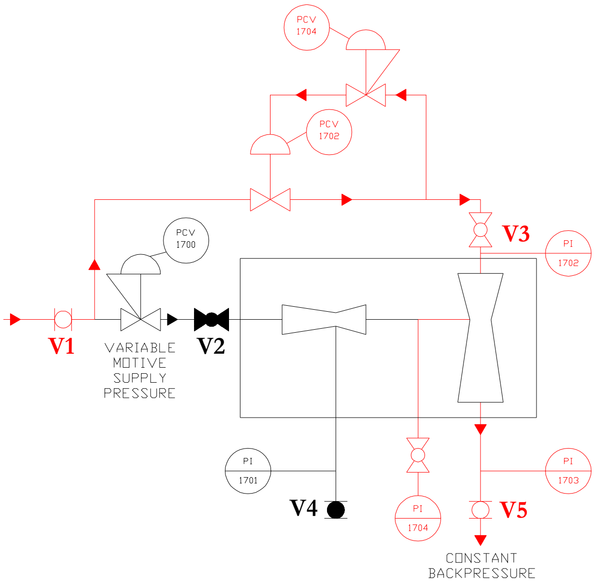

Figure 7. Factory Test Schematic Instrumentation Diagram, Step 2, Stage 2 Isolated.

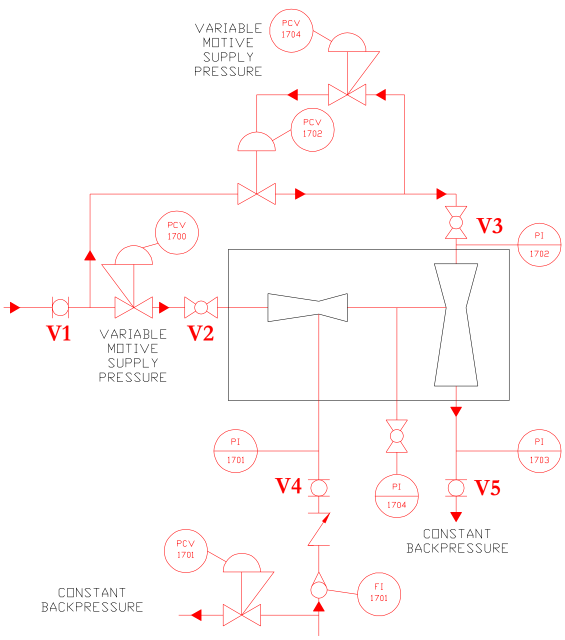

Figure 8. Factory Test Schematic Instrumentation Diagram, Step 3, Overall.

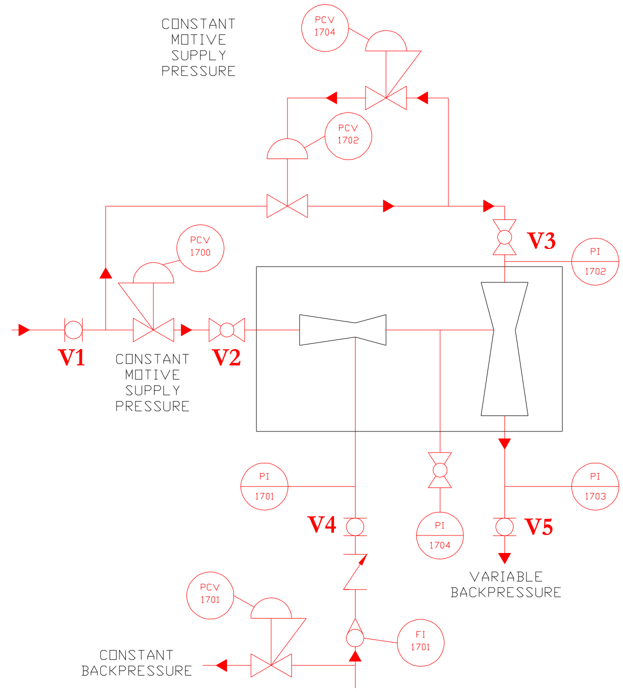

Figure 9. Factory Test Schematic Instrumentation Diagram, Step 4, Overall.

