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ADAPTIVE DESIGN OF 3/2 DIRECTIONAL CONTROL VALVE

by
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AN ABSTRACT OF THE THESIS

Mohamad Sleiman for Master of Engineering
Major: Mechanical Engineering

Title: Adaptive design of a 3/2 directional control valve

Design process represents an important major in Engineering. It involves creating solutions for confronted engineering problem through rational and scientific method. A *design process* is applied to make a *3/2 directional control valve*. This *valve* should be functioning as *Energy Recovery Device* for a *wave powered reverse osmosis desalination system*.

The proposed solution is a combination of *adaptive* and *variant* design. It involves applying modifications to an existing object so it can fulfill new application requirements. These modifications include optimization in the model geometry, size and material. Proposed solution is a *combination of two pilots operated check valve normally closed* and *normally open*. The working condition in a harsh environment such as seawater requires the use of plastic material (*Delrin*). The size of the plant and the plastic material are affecting the valve size.

Design process is made through different steps: *task clarification*, *conceptual design*, *embodiment design* and *detail design.* At the end a *finite element analysis* of the proposed model verifies its reliability. A production drawing is available for manufacturing. A 3d printed model is for demonstration.

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EQUATIONS

Equation

NOMENCLATURES

Q – Flow rate (L/min)

A – Flow area (mm^2)

P – Pressure (bar)

ρ – Density (kg/m^3)

ΔP – Pressure difference (bar)

α_0 – Seat angle (rd)

α – Opening angle (rd)

d_s – Seat diameter (mm)

d_b – Ball diameter (mm)

d_b – Opening diameter (mm)

d_{pilot} – Pilot piston diameter (mm)

x – Lift (mm)

F – Force (N)

f – Friction force (N)

μ – Friction coefficient

N – Contact force (N)

h – Effective lift (mm)

d_i – Seat inner diameter (mm)

d_o – Seat outer diameter (mm)

d – Oring cross section (mm)

g – Groove depth (mm)

E – Ring modulus of young (MPa)

σ_0 – Initial contact stress (MPa)

σ – Contact stress (MPa)

s_0 – Initial contact length of the ring (mm)

s – Compressed contact length of the ring (mm)

A_p – Intercept (MPa)

m – Slope

d_w – Wire diameter (mm)

D – Mean diameter (mm)

S_{ut} – Ultimate strength (MPa)

S_{sy} – Shear strength (MPa)

K_w – Whal factor

τ_{max} – Maximum shear (MPa)

CHAPTER I

INTRODUCTION

Mechanical design wheel has been ongoing through ages and millions of artefacts have been invented through tough and long procedures (Ullman, 2009). Design process represents an important aspect of study, because it does not only inspect the composition of technical system but also their development based on scientific methods. In fact, design is based on physics laws as well as on engineer's creativity and experience (Pahl, 2013). It is a method used to solve areas of human life problems through engineering principles. This area of engineering requires careful and deep thoughts. The solution can be made creating new objects or optimizing existing ones. In both case, design process shall improve objects quality and lower production cost (Ullman, 2009).

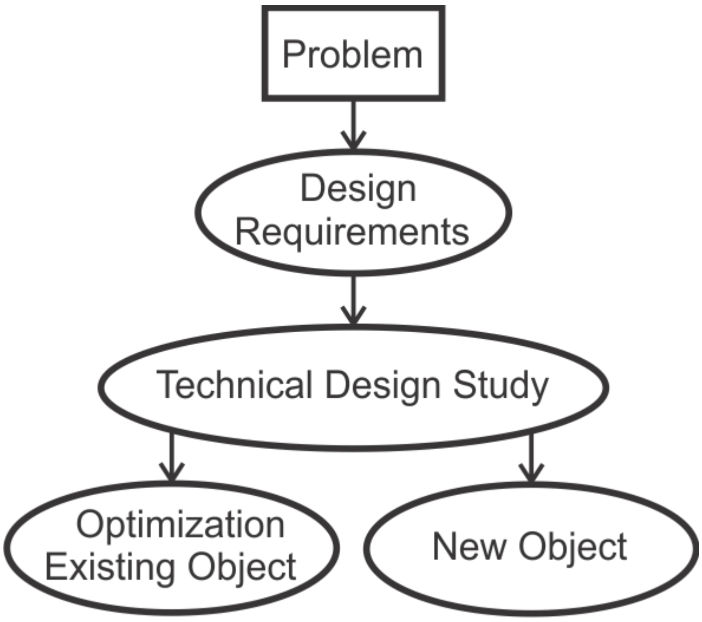


Figure 1: Problem solving using design

Solutions sought through design depend basically on the artefact main function. However, the choice is governed also by conflicting constraints, requirements and circumstances set mainly by material, manufacturing process, product form, working environment and economy (Pahl, 2013), (Ullman, 2009). The development that manufacturing undergoes along with revolution in material science is shaping the design process. New design prospects appear with new ideas and possibilities benefiting of this evolution. Although, a wider range of solutions becomes available to designer, the design process gets more complicated and challenging because of this variety of solutions. Yet, the design aims always to provide an optimum solution with respect to conflicting constraints. One should look for the best fitting feasible solution with the lower possible cost.

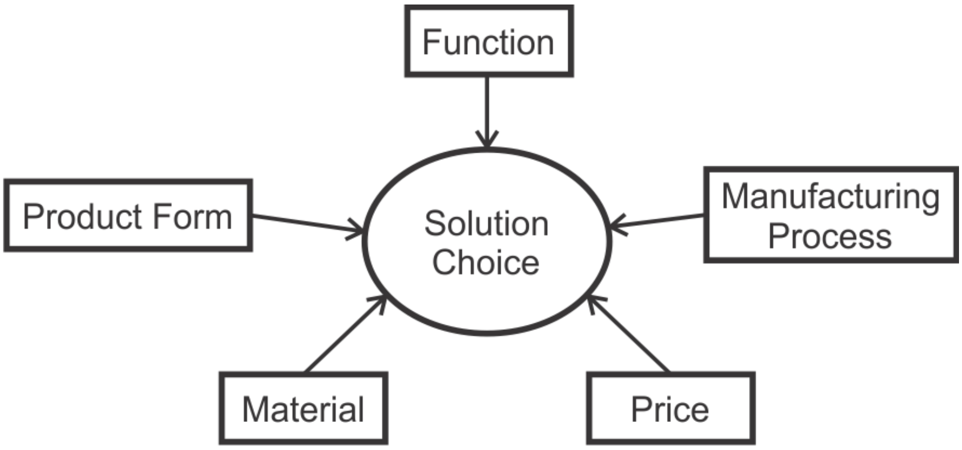


Figure 2: Main factors governing solution choice

Design process methodologies apply whether the design subject is a complex working system or a singular small component, the only difference resides in the degree of complexity of the designed object, constraints and requirements. Any artefact regardless the size and simplicity of operation is the fruit of tough and long design procedure. Even simple components acquire some complexity whether from the working conditions requirements or their operating principles. A mechanical component that seems simple and common such as a valve can hold within hidden complexity and challenges. It is the design process that reveals these complexities, highlights them in terms of task functions, derives requirements and analyzes possible solution. In conclusion, proper and reliable solution is chosen.

