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Digital valve for high pressure high flow applications

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ABSTRACT

To address the challenges, which are involved with the development of flow control valves that can meet the requirements of deep oil wells such as high pressure, high flow rate, limited power and limited space, the authors have conceived a novel design configuration [1]. This design consists of a digitalized flow control valve with multipath and multistage pressure reduction structures. Specifically, the valve is configured as a set of parallel flow paths from the inlet to the outlet. A choke valve controls the total flow rate by digitally opening different paths or different combination of the paths. Each path is controlled by a poppet cap valve basically operated in on-off states. The number of flow states is 2^N where N is the number of flow paths. To avoid erosion from sand in the oil and high speed flow, the seal area of the poppet cap valve is located at a distance from the flow inlet away from the high speed flow and the speed is controlled to stay below a predefined erosion safe limit. The path is a multistage structure composed of a set of serial nozzles-expansion chambers that equally distribute the total pressure drop to each stage. The pressure drop of each stage and, therefore, the flow speed at the nozzles and expansion chambers is controlled by the number of stages. The paths have relatively small cross section and could be relatively long for large number of stages and still fit in the strict annular space limit of a typical downhole region of an oil well. The paper will present the design configuration, analysis and preliminary test results.

KEYWORDS: Flow control, digital valve, downhole, oil well.

INTRODUCTION

Fossil fuels supply 85% of the world's energy needs. As part of fossil fuels, oil represents a large percentage. Developing novel methods of extraction and increasing the efficiency of reservoirs management increases the resources-to-production ratio giving the world time to develop more sustainable means of producing its energy needs. A team of engineers and scientists at JPL have developed a novel valve for flow control that can satisfy the stringent requirements of high pressure, high flow rate, limited power and limited space environment.

This design configuration consists of a digitalized flow control valve with multipath and multistage pressure reduction structures. Specifically, the valve is configured as a set of parallel flow paths from the inlet to the outlet. The choke valve controls the total flow rate by opening different path or different combination of the paths. Each path is controlled by a poppet cap valve basically operated in on-off states and the combination of N valves allows for the potential of 2^N flow states which has led to our designation of this valve as the "digital valve". To avoid erosion from sand in the oil and high flow rates, the flow speed is reduced and the seal surface of the poppet cap valve is located at a distance from the flow inlet away from the high speed flow. The path is a multistage structure composed of nozzle – settling chamber pairs. The pressure drop of each stage and, therefore, the flow speed at the nozzle for a set flow rate is controlled by the number of stages. The paths have relatively small diameter or cross section and could be relatively long for a high pressure differential and a large number of stages. Even with the large number of stages configuration and high pressure differentials the valve can still fit in the strict annular space limit of a typical downhole region of an oil well. Figure 1 shows the digital valve concept with a series of parallel paths each having a number of reduction stages.

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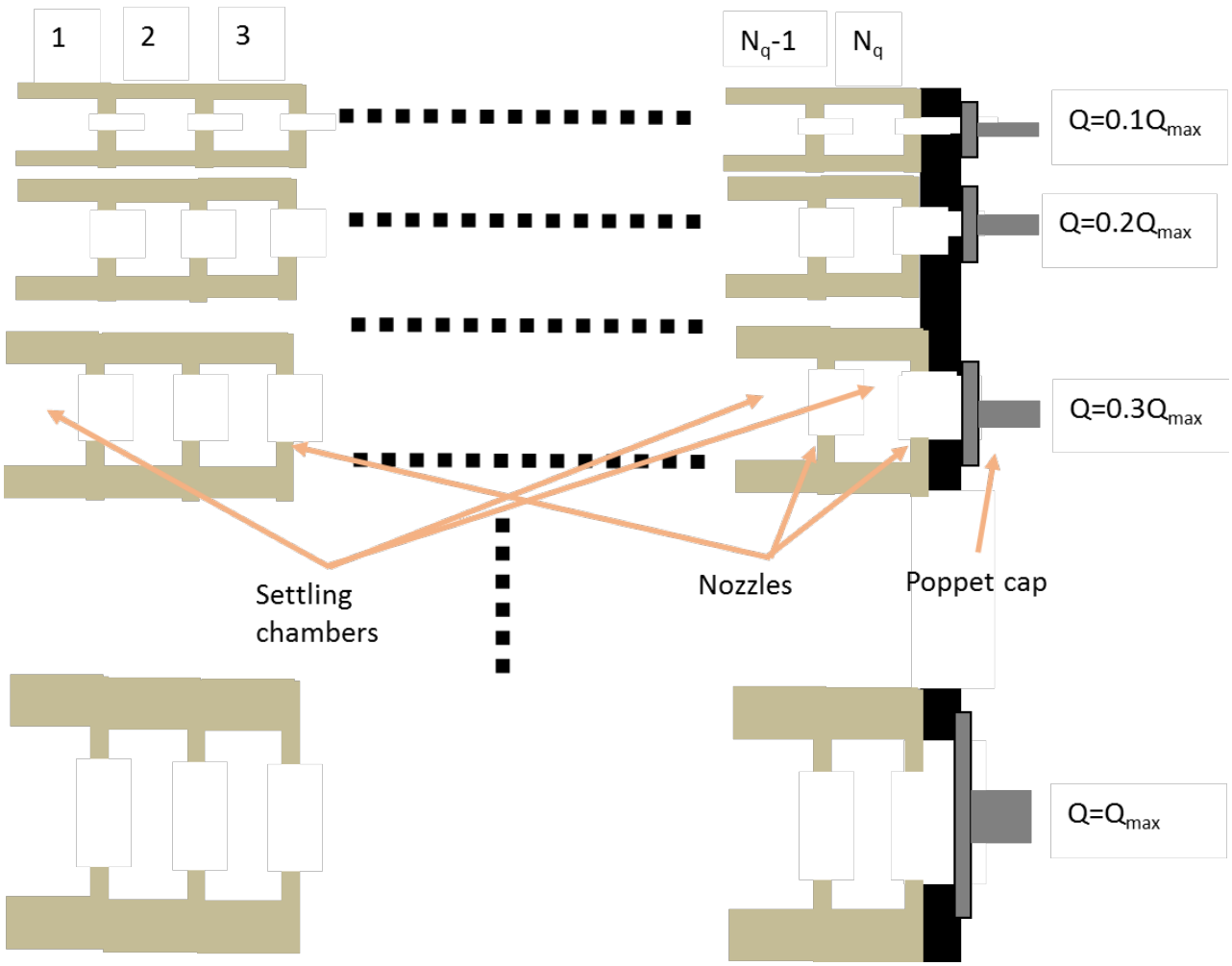

