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DESIGN OF FLAPPER VALVES FOR A CO_2 COMMERCIAL REFRIGERATION COMPRESSOR

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ABSTRACT

This paper discusses the design of suction and discharge flapper valves for a reciprocating piston CO_2 compressor intended for commercial refrigeration applications. The design process included simulation of the valves to predict performance characteristics and bending stresses. Dynamic cylinder pressure measurements from a prototype are also presented in an effort to validate the simulation.

1. INTRODUCTION

Robust flapper valves are a crucial part of compressor design. The use of CO_2 as a refrigerant poses additional challenges to the successful design of a suction and discharge valve for a reciprocating compressor due to the unique operating conditions and thermofluid properties experienced by the use of CO_2. Simulation and analysis of the pressures acting upon the valve and the resultant deflections during its dynamic (opening, wide-open, and closing) and static (resting against the valve seat) phases is necessary in order to produce a valve that does not exceed its infinite life endurance limit and to select a port size for optimum flow.

2. OPERATING CONDITIONS

This single-stage CO_2 compressor was designed to operate at 3.0MPa suction and 11.5MPa discharge pressures.

3. VALVE DESIGN PROCESS

3.1 General Procedure for Design of a Flapper Valve

Initially, a suction port size is chosen to provide adequate flow area for the expected capacity of the compressor. Based on this port size, the suction valve is designed around the geometric constraints of the cylinder, valve plate, and cylinder head, and an initial stop height is estimated. This combination of valve design and stop height is then subjected to pressure loading based on the refrigerant, operating conditions, and mechanism (bore, stroke, connecting rod length, etc.). The simulation uses a transient finite-element analysis coupled with a simple thermodynamic model to predict the pressure loading and solve for the valve deflection as a function of time. The deflected valve shapes, and hence the dynamic stresses in the valve, are computed from the instant of valve opening until the valve is fully closed on the seat. From this time history the peak stress, deflected shape, and flow rate are examined. In addition, the extrusion stresses, in which a pressure differential acting on the back of the closed valve attempts to force the valve through the port, are then analyzed as a static FEA case. The port size, valve geometry, and/or stop height are then iteratively modified until acceptable dynamic and static stresses and flow rates are achieved. The entire process is repeated for the discharge port, valve, and backer.

3.2 Suction Valve for CO_2 Compressor

An existing valve shape was chosen as the initial design for the CO_2 compressor and was slightly modified to fit the estimated port diameter. However, the simulation showed that the peak dynamic stress levels were unacceptably high, and the choice was made to iterate on tip stop and valve thickness to lower the stresses. However, neither parameter gained enough improvement to reach the target stress of 690 MPa (see Figure 1).

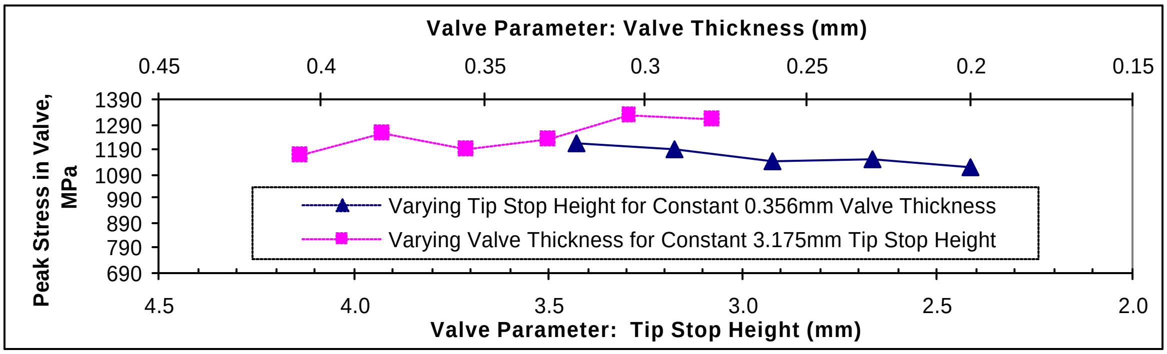

Figure 1. Initial choice of iterated parameters for suction valve stress improvement.