This work represents the dissertation of a master thesis that aims to make the design of a directional control valve used as energy recovery device for wave powered reverse osmosis system. A combination of two pilot operated check valve fulfills this function. One valve is normally closed while the other one is normally opened. The proposed solution design process is presented relying on systematic approach. The design shall proceeds through clear steps involving: task clarification, conceptual design, embodiment design and finally detail design. Execution of quantitative and qualitative analysis comes along with a choice of material and manufacturing process.

CHAPTER II

REQUIREMENTS

A. Solution Operation

The start point of design is defining the problem requirements in order to search for appropriate solution. The design subject operation needs to be well defined and described. The system function and interaction with the surrounding environment needs to be clarified. This is essential in order to extract task specifications and operation requirements. Any ambiguity, missing or misleading information at this initial step obstructs design process and makes any proposed solution subject to failure.

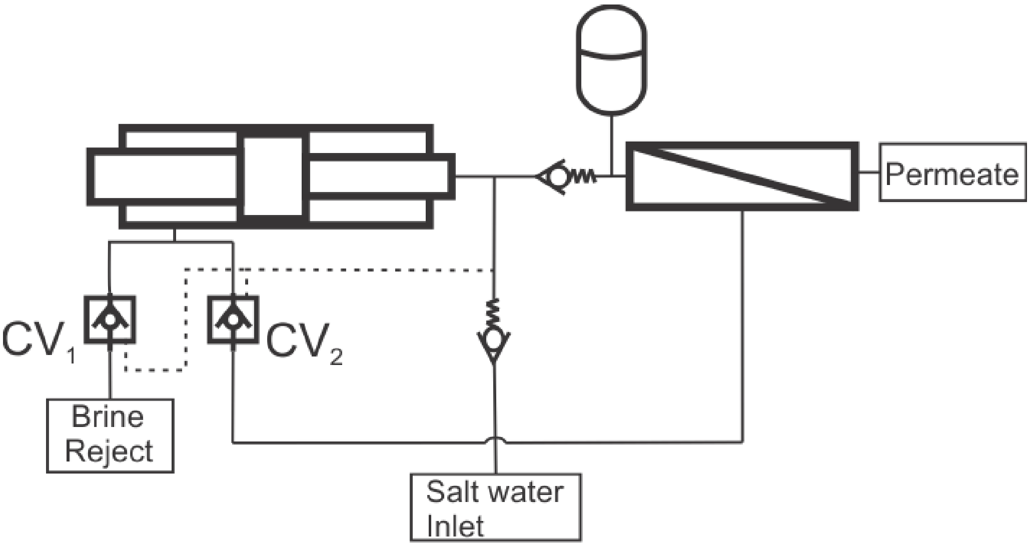


Figure 3: Wave powered RO desalination system

The design subject is a directional control valve. It is used in wave powered reverse osmosis desalination system as energy recovery device as energy recovery device figure 3. The valve is controlled by hydraulic means. It is meant to be pilot operated. Also, it is working in seawater (corrosive environment) and is meant to operate at least one year without maintenance. The proposed solution design to achieve this function is a combination of two pilot operated check valve figure 3 and 4. One is normally open the other is normally closed figure 3.

Normally closed valve CV1 is connected from one port to the membrane reject port preventing waste of high pressure concentrate rejection, and so waste of energy. Also, it is connected from other port to cylinder chamber. Connection between concentrate and cylinder is achieved in a way preventing flow of concentrate to the cylinder chamber at initial state. Meanwhile, normally open valve CV2 is connected to cylinder chamber through one port and it is open to tank through other port in a way that fluid can flow out of the left side of chamber to tank. Pilot flow switches both valves simultaneously, so that normally closed valve is to open and normally open valve is to close. This allows high pressure concentrate flowing to left chamber of the cylinder, operating the piston.

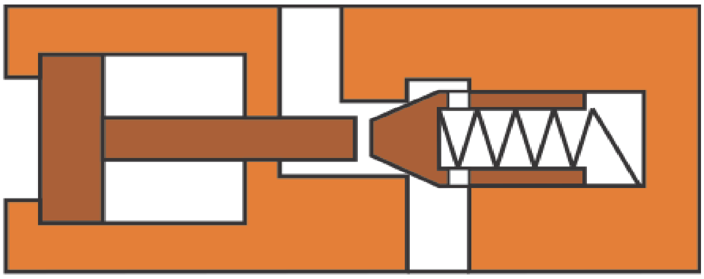


Figure 4: Pilot operated check valve

B. Task Clarification

Design is a method used to fulfill engineering needs. These needs arise from required functions or operations to be performed in certain working conditions. Required functions and working conditions generate conflicting constraints. These constraints provide design requirements. By this means the system tasks to be accomplished in certain working conditions establish the need for a solution. Therefore design starts by identifying the system operation and condition in order to derive a requirements list. The identification proceeds from qualitative states to quantitative states. At the beginning the artefact is analyzed as one body. Later, it is divided into components and subassemblies each will be analyzed separately. Design process converts design operation requirements into designed object (Manjula B. Waldron, 1996).

The main task of the valve gives the main requirements. The desired design is a hydraulic piloted check valve. This is a directional control valve. It provides flow control, whenever a pilot signal is given, without affecting flow of energy. This means that flow rate and pressure are held constant through the valve. The function or task outlines main requirements. These can be stated as: controlling flow direction, maintaining constant flow rate, maintaining pressure and providing switching possibility.

Tasks	**Requirements**
Flow control	Direct flow
Pilot operation	Pilot operated switching
Pressure conversation	Low pressure loss across the valve
Flow rate conservation	Tightness
Operation in corrosive media	Corrosion resistance
High pressure flow compatibility	High strength
Ease of maintenance	Ease of assembly and manufacturing

Table 1: Requirements list

Other requirements are derived from working conditions. The valve operates in saltwater at a rated pressure and flow rate. This component can be subject to stress generated by flow pressure, corrosion caused by saltwater and wear during operation. Strength of the component, corrosion and wear resistance are additional requirements to be listed. In addition, it is recommended to have a device that is easily manufactured and assembled. These requirements are functions of material and geometry. So the requirements of the valve can be tabulated in table 1.

CHAPTER III

CONCEPTUAL DESIGN

Task clarification is followed by a conceptual design step. At this stage, problems urging from requirements list are subject to abstraction. Functions and subfunctions structures are created based on the problem identification. Also, a designer identifies main functions and auxiliary functions. The latter are functions that help accomplishing main functions. Then working principles and geometries fulfilling these functions requirements are established and analyzed.