Figure 1 The digital valve concept

The development of the digital valve has progressed in phases where in the first phase we implemented a low pressure single poppet valve configuration. In the following phase, we implemented a dual flow path with back-flow control form, fit and function integrated valve configuration and we are in the process of the full implementation of the complete valve configuration. The single poppet and the dual flow path valve implementations are the subject of this paper.

DESIGN AND ANALYSIS

The single poppet valve implementation was fabricated to test the sealing capability of the poppet cap and the force necessary to open under pressure as well as confirm the fabrication and assembly of the reduction stages. The features of the prototype design include dual inlets, the velocity reducing stages, mounting flanges, bleed and relief valves, the exit from the velocity reducing stages and the linear actuator motor. Figure 2 shows the top and side views of the CAD model and the Figure 3 shows the valve components in an exploded view. The linear actuator, poppet, nozzles and expansion chambers were fabricated having the space constraints in mind and the cylindrical housing and interface to the pump and safety valves were designed just to accommodate the tested components.

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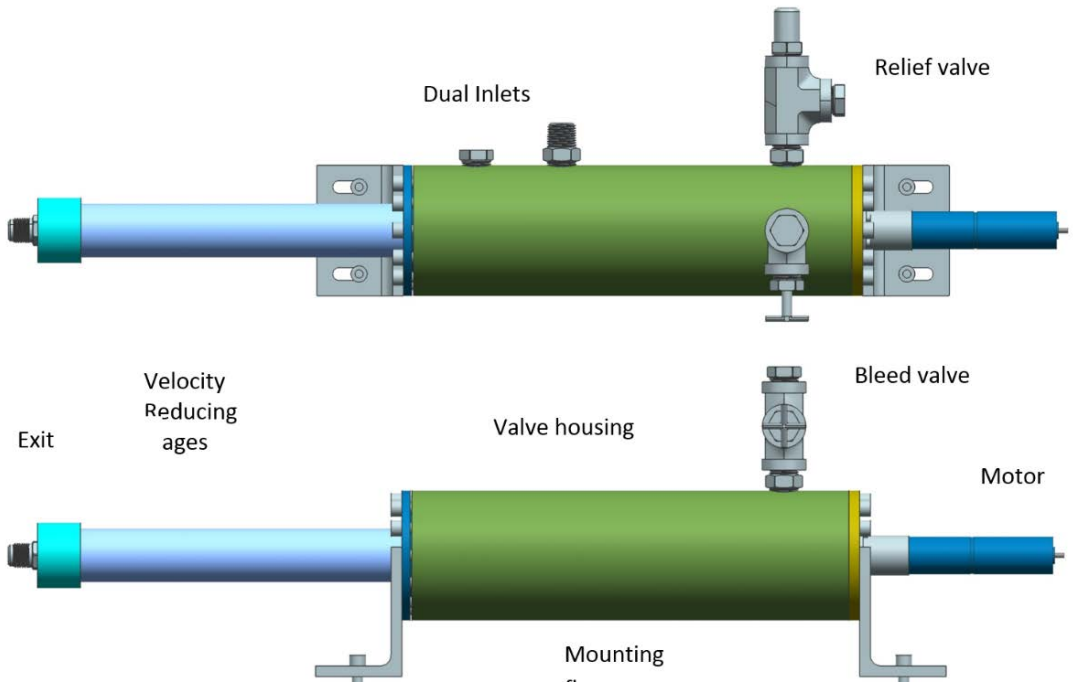