This first part of the analysis provided three significant pieces of information: (1) the valve would require a shape change in order to bring the stresses to the target level, (2) based on the flow data predicted by the simulation, the initial estimate for port diameter was correct, and (3) static analysis of extrusion stresses of the given port diameter showed acceptable stresses through a wide range of valve thicknesses. Since extrusion stress is a function only of thickness and port geometry, and the static stress level was acceptable by a wide margin at our port diameter, we could now safely proceed with the optimization of the dynamic stress levels without needing to simultaneously consider the static stress level at each point in the iteration.

A total of five shape changes were made on the valve. For each change, the simulation was used to calculate the peak dynamic stress and to ensure that the flow characteristics had not been adversely affected by the changes in the valve. Since the length of the valve was fixed by the desired cylinder, port, and valve plate design, modifications were made on the width and curvature of the valve, with significant rework being done at the base of the valve to more efficiently distribute the strain along the valve stem. The shape changes decreased the stress in the valve while slightly improving the flow rate, but the peak stress was still above the acceptable level (see Figure 2.) Further useful shape changes were unfeasible due to the other geometric constraints surrounding the valve. Therefore, it was necessary to achieve additional stress reduction through tip stop height and thickness changes applied to the optimized shape in order to avoid a complete redesign of the bore, valve plate, and cylinder head.

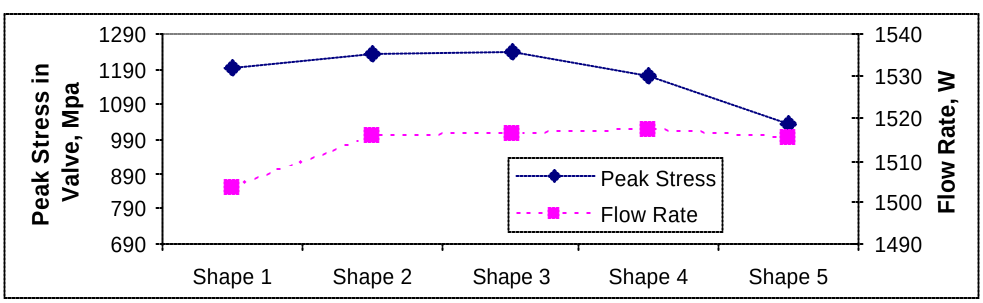

Figure 2. Improvement in Valve Stress Achieved through Shape Modification

The tip stop height was iterated through a broad range of values, and a value was found that resulted in an acceptable dynamic stress level. (see Figure 3) Furthermore, the expected decrease in flow rate did not occur even though the final tip stop height was below half of the original estimate, leading to the conclusion that a poor initial estimation was made for the original tip stop height. This combination of shape and tip stop height was checked at a valve thickness above and below the current value, but no improvement was seen. As a final step, the shape was analyzed in the static case for extrusion stresses, which were found to be acceptable. The design of the suction valve was then determined to be complete. For the final design, see Figure 4.