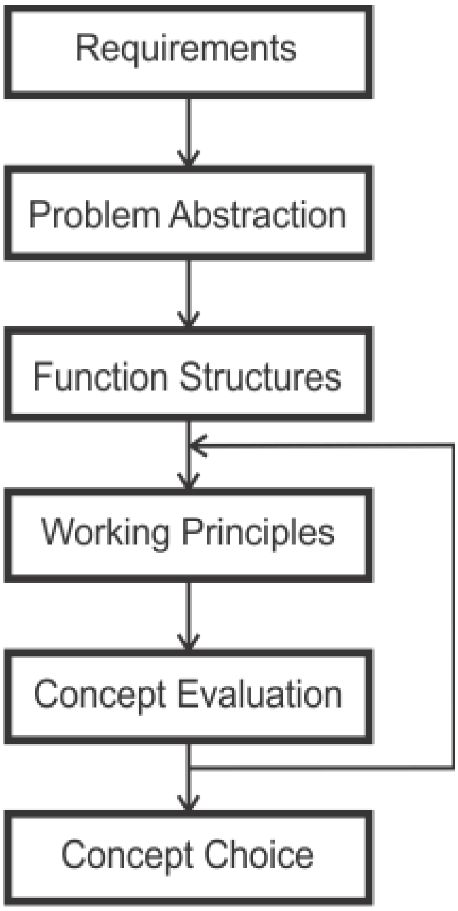


Figure 5: Conceptual Design Process

This analysis, allows designers to evaluate concepts (Ullman, 2009). Following the designer chooses the best concept or combination of concepts creating a solution to the problem. This phase (shown in figure 5) contains an iterative process. Whenever a concept is subject to fail in the evaluation criteria, the designer repeats the conceptual design steps choosing alternative working principle. And this process applies to each requirement imposed by the object tasks.

Design object is considered a technical system interacting with the environment through inputs and outputs (Pahl, 2013). It is meant to fulfill the tasks with respect to flow of material, energy and signal. Therefore system functions manifest by the mean of changing /transferring energy form, material property or signal. It is the flow that helps defining a component functions/subfunctions (Ullman, 2009). This relation of flow to function (shown in figure 6) is the basis on which a system is subdivided into components in later stages. In some cases these flows can be related imposing additional constraint to the design.

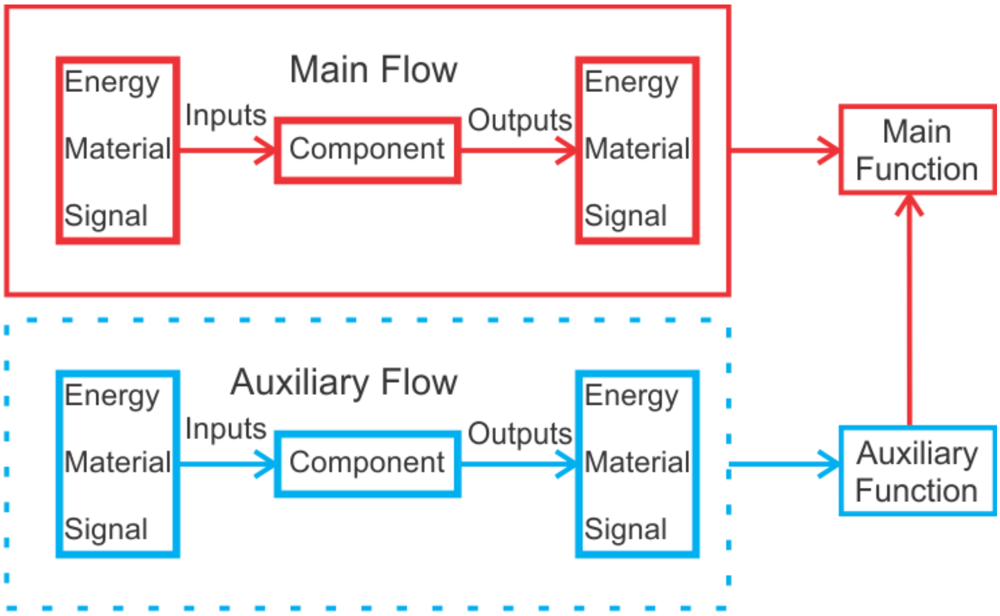


Figure 6: Flow-function diagram

In the present work, the valve is a directional control valve. Because it only directs flow while preserving pressure and flow rate are to be conserved. It only transfers hydraulic energy to actuate a hydraulic cylinder. This means that the main function is energy transfer through the valve using flow directional control. Eventually, the main flow through the valve is the flow of energy. This energy is in hydraulic form (fluid energy) so the energy flow is coupled to a material flow (concentrate).

Other flow and function might exist. Directional control and switching possibility help making appropriate energy transfer whenever needed. These tasks generate auxiliaries' functions. The goal of these functions resides in serving fulfillment of the main function. Directing flow function is related to switching function. In fact, the switching possibility gives the valve flow direction ability. So, it can allow/prevent creating the flow through an open/closed valve. Eventually two state of the valve exist open/closed. In consequence additional flow need urges for the sake of this switching function fulfillment. In this case it is the signal flow represented by the pilot flow. This is an auxiliary flow which is defined as a flow triggers the valve directional function opening.

Task	Function	Function Type	Flow	Flow Type
Flow control	Energy transfer	Main function	Energy flow Material flow	Main flow
Directional control	Directing flow	Auxiliary	Energy flow Material flow	Auxiliary flow
Pilot Operation	Switching Possibility	Auxiliary	Energy flow Material Flow Signal Flow	Auxiliary flow

Table 2: Function and flow identification of the design object

The valve is pilot operated by hydraulic means. So the auxiliary flow (signal) is transferred by hydraulic means (flow of material). This material flow shall operate the valve. This operation requires some energy. So there is an auxiliary flow of signal, material and energy. Hydraulic energy stored in the auxiliary material flow is transferred into hydraulic force so the valve operation function is made possible. Material flow (brine flow) is transferring signal so the material property does not have to be changed. Yet, the closure of the valve requires a counterbalance force to the opening force. An energy flow generates the required closure force of the valve. The function/flow diagram of the valve appears in table 2.

A. Adaptive Design

Design can be adaptive. An existing design got adapted for new application (Manjula B. Waldron, 1996). It can be a subject of design in order to improve its performance or change its material with adaption to new application and constraints in the embodiment design step. This change of material involves in some case the change of artefact scale, dimension and layout. This is another design aspect that is referred to as variant design (Ashby, 2013). This type of design benefits of the material evolution and optimizes existing objects. Meanwhile the shape and dimensions get modified with respect to new constraints set.

The conference paper (Kuehnlein, 2010) provides a potential solution model that can be used as subject to the design. A combination of two pilot operated check valve is used for self-energizing hydraulic brake (Kuehnlein, 2010). This solution is very similar to the study case in the present work. It is working conditions that differ. The solution extracted from (Kuehnlein, 2010) depicted in figure 7.