Figure 2 Single poppet valve implementation top and side views

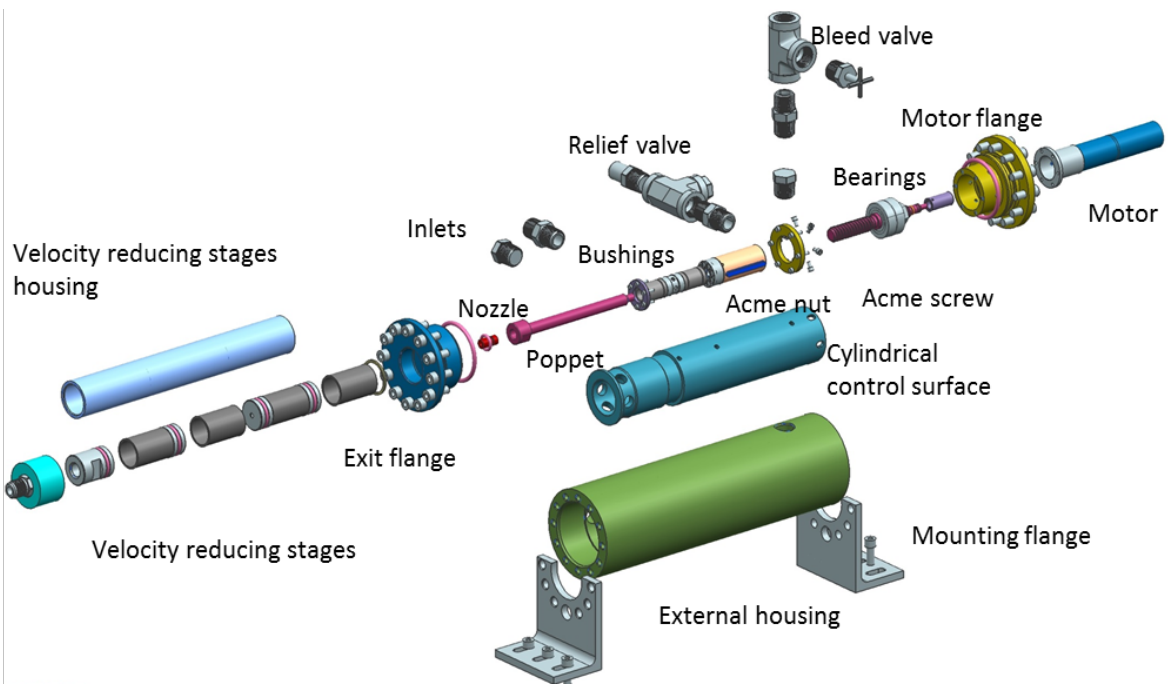

Figure 3 Exploded view of the single poppet valve implementation

The linear actuator consists of a motor, an ACME screw and an ACME nut. The motor shaft is connected to the screw via an adaptor and mounted to the housing on the motor flange. The ACME screw is retained by two bearings that take all the axial load of the screw. The ACME nut is guided inside a cylinder on two slots and is prevented from rotating. As the screw rotates the nut moves in the axial direction. The nut moving direction is controlled by the motor clockwise or

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counter clockwise turning. The bearings are angular contact bearings which support both the axial and radial forces. The poppet is mechanically connected to the acme screw and moves toward the nozzle to close the valve or away from the nozzle to open the flow path. In this particular design we have both face and side sealing O-rings between the poppet cap and the nozzle. The flow through the nozzle then goes through four velocity reducing stages. The bleed valve is used to remove the air from inside the valve chamber and the relief valve will prevent pressure build-up above the design value.

For testing, oil was used as working fluid to prevent corrosion on the control surfaces. A manual pump was used to increase the pressure inside the valve chamber and open the poppet under pressure. The motor used approximately 5W of power to actuate the poppet to open under 10.3MPa (1500 psi) internal pressure. The better performing seal was the face seal and was decided to implement a dove tail seal gland to retain the seal in the gland during valve opening. Also for opening the poppets under higher pressure the ACME screw linear motion conversion mechanism needed to be replaced with a roller screw mechanism. The roller screw includes a nut and a screw. The nut includes a series of threaded rollers located between two guide rings and being engaged with the teeth of a toothed ring. These threaded rollers have a matching thread with the shaft and roll on the shaft as the shaft rotates relative to the nut. The threaded rollers have a similar motion as the satellite gears around a sun gear and are also called satellite screws. When the nut is constrained to rotate, the shaft rotation causes the nut to have an axial motion. Having a rolling motion in the satellite screws creates a higher efficiency that the ACME nut screw configuration which require a sliding motion. In addition, the roller screw has a larger linear force capacity than the ball screw of the same diameter. These advantages suggested that we select the roller screw as the rotary to linear motion transforming mechanism for the next valve implementation.

The two poppet valve implementation

In this implementation, the valve was located in an annular section with a radial thickness of 31 mm, between two pipes (see Figure 4). Two flow paths were implemented for the direct flow and a backflow control solution was implemented to prevent the reverse flow through the reduction stages. The main section of the valve are the velocity reduction stages, integrated poppets and linear mechanisms, motors and backflow control. The reduction stages section includes two paths for the controlled speed oil flow, paths for bringing the oil from the filter to the poppets head cavity, a feed-thru channel for electrical feed through, openings to the inner pipe from each flow path and interface for the backflow control. The integrated poppets and linear mechanisms section includes the poppets, poppets locking mechanisms and roller screws (Figure 5). The motors section includes the motors for the two flow paths, bearings for the roller screw shafts, bellows for clean enclosure volume change mitigation and motor connectors. The backflow control section includes a motor, linear mechanisms, and two poppets. The motor is required to run in clean oil and a clean enclosure was created for each flow path that includes the motor, bearings, roller screw, poppets locking mechanisms and poppets' shafts. Due to the fact that the length of poppets shafts included in the clean enclosure varies depending on the open or closed position of the poppet the volume of the clean enclosure varies and we included a bellows to mitigate this volume change. During the poppet actuation part of the oil inside the clean enclosure migrates from one side of the enclosure to the other using clearance between moving parts or orifices designed in the parts when clearances were not possible to implement. The velocity reduction stages and integrated poppets and linear mechanisms sections were ruggedized by building the cavities inside of a solid thick wall pipe. Ruggedized covers for the motors sections were designed but were not fabricated for this development phase.