MEANLINE PREDICTION OF SSE OPERATING MAP AND COMPARISON WITH TEST

The one-dimensional, mean-line approach [5] was applied to evaluate flow parameters in the SSE. This method uses isentropic relationships with empiric corrections accounting for friction and mixing losses in the ejector nozzles and the supersonic diffusers.

Shock is predicted based on adiabatic flow parameters in the diffuser with the assumption that conditions at the nozzle exit permit drafting the suction flow and the diffuser exit pressure is sufficient for discharging into the fuel chamber. Flow parameters at each ejector stage are calculated in series, as discharge flow conditions at the first stage should satisfy conditions at the exit of the second-stage nozzle.

The difference between operating maps for the SSE running on nitrogen and hydrocarbon is illustrated by Figure 10 and 11. The test points shown on both figures were taken from the field test and were used for tuning empiric coefficients in the computational model [5]. As shown on the charts, pressure ranges and flow rates are different due to differences in compressibility while motive pressure was kept the same at the design point. Other factors, like viscosity or real gas properties affecting the performance, were not taken into account under assumptions of one-dimensional, inviscid, adiabatic model. They could be taken into consideration in the future, if more sophisticated models are implemented.

While map contour plots shown in Figures 10 and 11 visualize the ranges of multiple parameters on the SSE operating map, 2D plots in Figure 12 help investigate the impact of a single parameter on the ejector performance.

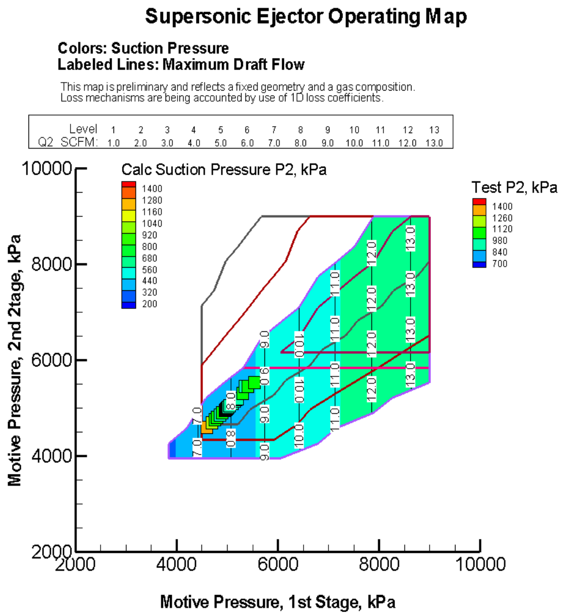

Figure 10. Calculated Operating Maps of SSE Operating on Hydrocarbon.

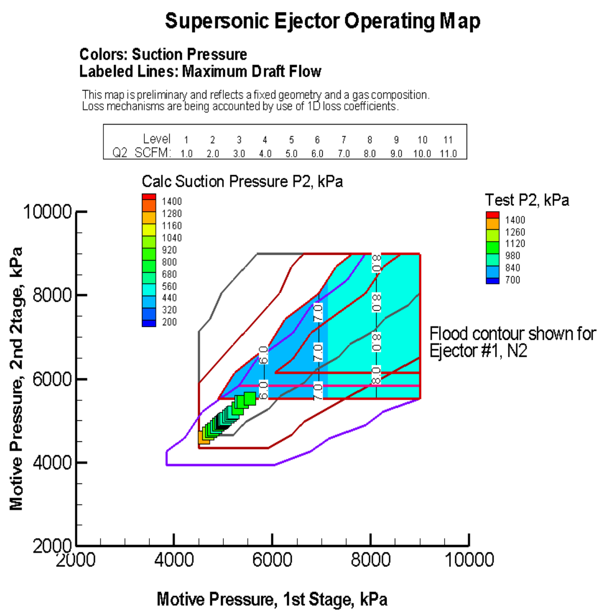

Figure 11. Calculated Operating Maps of SSE Operating on Nitrogen.