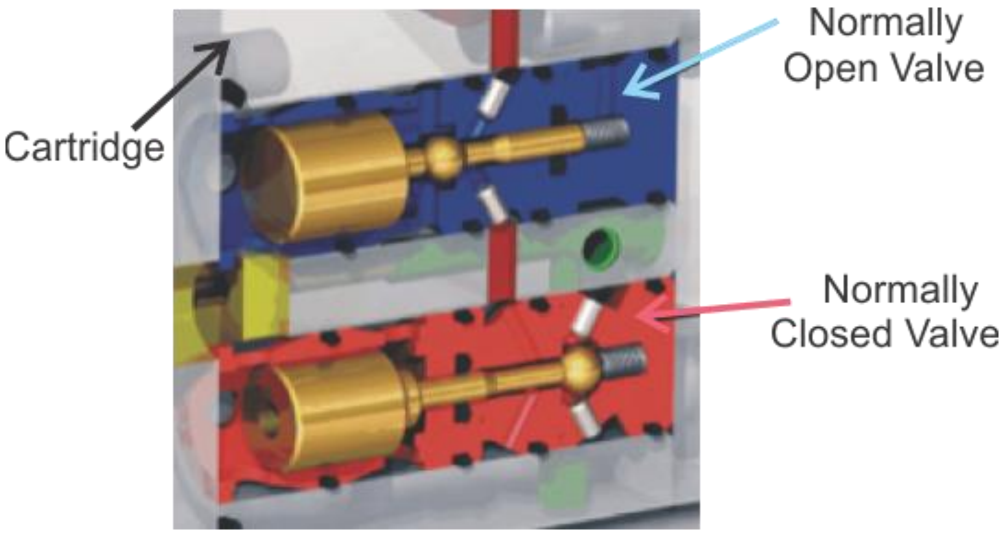


Figure 7: Two pilot operated valve for self-energizing brake (Kuehnlein, 2010)

Adaptive design recommends analysis of the proposed solution components and elements on basis of structure functions (Pahl, 2013). Adaptive solution model serves in analyzing functions and concepts. Later, in the embodiment stage modifications are suggested so that a possible solution is generated with the respect to the current operation case requirement. In order to make appropriate analysis, the system is divided into components and subassemblies. Valves are shown in detail in figures 8 and 9.

First, the valve consists of a cartridge and a valve body (figure 7). The cartridge has many functions. It provides an enclosure containing the valve body and holding its parts together. Also it has flow ports A, B, C and D connecting valve to the environment. These ports allow material, energy and signal flow through the valve. Considering NC valve flow ports C and D are meant to achieve main functions. Through these ports main flow is created because they represent the main flow path. As for the NO valve this task is fulfilled by ports C and B. Port A helps fulfilling an auxiliary function. It is allowing the pilot flow through the valve for both NO and NC.

Second, the valve has a body that can be subdivided into subassemblies and components. Subassemblies analysis helps understanding the way the valve components are assembled together. The valves shown in figures 6 and 7 have 4 subassemblies: a pilot subassembly, an intermediate body subassembly, a seat subassembly and a spring subassembly. Pilot subassembly consists of a pilot piston with a seal (1) sliding in a pilot housing with an Oring (1). Intermediate valve body is defined by intermediate housing having an Oring (2) with a sliding rod and a seal (2). The seat subassembly is refers to seat housing with Oring (3) and poppet. And spring subassembly is the defined by spring housing with an Oring (4) and a spring. The operation of NC valve may differ from that of NO. It seems better to make interpretation of conceptual design for both valves separately.

B. Normally Closed Valve

Normally closed valve (NC) is meant to be initially closed preventing flow between ports C and D. Once pilot signal is given it shall switch open and allow flow from C to D. Main function of flow control is done using two separated flow ports C and D. This function is fulfilled using holes through seat housing and spring housing. It is meant to provide flow path.

Directional control task requires allowing flow in a direction and preventing it in the other. The flow is created by opening flow path C to D or closing it. This subfunction is achieved using the poppet resting on/displaced out of seat. The poppet component in the seat housing assembly fulfills the subfunction of directing the flow. It is initially seated preventing flow.

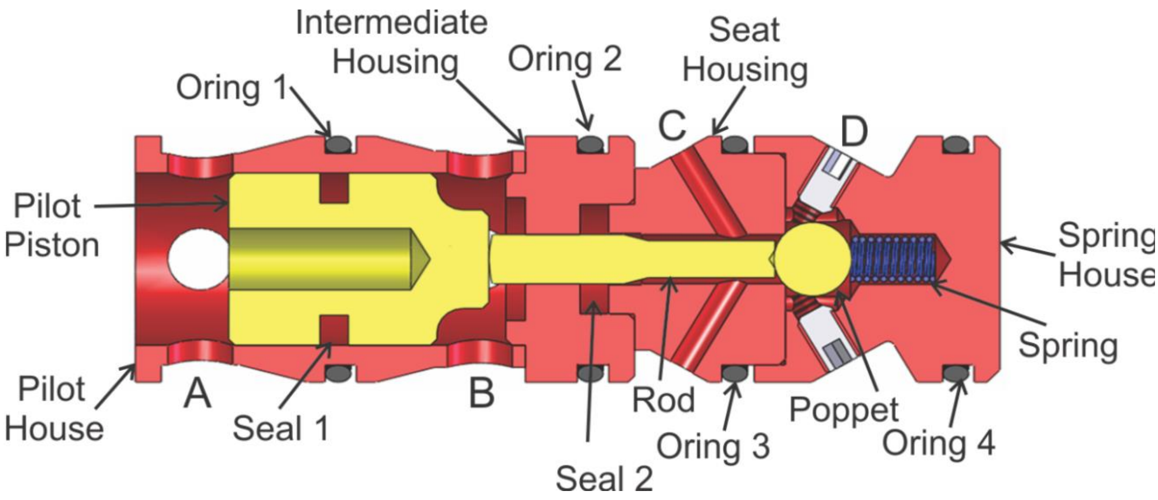


Figure 8: Normally closed (NC) valve (Kuehnlein, 2010)

The valve is required to have a switching possibility so that flow can be allowed or prevented. Switching possibility is assured by seating the poppet on its seat and unseating it. The switching mechanism function is provided by mean of pilot piston driving the rod and the spring. A pilot signal flows into pilot housing through port A. It generates operating force when it acts on the large surface of pilot piston. The low pressure held in the pilot flow is transferred into required mechanical force when it acts on pilot piston surface. This force drives the pilot piston in translational motion. This latter drives the rod in contact with the poppet. The poppet is unseated and flow path C to D opens. This mechanism generates a compressive force on spring generating an energy flow to the spring. Whenever there is need for the flow path to close the pilot signal is removed and energy stored in the spring generates a force driving poppet back to its seat. The pilot piston, the rod and the spring functions as switching group allowing the valve to have switching possibility.

Tightness of the valve and pressure conservation is assured using Orings and sealing. Subfunction of leakage elimination relies on sealing and rings placed in grooves. Each one of the housing is having groove to seat the ring and prevent losses.

Mainly intermediate housing has a seal to prevent flow from high pressure chamber D to tank B when flow path C to D is open.

C. Normally Open Valve

Normally open valve (NO) is meant to be initially open allowing flow between ports C and B. Once pilot signal is given it shall switch closed and prevent this flow. Main function of flow control is done using two separated flow ports B and C. This function is fulfilled by drilling holes in seat housing and intermediate housing which provides flow ports.