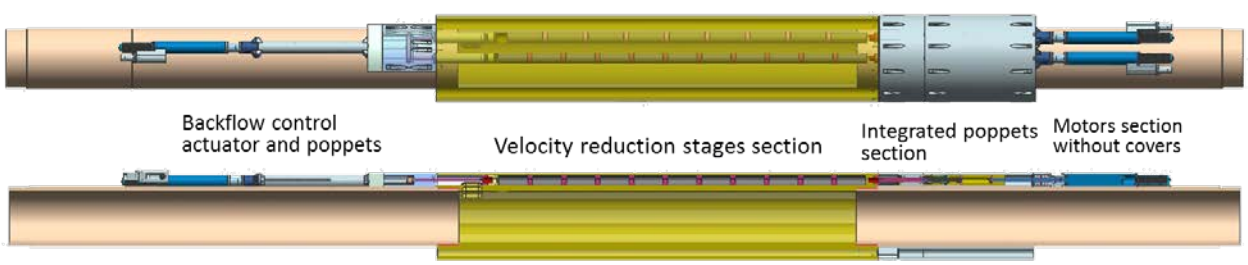

Figure 4 Two flow paths valve implementation

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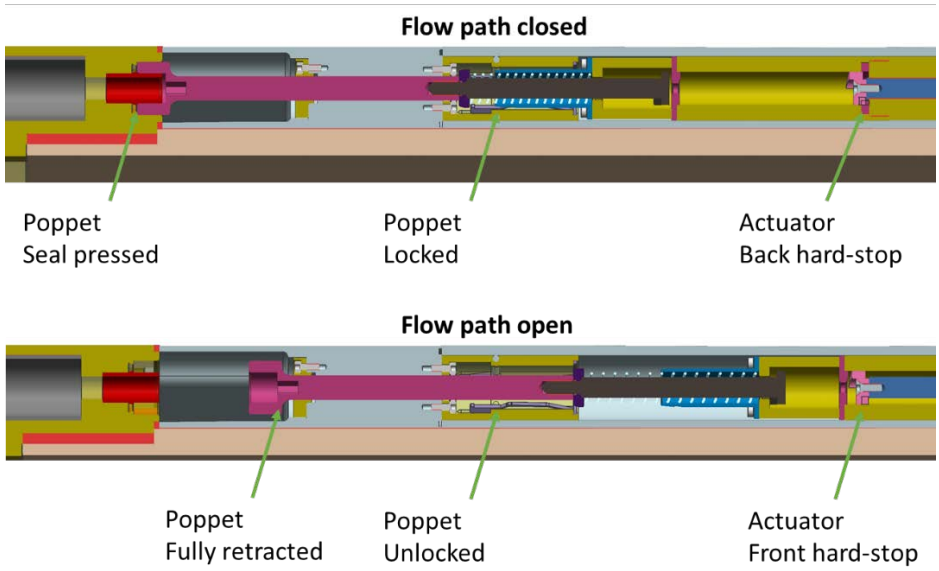

Figure 5 Linear mechanism and locking flexure

The poppets locking mechanism consists of a flexure and a sleeve coaxial with the linear actuator and poppet. While the poppet is pushed toward the seal surface the sleeve bends the flexure fingers and move the free cantilevered ends of the fingers to block the poppet from retracting. A groove on the sleeve acts as a detent and prevents sleeve from being pushed back, toward the motor, by the poppet spring to back-drive the roller screw. To open the poppet the roller screw nut is retracted pulling back the looking mechanism sleeve which releases the flexure fingers that move away from the back of the poppet. During this time the poppet is held pressed against the seal by the oil pressure. Retracting the roller screw nut farther toward the motor engages the poppet and pulls it away from the sealing surface, opening the oil path. The linear mechanism was instrumented with front and back hard-stops that prevent the screw from rotating when the predefined stroke boundaries are reached, avoiding the screw and nut locking.

The backflow prevention mechanisms were created to prevent the flow from the inner pipe to the formation when the pressure in the inner pipe is larger than that of the formation. It also serves to protect the reduction stages flow paths from erosion in case of extreme pressure differential. As it is not expected to be actuated against pressure, a valve with one motor and multiple poppets was implemented. Also, in this implementation the linear mechanisms are identical for all three paths of flow control and back flow prevention. In a future implementation the backflow prevention mechanisms travel will be larger to guarantee the poppets' heads completely clear the openings into the inner pipe and stay out of the flow path.

Critical components were analyzed to determine the strength margins for test environmental conditions. Analysis of two of these components is included in this paper: the reduction stages housing and the poppet locking flexure mechanism. The reduction stages housing was modeled directly from the geometry via linear tetrahedral elements with constraint elements (NASTRAN RBE3) to provide a connection to ground for static pressure calculations. The constraint elements for supporting the Pipe are shown in Figure 7 on the left. The two modes of operation were considered in setup of the boundary conditions: for a net internal pressure, a uniform load was applied to all interior faces in contact with interior volume of the pipe as shown in Figure 7 on the right, while the case of a net external pressure applied a uniform load to all external faces. The Smart Pipe model is a section of the larger pipe system, and requires that the reaction forces at the end of the section and at the periphery of the poppet valve tubes due to the external or internal pressure on the cross-section of the tubes be included in the total load.