The mean-line prediction method [5] assumes that suction flow reaches sonic conditions at mixing with motive flow meaning that suction flow has reached its maximum. At the same time, second-stage diffuser discharge pressure is assumed to be high enough to overcome back-pressure of the fuel gas.

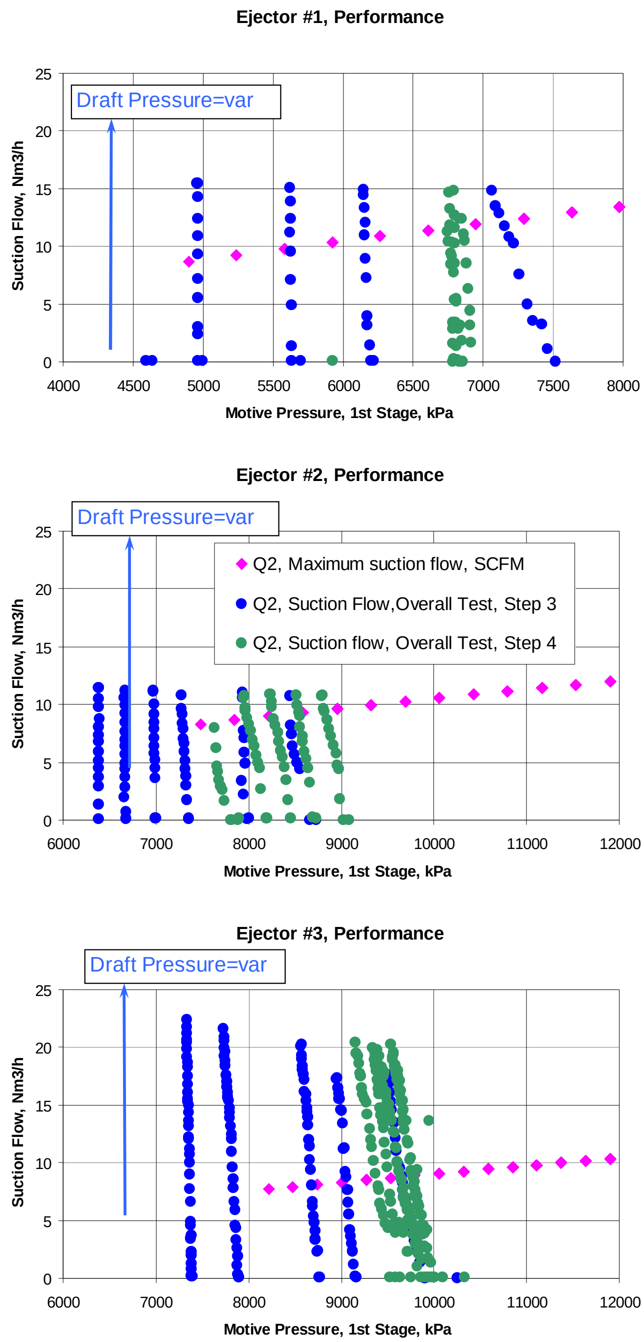

Figure 12. Comparison between Test Data and Prediction, Draft Flow vs. Motive Pressure.

The charts in Figure 12 show that the measured operating range is larger in capacity than predicted because of a varying suction and motive flow conditions. This was expected because the modeling assumptions represented a conservative approach that led to under-predicted operating range. For any given suction mass flow, even exceeding the calculated values, draft pressure remained within SSE operating range, as shown in Figure 13. This makes a user assured that the ejector will work properly at specified motive flow conditions. The test results confirmed the ejector system could operate with a wider performance map than originally intended.