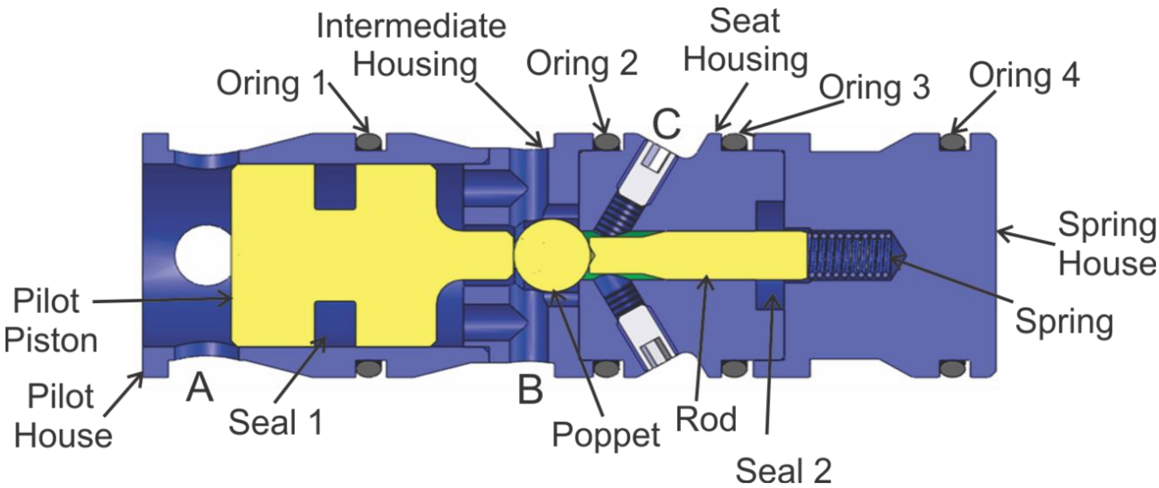


Figure 9: Normally open (NO) valve (Kuehnlein, 2010)

Directional control task requires allowing flow in a direction and preventing it in the other. The flow is prevented /created by closing/opening flow path C to B. This subfunction is achieved using the poppet resting on/displaced out of seat. The poppet component in the seat housing assembly fulfills the subfunction of directing the flow. It is initially unseated allowing flow.

The valve is required to have a switching possibility so that flow can be allowed or prevented. Switching possibility is assured by seating the poppet on its seat and unseating it. The switching mechanism function is provided by mean of pilot piston, spring rod and the spring. A pilot signal having low energy flows into pilot housing through port A. It is amplified when it acts on the large surface of pilot piston. The low pressure held in the pilot flow is transferred into mechanical force when it acts on pilot piston surface. This force drives the pilot piston. This latter in contact with poppet brings it on its seat. The poppet is seated and flow path C to B closes. This mechanism generates a compressive force on spring generating an energy flow to the spring transferred by the mean of spring rod. Whenever there is need for the flow path to open the pilot signal is removed and energy stored in the spring generates a force driving poppet out of its seat. The pilot piston, the spring rod and the spring functions as switching group allowing the valve to have switching possibility.

Tightness of the valve and pressure conservation is assured using Orings and sealing. Subfunction of leakage elimination relies on sealing and rings placed in grooves. Each one of the housing is having groove to seat the ring and prevent losses. Intermediate housing initially connect tank to low pressure chamber.

Corrosion resistance and strength requirements depend on the material and sizing of the valve. This is dependent of qualitative and quantitative analysis. This is a subject of embodiment design where modifications to the present design are proposed. This requires deeper investigation and inquiries. It is discussed in upcoming section. Elements function and working concept of the valve can be summarized in table 3.

Task	Function	Elements
Flow control	Directing flow (flow path)	Intermediate housing Spring housing Seat housing Poppet
Pilot operation	Switching possibility (Open/Close)	Pilot housing Pilot piston Rod Spring
Tightness	Maintaining flow and pressure	Poppet Seat housing Rings Seals

Table 3: Tasks and functions fulfillment based on system element

D. Concept Generation

Working concept are derived from these function analysis. In conclusion the valve operation requires the combination of the following concepts. Flow path is generated creating holes in appropriate parts. Also it requires an appropriate flow port configuration with respect to poppet in a seat creates/blocks the flow path at initial state. For a NC valve ports are initially separated by the poppet resting on its seat. For a NO valve ports are initially connected with the ball set off its seat.

Switching possibility depends on pilot operation. Pilot is provided with the use of pilot port allowing pilot flow and a large area pilot piston. The hydraulic pressure of pilot flow generates a driving force on the pilot piston area. The switching is requires to seat/unseat poppet. It relies on translational motion of the pilot piston. The pilot piston force is transmitted to the poppet by the mean of the rod in NC valve. Meanwhile the pilot piston is directly connected to the poppet in the case of NO valve. This force is also compressing the spring whether through poppet motion in NC case or through rod action in NO case. The compressed spring store energy and relief it when pilot is removed. This is how switching concept is generated. Briefly, hydraulic pressure generates a force on a large area. This force drives the pilot piston. This piston connects to poppet (directly or through connection element). So the pilot force generated is first delivered to poppet than it is transmitted to a spring. The spring being compressed generates the returning force driving poppet back to its seat.

Requirements/Function	Concept
Flow direction	Poppet on seat/port configuration
Flow path	Hole throughout a part
Pilot possibility	Hydraulic pressure applied on a surface
Switching possibility	Translational motion using pilot function/spring force
Force transmission	Connecting element (rod)
Tightness	Use of elastomeric sealing
Ease of manufacture and assembly	Breaking the system into several components and making loose fit

Table 4: Solutions concepts

Tightness is simply provided through rings and sealing in grooves. This concept helps fulfilling other requirements. Using rings allows designer to avoid tight fit with high tolerances. Tolerance manufacturing range can be increased using loose fit. So the ease of manufacturing and assembly are achieved. Also breaking the valve body into separate parts is beneficial for the sake of having easy manufacturing and assembly.

CHAPTER IV

EMBODIMENT DESIGN

At this design starts converging from abstraction and concepts into more details. The layout, preliminary forms, material, manufacturing processes and quantitative analysis start coming into considerations (Pahl, 2013). Concepts developed in previous section are the bases of the solution development through this stage. Design process cannot evolve to this step before a solution choice is made. Designer shall start setting crucial requirements. These are set with accordance to space constraint, size, output and material requirements. More details come into picture. At this stage not only function is engendered but also safety is encountered.

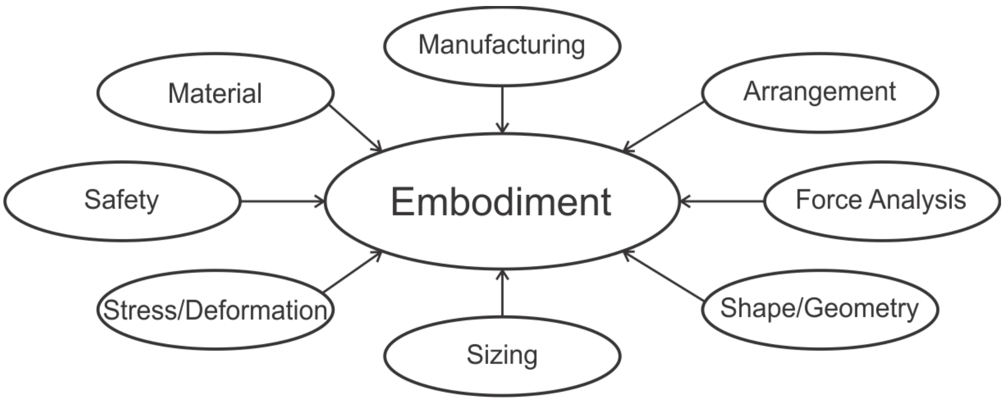


Figure 10: Embodiment design different stages

The present design of pilot operated check valve is dependent mainly on fluid working pressure and flow rate. The working pressure is expected to range from 60 to 80 bars. The maximum flow rate of concentrate through the membrane is of 22 L/min. These are main output of the valve. Valves are usually rated with specific flow rate at certain pressure difference based on the following equation:

Equation 1

$$Q = 0.6\, A \sqrt{\frac{2\, \Delta P}{\rho}}$$

The parameter determining the flow rate that can be manipulated through layout and geometric design is the flow area A. This flow rate shall be obtained for a minimum pressure difference, because the pressure loss minimization is one of the crucial requirements in directional valve design as listed in previous section. Nevertheless, the flow area size affects the valve sizing. The design process aims for minimum material and compact design. Solving this contradiction requires the choice of an appropriate reference pressure difference and flow rate. This helps defining the optimum required area for an optimum pressure difference. A maximum flow of 22 L/min shall occur at a pressure difference of 2 bars full open valve. This makes the required flow area is A = 30 mm^2. This flow area is one of key parameter in valves sizing. This is preliminary requirement. Other factors influence the design sizing come along in the following steps.