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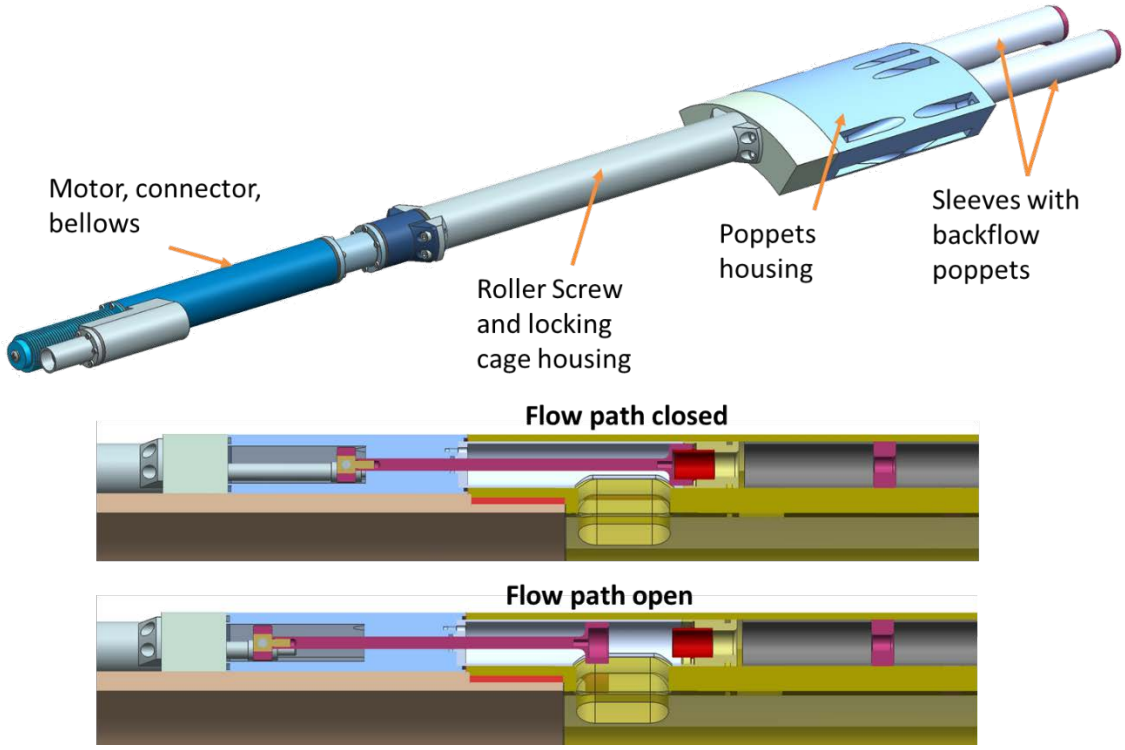

Figure 6 Back flow prevention control mechanisms

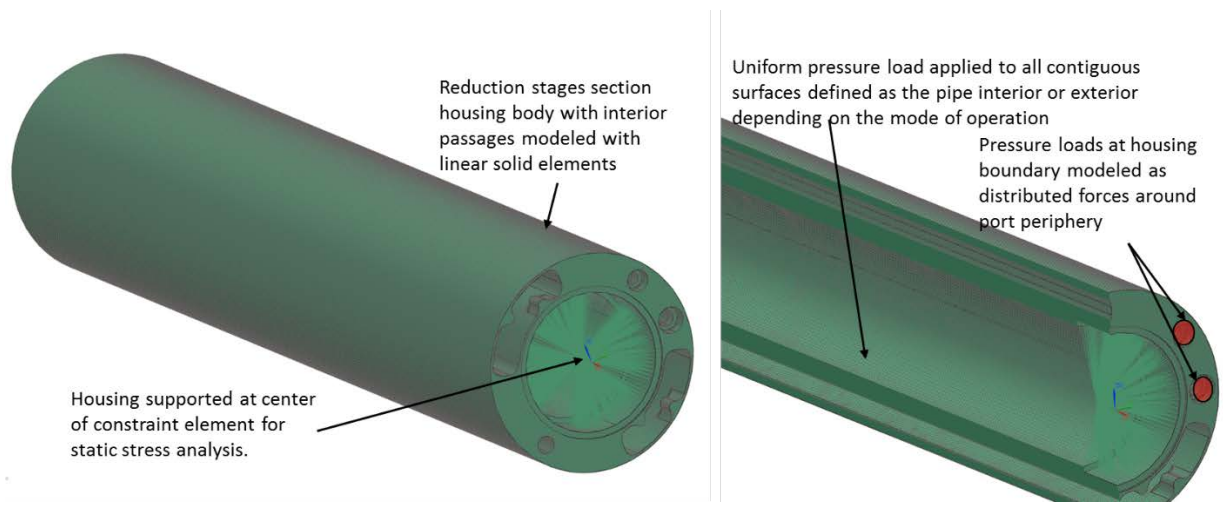

Figure 7 Reduction stages section housing FEA model

The stresses are shown in the plot in Figure 8 are for a net internal pressure of 34.5 MPa (5,000 psi), consistent with the test plan for the demonstration of the valve in this development phase. The stresses are significant through the pipe section and around the interior surfaces due to the high pressures contained. The elevated stresses are due to the openings through the side of the pipe section to accommodate flow, requiring the tube wall on either side of the opening to absorb the load that is placing the tube wall in tension.