The discrepancy between predicted and measured maximum suction flow is relatively low for ejectors #1 and #2, with slightly under-predicting the maximum capacity if compared at the same motive pressure. A larger discrepancy for the ejector #3, the smallest in size, may be explained by stronger impact of factors not accounted in the computational model and mentioned above. Motive pressure in experiments did not exceed 10000 kPa but this limitation was only because of the test setup.

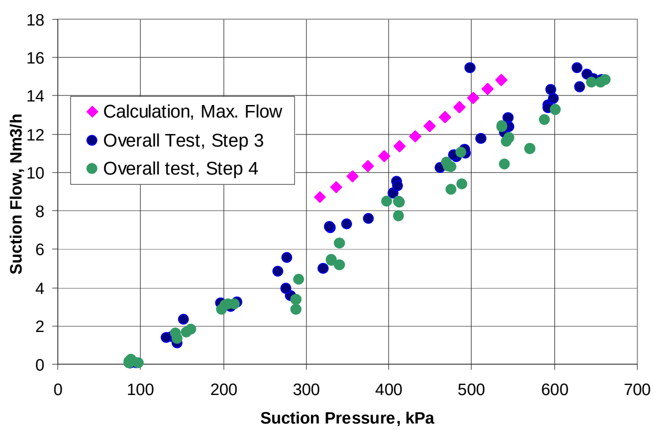

Figure 13. Comparison between Test Data and Prediction, Draft Flow vs. Suction Pressure.

As illustrated by Figure 13, gas seal leakage mass flow depends linearly on suction pressure both in test and prediction while test data generally lie below the predicted values. The difference between Figure 12 and 13 is due to variable suction pressure for the former and variable motive pressure for the latter.

Future work should concentrate on improvement of computational modeling to increase accuracy of prediction at variable suction and discharge flow conditions, and to account for viscous effects and heat transfer. Data collected at factory test will provide a ground for further tuning of the prediction tool.

CONCLUSIONS

The benefits of a two stage supersonic ejector and associated system have been discussed and they are as follows:

- The simplicity of design and absence of moving parts enable the SSE to be more reliable and require less maintenance than traditional solutions.
- No electrical energy requirement. The SSE is driven by the pressure of the gas in the compression system.
- The SSE system can take a low volume of gas at a low pressure and boost it to a high pressure.
- The SSE system can feed the captured gas into a steady state fuel system.
- A full recovery of gas-seal leakage gas was achieved within the operating range of motive pressure.

Efforts to feed the dry seal gas into the utility fuel gas system of the compressor station, a natural fit due to the low pressure of the system, have in the past not worked since the utility flow demand fluctuates over the course of a day. The fuel gas for the compressor engine, which is at a higher pressure than the utility system, would require fuel gas at a relatively steady rate and the need for fuel would typically align with when the SSE would be operating. When there is pressure in the compressor, during standby, idle and operating, there is gas flow through the dry gas seals. It is during idle and operating that the captured gas can be directed into the fuel gas of the unit. During standby the captured gas can be directed to the fuel line of an operating engine at the same compressor station.

The SSE system design features factory set up, capacity to operate within known process variations, and minimum on-line required adjustments. Similar schemes can be employed so that the captured gas can be returned to compressor suction or to pipeline station heaters or other utility gas applications. The result is a favorable reduction in hydrocarbon footprint for gas transmission pipeline operators.

An SSE family consisting of three different sizes targeting pipeline compressor units driven by different gas turbines was designed and successfully tested on inert gas at OEM's factory rig. Valuable test data were collected during the four-step factory test.

A mean-line adiabatic model was applied to create a SSE performance prediction tool at maximum suction flow conditions. Predicted maximum suction flow lies within the range of measured suction flow values, thus ensuring the successful SSE operation within the range of motive flow conditions. Future improvements in SSE modeling should improve the accuracy of prediction at variable suction flow conditions.

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