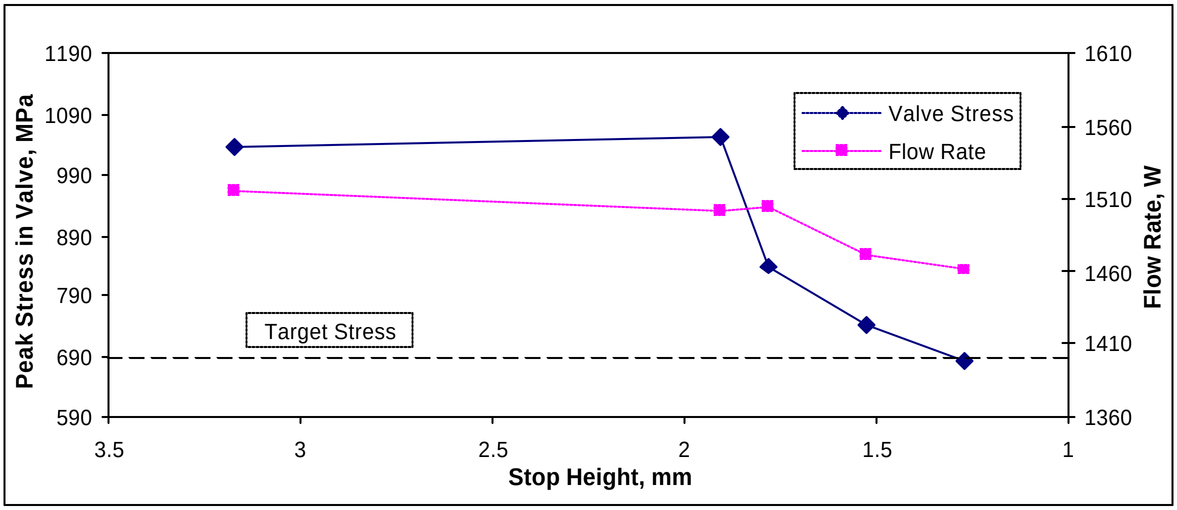

Figure 3. Iteration of Tip Stop Height on the Optimal Suction Valve Shape

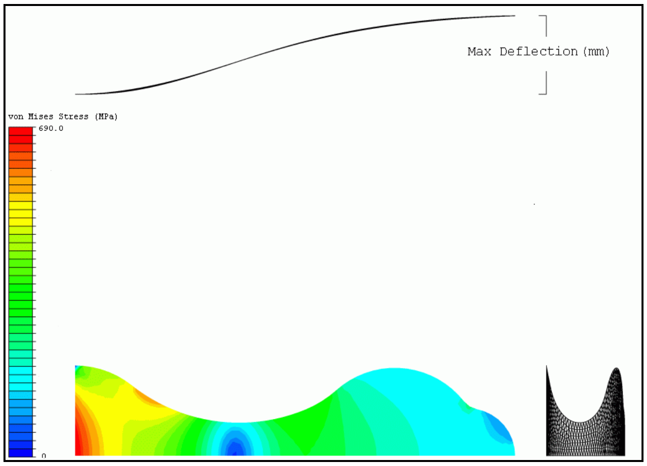

Figure 4. Final CO_2 Suction Valve Design

3.3 Discharge Valve for CO_2 Compressor

As outlined above in Section 3.1, a similar process was followed for the discharge valve. An initial valve and backer design were constructed, and simulation results predicted excessively high valve stresses. Upon close examination, the shape of the valve seemed to offer considerable opportunity for improvement. Hence, four different valve shapes were analyzed with the current backer. Although the stress of the redesigned shapes was lower, optimization did not succeed as well as expected and the peak stress was still well above the target stress level (see Figure 5).

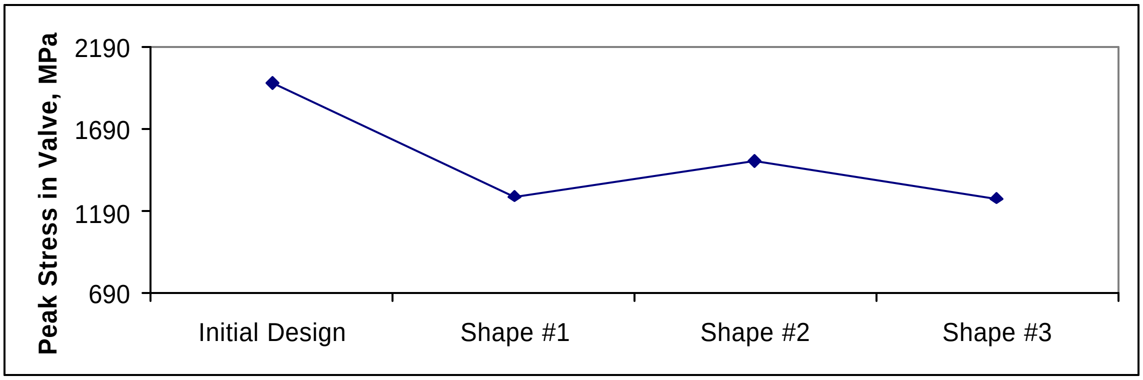

Figure 5. Stress Improvement in the CO_2 Compressor Discharge Valve by Shape Optimization

Iteration upon the backer radius was then performed. A large increase in backer radius provided a solution in which the peak valve stress reached the target (see Figure 6) at only a slight cost in flow rate. The simulation calculates a time-averaged value of the amount of discharge flow limited by the port throat compared to the amount of flow limited by the lift of the valve, which is a useful measure in determining if the flow is being disproportionately restricted by either the lift or the port. As expected, the amount of flow limited by the lift increased as the backer radius increased, but the flow rate decreased only slightly. The extrusion stress of the discharge valve was then analyzed and found to be acceptable, concluding the valve design for the compressor. For the final discharge valve design, see Figure 7.