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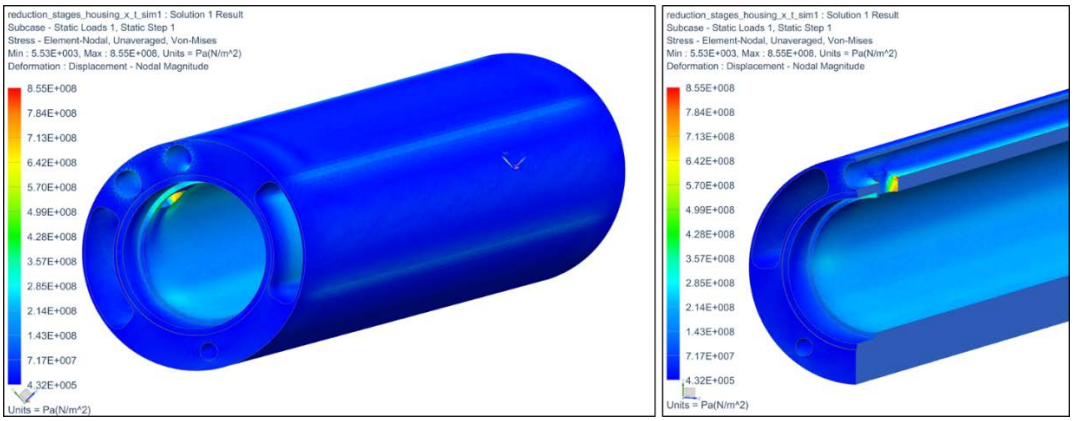

Figure 8 Reduction Stages housing stress analysis

The NASTRAN structural model of poppet locking mechanism for the Smart Pipe is shown in Figure 9. The model is shown in the fully disengaged state with the sleeve fully retracted from the flexure. The purpose of the model was to evaluate the stresses the flexure fingers and study the effect of friction on the peak force required to engage and disengage the lock. The fingers and sleeve are modeled with solid elements in order to provide a surface for evaluating surface contact and friction effects. The pins that support the fingers are modeled as perfect revolute joints using a spring element at the center of each pivot, connected to the interior of the joint with a constraint element on one side and grounded at the other. The actuator is reduced to a single node on the sleeve as shown.

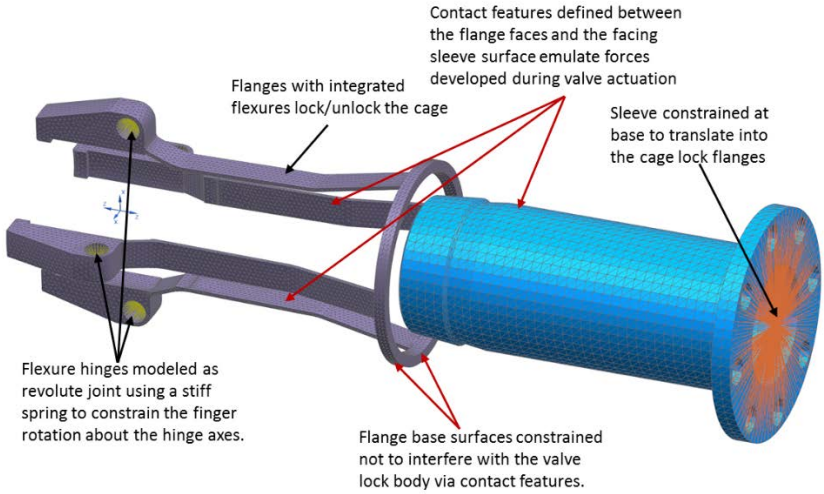

Figure 9 Poppet locking mechanism FEA model

The NASTRAN (601) nonlinear statics solution was selected for the model in order to evaluate the large displacements and surface contact effects. The actuator node is constrained and driven by a function which displaces the sleeve to the end of travel fully engaging the lock and then retracts to the fully disengaged state. Tracing the component stresses of the contacting surfaces, and the required load through the full travel of the sleeve provides insight into the behavior of the mechanism for fine tuning the flexures profiles.

The required input force over the entire travel of the sleeve is shown in Figure 10 and the pictures of the mechanism at four key operational points is shown in Figure 11. The force peaks corresponding to the contact of the flange fingers with the sleeve and sliding across the detent feature can be seen clearly. Note that the peak force occurs while the sleeve is withdrawn from the cage at the detent location. The analysis results shown above assume a contact friction of 0.2. Varying

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the coefficient from 0 to 0.2 demonstrated the cage lock mechanism is not very sensitive in terms of overall behavior or required peak force. The sequence of four pictures shown below correspond to peaks in the actuator load in the previous plot. Significant stresses are developed both from contact pressure between the sleeve and the flanges, and within the flange cross-section due to bending. The time shown in the Figures represents the simulation time and not the actual operational times.