A. Design Layout

This phase requires making clear identification of components functions, form, manufacturing and assemblies (Hales, 2011). Also it involves justification the choice of working principle based on cause and effect (Pahl, 2013). This gives the design additional clarification and helps in optimizing or modifying it later. Yet, another constraint characterizes this stage. Designer aims through process of choosing working principle, geometries, sizing, assemblies and manufacturing process to simplicity. This is a concept that serves clarity but is independent of it. Always, artefact shall be designed with minimum number of components, fulfilling required task (Pahl, 2013), (Hales, 2011). As in conceptual design there is an identification of functions and functions carrier through embodiment design.

Material	Concentrate (flow material) Valve components (design material)
Geometry	Seat for the poppet Poppet form Pilot piston area Flow area
Energy	Concentrate hydraulic energy (main flow) Brine hydraulic energy (pilot flow) Kinetic energy (pilot piston motion) Potential energy (compressed spring)
Kinematic	Translation of pilot piston Translation of the rod
Forces	Main flow pressure force applied through flow path and seat housing and on poppet Pilot flow pressure applied on pilot house and pilot piston Spring force applied on poppet (valve closing) Flow force applied on spring (valve opening) Friction force
Signal	Pilot line

Table 5: Valve functions and parameters

The basic requirement in design is to produce task fulfillment. An artefact shall operate clearly and safely. These requirements make simplicity and clarity crucial for the design. In fact, layout of the design is related to strength and deformation of the components. Following any analysis of the system work and expected failure can be easily detected. Based on this analysis corrective and protective measures are taken in advance. When dealing with complex or ambiguous design the analysis become harder. Force transmission and expected deformation are not clear. This makes the design difficult.

Table 5 contains main functions and parameter applied to the design subject (piloted check valve). Component arrangement helps assigning these functions to each part and subassembly. The analysis of the proposed model in the adaptive design section is beneficial for the layout illustration.

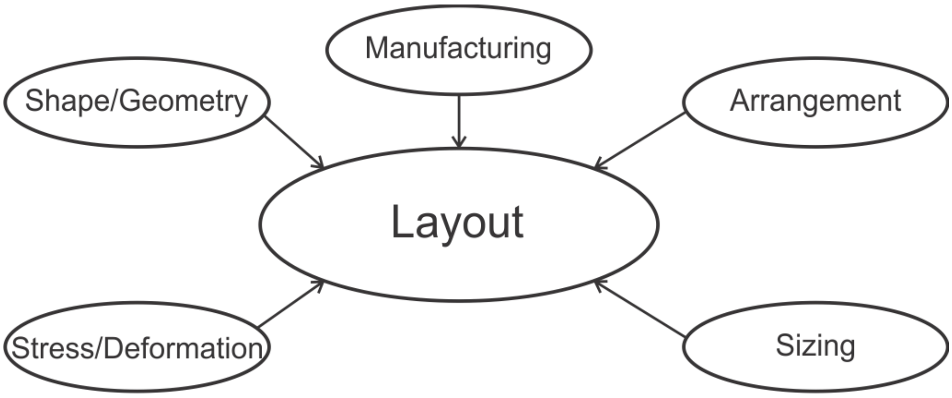


Figure 11: Embodiment design layout process

1. Arrangement Forms Geometry and Function Carrier

Referring to figures 8 and 9, valve bodies are mainly made out of cylindrical shapes. This provides simple geometries and makes manufacturing process simpler because these shapes can be easily made on lathe machine. The groove made in some component serves as seats for rings and sealing. These seals fulfill the tightness function. Grooves can be easily made on lathe machine. Flow path and flow ports consist of making holes in the parts. These holes are made easily on lathe. The phase made on the flow ports is because the flow path needs to be inclined; this makes the flow through the valve easier. In order to have the drill perpendicular to the face with hole (flow port) a phase has to be made. Several flow ports are made. These ports are symmetric for the sake of crating hydraulic balance.

The poppet can have different shapes. The current poppet used is a spherical poppet. This reduces manufacturing (especially precise manufacturing) because ball poppet can be obtained from ball bearing. These balls have extremely nice surfaces and tolerances. The seat is defined by a hole in seat housing part. This seat can be improved having a conical shape (chamfered) seat instead of cylindrical (sharped edge) one. Experiments lead in (Vaughan, 1992) showed that chamfered seat have less flow resistance coefficient (lower pressure drop) and flow force coefficient for certain opening to seat ratio (above 0.05) (Vaughan, 1992). The blind hole in the spring house provides a seat for spring. Pilot piston and driving rod have cylindrical shapes which make their motion and manufacturing easier.

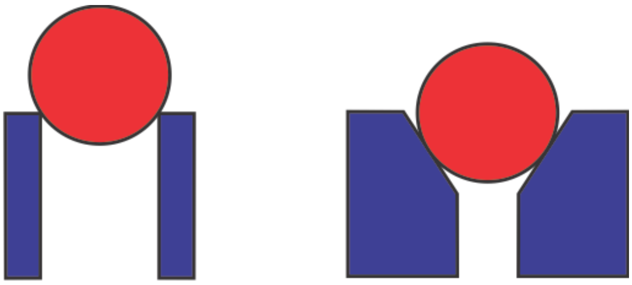


Figure 12: Cylindrical and conical seat

Spatial arrangement constraint is essential in the valve design. In the present case it is not a crucial parameter. There is no spatial limitation. In this case arrangement of subassemblies is set with respect to some requirements. Main function is to close (NC valve)/open (NO valve) valve initially. The high pressure port (D in case of NC valve/ C in case of NO valve) allows flow in the direction of closing/opening the valve. This arrangement helps keeping valve at the intended position when no signal is given.

Inflow and outflow ports are made in two different pieces. This allows the poppet to make appropriate connection/disconnection whenever required. The seat arrangement comes in a way that flow diverges at valve opening for both valves. Seat housing provides seat and flow path for inflow in case of NO valve, outflow in case of NC valve.

Spring house is connected to high pressure chamber, so that the spring is directly connected to the ball in the NC valve case and connected to the ball through a rod in the NO case. This latter arrangement seems better to make because spring is guided in its housing by the rod. The rod diameter is smaller than the flow channel diameter and this reduce flow resistance and reduce friction and wear resulting from the rod sliding motion.