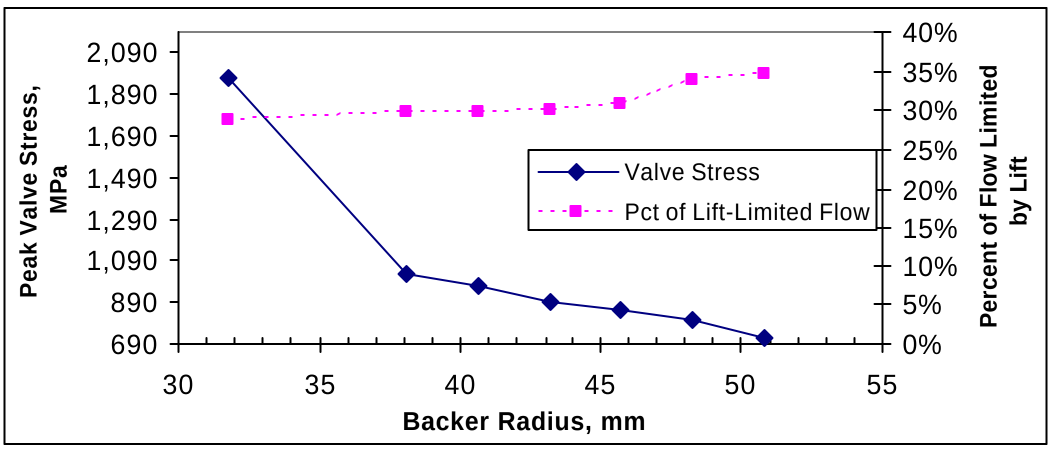

Figure 6. Iteration of Discharge Backer Radius for a Successful Valve Design

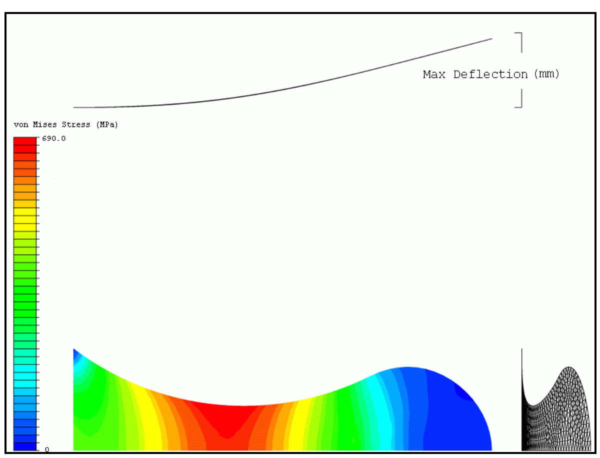

Figure 7. Final Discharge Valve Design

4. EVALUATION OF VALVE DESIGN

Prototype valves were manufactured and installed in the compressor. The compressor design was evaluated across a range of conditions on a load stand and on various applications. There were two primary concerns to be evaluated on the compressor; durability and performance. To verify structural integrity of the valve design, prototype compressors were run for 100 hours at a several conditions. For structural fatigue of valves, infinite life is considered to be 10,000,000 cycles, this takes slightly less than 48 hours at 3550 RPM. Instrumentation was used to verify the performance of the valves (see Figures 8 and 9). A significant challenge with CO_2 is over pressurization of the cylinder, which may result in very high bearing loads. Measurement of the cylinder pressure during operation showed no excessive pressure pulsations and confirmed the port sizing is correct (see Figure 10).

5. CONCLUSIONS

Using a combination of finite element analysis and mathematical simulation, a suction and discharge valve were designed for a CO_2 compressor. The durability and performance of the valve design were successfully verified in the compressor application. The success of the design process validated the use of the simulation in order to rapidly converge on successful valve designs.