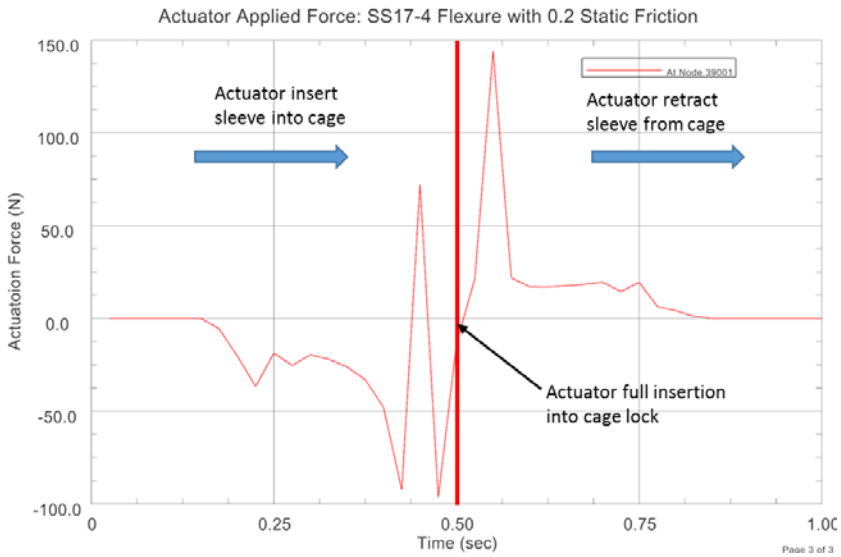

Figure 10 Actuator force required to operate the poppet locking mechanism

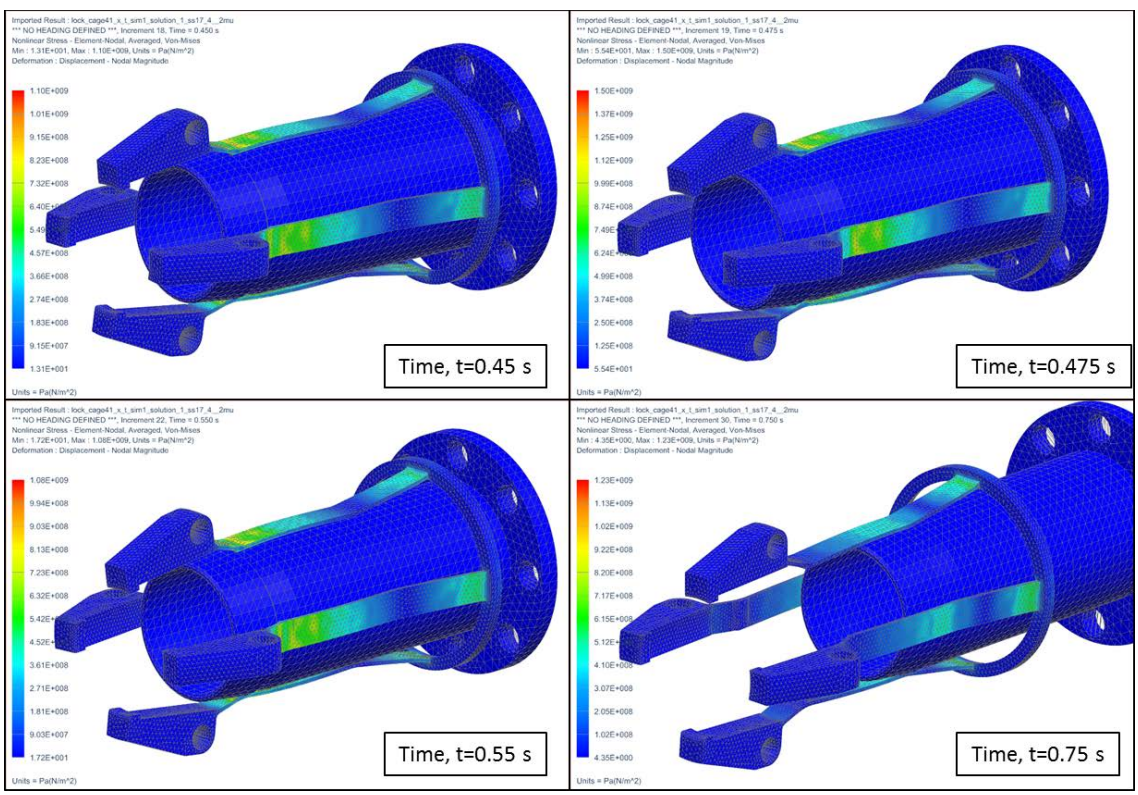

Figure 11 Mechanism's stress distribution at four key operational points

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FABRICATION AND PRELIMINARY TEST RESULTS

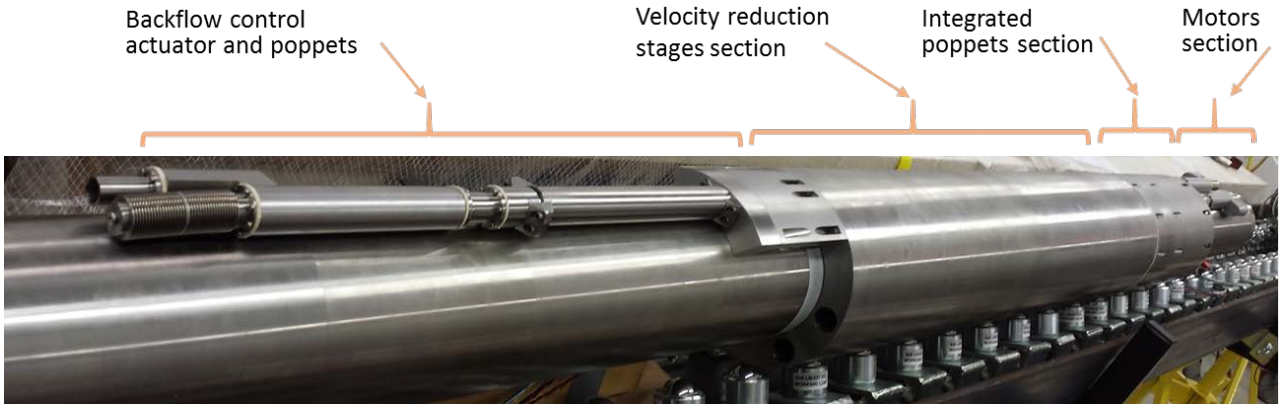

Figure 12 Digital valve two flow paths prototype

The design of the valve prototype with the two flow paths implementation was finalized and the parts were submitted for fabrication. The material selected of this implementation for fabrication was the 17-4 PH and the pressure bearing parts or parts with sliding interfaces were heat treated in the H900 condition. Upon delivery the parts were inspected and fit checked. The actuators and poppets subassemblies were assembled separately and then integrated into the valve assembly. Finally the valve subsystem was integrated with control electronics and into the Smart Pipe assembly. A picture of the integrated valve subassembly is shown in Figure 12 with the backflow control section on the left side and the motors section of the two flow paths on the right side of the picture. The valve is 2.86 m long with a projected mass of 270 kg.