Pilot housing contains the pilot piston and provide flow path for pilot signal. The piston is installed in a way that it separates the pilot housing into two chambers. One provides pilot mean, while the other one is a drain chamber. Pilot chamber has holes considered flow ports connected to pilot line. Drain chamber has holes avoid entrapping air in this chamber and to drain this chamber from any liquid that may enter through leakage. The pilot chamber connects pilot housing to pilot line providing pilot signal flow path. The other chamber connects the housing to tank allowing the drain. Pilot piston and housing are both provided by oring assuring tightness and preventing flow from tank to pilot.

An intermediate housing separates pilot housing from seat housing. In the case of NO valve this housing provides tank port connection for pilot housing drain and outflow ports for valve. Also, it has the seat for the poppet. In case of NC valve intermediate housing separates pilot drain chamber from seat chamber. The intermediate chamber in the NC valve is provided with oring to avoid leakage from high pressure chamber to tank when valve opens. In the NO case this is not necessary because this valve is meant to deliver flow to tank. Functions and function carrier are identified based on this arrangement in table 6.

Function Carrier	Functions
Seat housing	Providing flow ports and flow path Providing poppet seat
Spring housing	Providing spring housing Providing flow port (NC valve)
Intermediate housing	Separating pilot housing from high pressure chamber Providing flow path to tank (NO valve) Sealing high pressure chamber at open (NC valve)
Pilot housing	Providing pilot flow path Providing enclosure for pilot piston Providing drain flow path for entrapped fluid
Poppet	Creating/blocking flow path
Rod	Driving poppet
Pilot piston	Operating the valve
Spring	Getting poppet to initial position when pilot removed

Table 6: Functions and function carrier

2. Manufacturing Process

Manufacturing process is mainly a function of material choice, shapes, size and geometry. But also the designer can flip the constraint making manufacturing process one of the key choice affecting design procedure. The design of the valve shows that all pieces can be machined on lathe. This is one of the simplest and lowest cost methods.

Every feature is made with a special cutting tool and configuration. This valve type can be made with tolerance provided by lathe. Most important feature is the seat. It should provide tightness. This feature can be made using countersink tool in order to achieve good surface quality and assure required alignment. This choice of manufacturing process provides additional constraints to both size and material choice. The material to choose should be machinable and the sizing will be in accordance with available countersink tools size.

3. Stress and Deformation

External loads generate stress in components. It is important through design stage to determine stress magnitude and behavior (steady/alternating). This would help in the components sizing and material choice. In fact, any material shall be loaded beneath its stress limits, or else the component may exhibit sudden failure. Yet, also the stress mode is important because it affects the selection criteria and failure mode of the component. Design should inspect the stress and deformation characteristic such as magnitude and mode. Preliminary study is essential in order to obtain certain range of the initial sizing step. Later, when making a details force analysis stress and deformation are analyzed in details. To this stage, the expected stress mostly affecting the valve is the flow pressure. This pressure might reach 8 MPa bringing valve to expand mainly. For the case of the seat valve this expansion does not have important leakage effect as in other valve type.

B. Design Sizing

Sizing in design follows special laws. Similarity laws are preferred whenever it makes possible (Pahl, 2013). In this case, similarity cannot be applied. Size is mainly a function of different parameters. First one governing this choice is flow area. Flow area is function of seat area and travel of the valve. Seat is related to ball diameter and manufacturing process. This helps in the first size decision. Other constraint comes from material resistance, machining, stress distribution and deformation.

The seat area should provide the required flow area at full opening. But also it is subject to flow pressure. This internal pressure is mainly creating expansion deformation. The ball in always in contact to seat providing required tightness. Also, the flow path is subject to inlet pressure and expansion.

Seat, ball and flow area are depicted in figure 13. The parameters in the figure are related by the following equations extracted from (Rabie, 2009):

Equation 2:

$$\alpha_0 = 2\, sin^{-1}\left(\frac{d_s}{d_b}\right)$$

Equation 3:

$$\alpha = 2\, tan^{-1}\left(\frac{d_s}{d_b\, cos\frac{\alpha_0}{2} + 2x}\right)$$

Equation 4:

$$ab = \frac{d_s}{2\, sin\left(\frac{\alpha}{2}\right)} - \frac{d_b}{2}$$

Equation 5:

$$d_p = d_b \sin\left(\frac{\alpha}{2}\right)$$

Equation 6:

$$A = \frac{\pi}{2}\, ab\, (d_s + d_p)$$

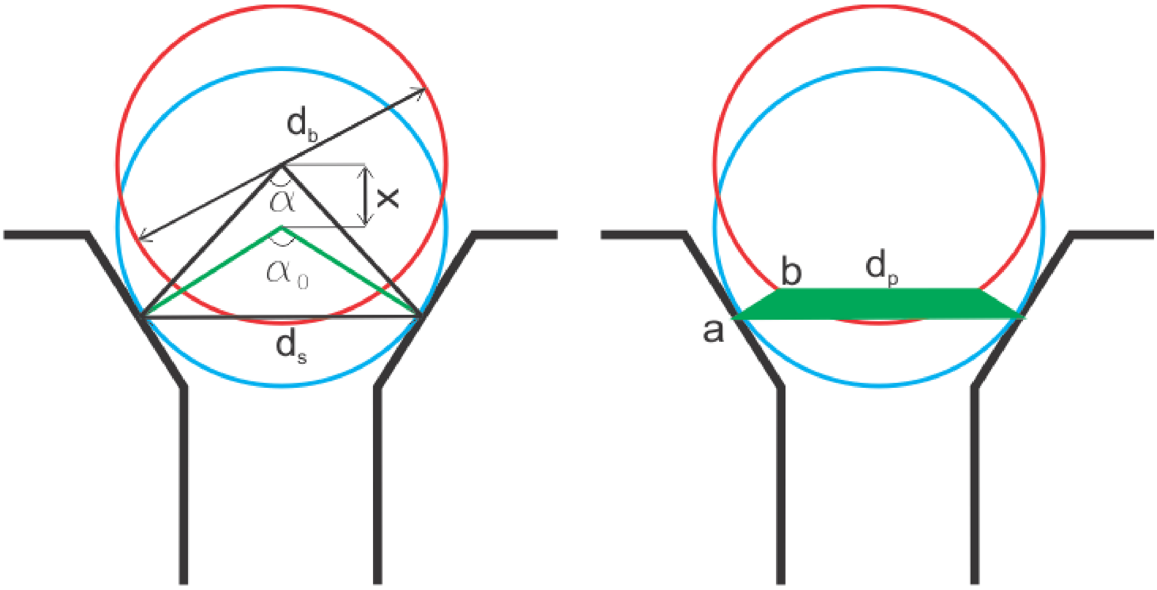


Figure 13: Ball seat and flow area parameters

These equations show the relation of flow area A to ball diameter d_b, seat diameter d_s, lift x and seat angle. Seat angle and chamfer angle are complementary angles. Ball diameters are standard and function of bearing size. Chamfer angle is function of the countersink tool angle. Different combinations of lift, ball diameter, seat diameter and chamfer angle can be chosen in order to achieve the required flow area.