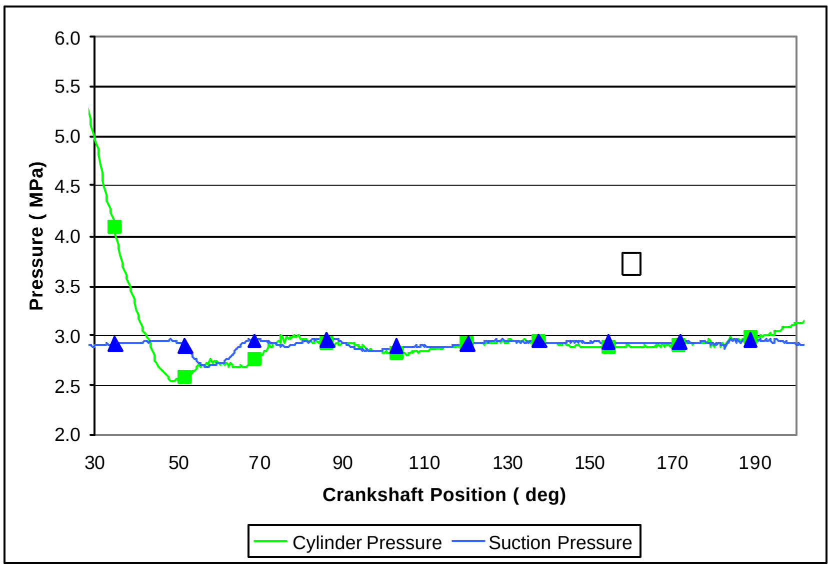

Figure 8. Cylinder Pressure vs. Suction Plenum Pressure

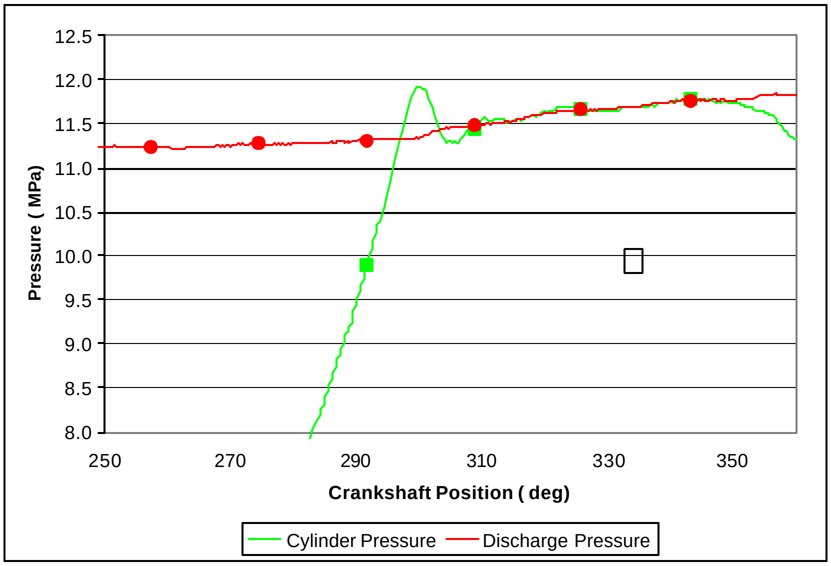

Figure 9. Cylinder Pressure vs. Discharge Plenum Pressure

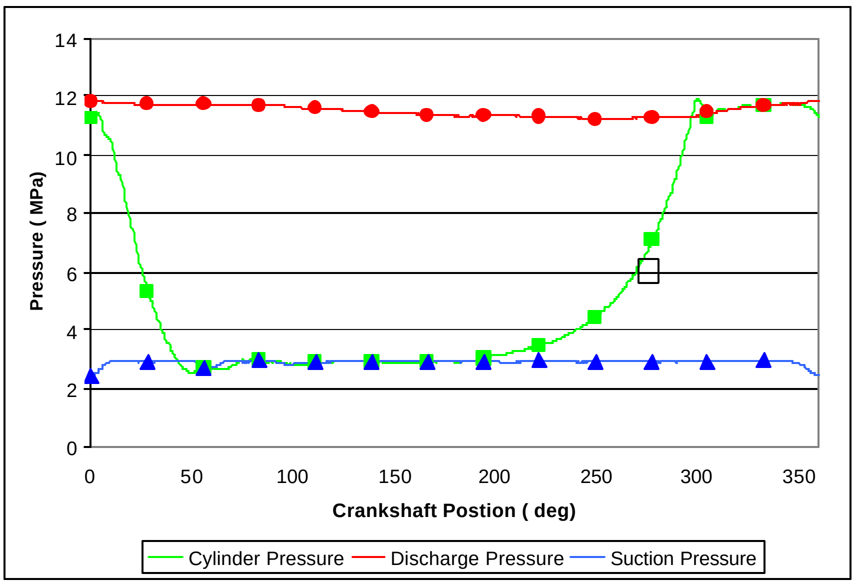

Figure 10. Operating Pressures