The clean enclosures were filled with oil and sealed and the motor connectors were attached to the drive electronics. The poppets were moved between closed and open positions from hard-stop to hard-stop and the motor current recorded as part of a preliminary valve testing. A plot of the motor current is shown in Figure 13 with a running power of about 2W and power spikes when the hard stops are reached.

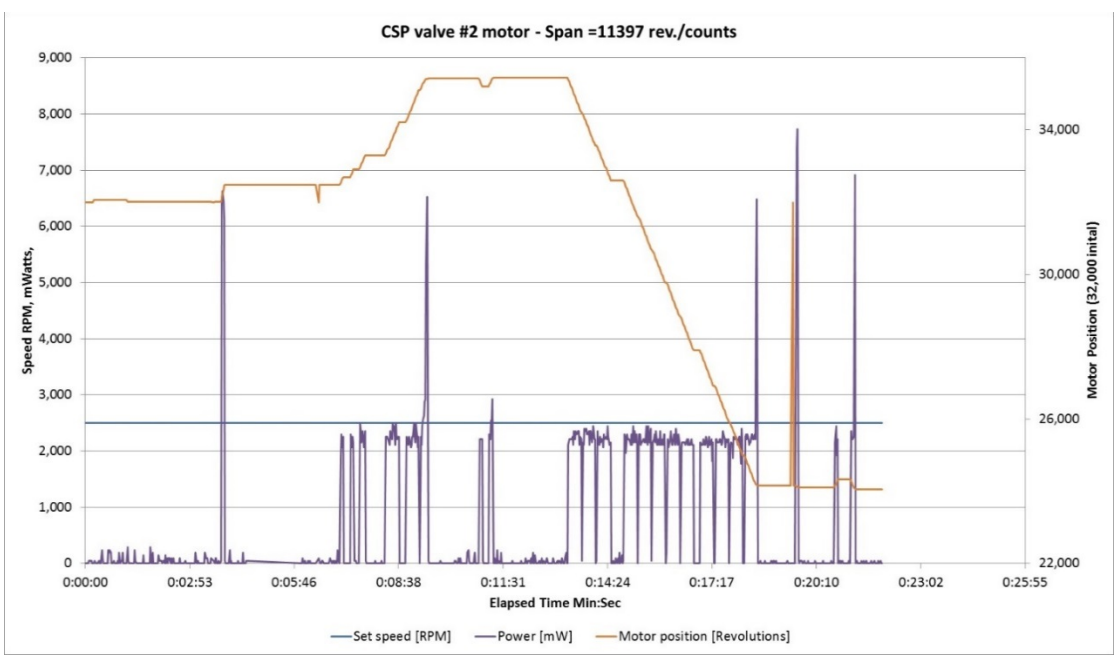

Figure 13 Motor power and position plots

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CONCLUSIONS AND FUTURE WORK

Two designs and fabricated prototypes of a high pressure high flow control valve as part of a Smart Pipe were presented. The valve is 2.86 m long with a projected mass of 270kg. Currently the valve is being prepared for pressure and flow testing.

We are continuing to investigate the three areas of concern as we transition to the next design implementation. These include the 69 MPa (10 ksi) differential pressure in the pipe with inlet holes, the increased cross sectional area of the oil feed conduits and the electrical connector interface. The area of the annulus that houses the velocity reducing stages will need to be reconfigured with special attention to the poppet area, oil feed conduits area and cabling pass through area. The current electrical connector adaptor does not fit in the space allocated for a six flow paths implementation and it will require a more compact redesign or stagger the motors axially in order to accommodate the cabling connectors.

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