SKF bearing catalogue has different range of bearing size offering wide range of ball diameter. These balls are proportional to inch size starting from ¼ inch (3.175 mm). Chamfer angle, which is function of countersink tool, is limited to the following values 30°, 41°, 45°, 50°, 55° and 60°. Seat diameter is function of ball diameter to chamfer angle as shown in equation 2. Lift of the valve is in this case function of the choice of angle and ball diameter and flow area.

The ball size should be optimized with chamfer angle in a way that seat area is minimized. This minimization reduces flow force closing the poppet against seat. Pilot force requires large area in order to amplify pilot pressure force. Eventually, smaller force applied to seat result in smaller pilot piston area so the valve size can be minimized. At the same time the lift to seat diameter should be optimum in order to reduce opening time and flow force applied on poppet. In addition to these conflicted conditions flow force on seat shall maintain valve tightness. Closing force effect on leakage flow is presented by (Schmidt, 2008). Increasing contact force applied on seat reduces leakage. In conclusion, the choice of ball diameter, chamfer angle and lift need to provide required flow area (30 mm^2), low closing force and sufficient force to maintain tightness. In an iterative process, trying to fulfill all these requirements, the best combination is: a lift of 1.56 mm, a ball of 12.7 mm (1/2 inch) and a chamfer angle of 45°. Following that the seat diameter is d_s = 8.98 mm (~9 mm). The maximum flow closing force would be:

Equation 7:

$$F = P_{max} \frac{\pi}{4} {d_s}^2$$

Computing for d_s = 9 mm and the maximum flow force of 80 bars (8 MPa), the force closing the poppet is of 509 N. Contact force providing tightness of ball on the seat is dependent of the spring force in the following equation extracted from (Schmidt, 2008):

Equation 8:

$$F_{cl} = \frac{F_{pressure} - F_{spring}}{\pi \; d_s \cos(\alpha/2)}$$

Spring is considered initially is not compressed so the expected closing force is 25.46 N/mm. Based on experiments in (Schmidt, 2008) this closing force is enough to minimize leakage through valve. Pilot piston and house are to be determined in the upcoming section based on force analysis.

C. Force Analysis

Flow line of force transmission must be clear. The application of force (bending, twisting) should be understood because it affects stress mode (normal/shear stress) (Pahl, 2013). External loads applied to a component must be in equilibrium to internal stress generated by internal stress. Also, force transmission should be transmitted with minimum deformation. In fact, always strain is related to stress. Minimizing deformation reduces deformation and eventually reduces internal stress. Applied force shall be always lower than the peak force so even if load is increasing beyond yielding point the component can withstand more stress and deformation.

Designer can identify functionally main forces as main function has been defined previously. These are forces that serve the function directly (Pahl, 2013). Associated forces are forces that don't serve main function directly but must be taken into consideration. These forces can either fulfill auxiliary function or generate unwanted effects. Those must be balanced whenever possible either by symmetrical layout or through a balancing element. An effective tool in force analysis is making sketch of free body diagram. This is beneficial in visualizing applied force, surface undergoing stress and potential deformation. The free body diagram is shown in figure 14.

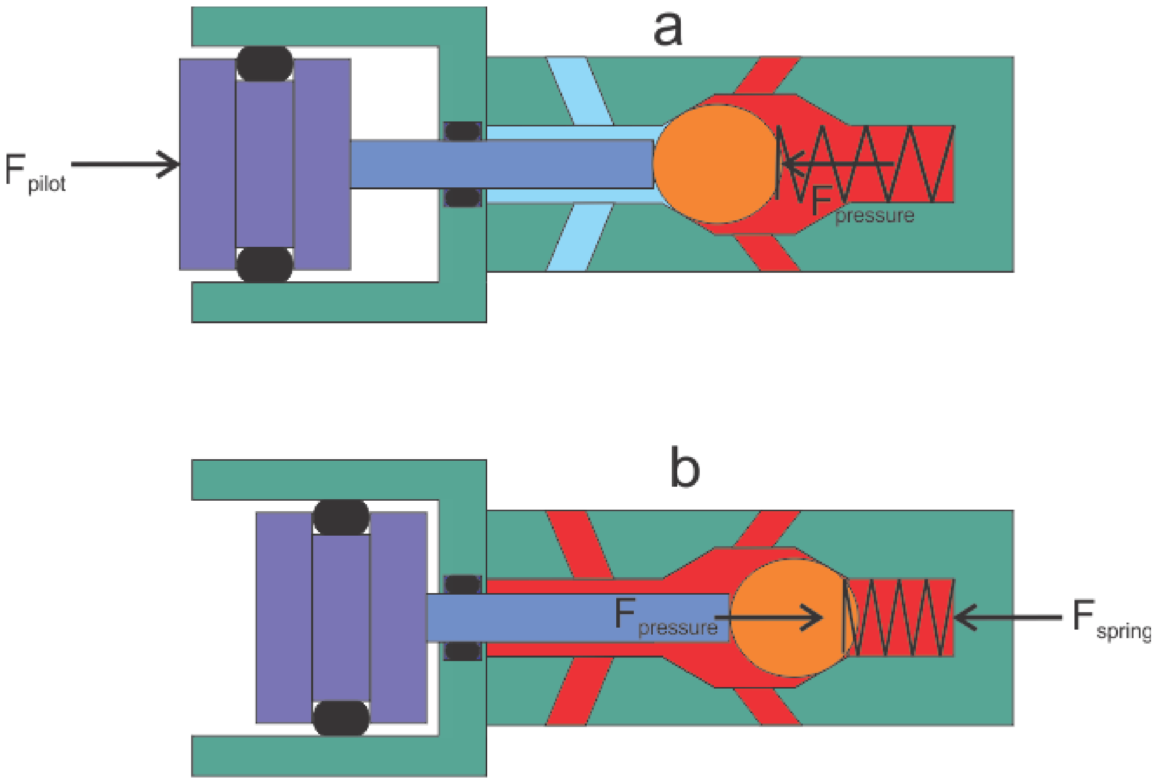


Figure 14: NC free body diagram opening (a), closing (b)

In the current design problem, based on valve functions definition in previous section and working principles, forces are divided into main and associate forces. For the NC valve, the concentrate flow pressure is originally creating force on the poppet keeping it closed. This force is required initially because it is preventing flow of concentrate to tank. When valve is to open, flow forces shall be balanced in order to make the appropriate switching. At this stage, the pilot force becomes important because it should overcome the closure force of the concentrate allowing flow to the cylinder on power stroke. Once, valve opens the flow pressure generated force is acting on the poppet such that it is keeping it opens. This force is unwanted because it prevents valve closure when pilot is removed. This force needs to be balanced. Computing for seat diameter and maximum pressure (8 MPa) this force is of 508 N. The spring cannot be used to balance this force. In fact, this force requires very stiff spring or high spring precompression. Both cases are unwanted in the design. The best way to balance this flow unwanted effect is to provide a hydraulic balance on the poppet. So the flow force opening and closing the valve are going to be in balance. It is recommended to allow fluid flow to the spring seat chamber so that the flow forces are in balance. In the NO valve this problem does not exist because flow forces are always opening the poppet. And in case the valve is closed the pilot force counterbalances these flow forces.

Pilot force generated by pilot flow is a main force. It allows valve operation control whenever required. And this force after power stroke is done can be removed by eliminating pilot flow. It makes balance with the closing/opening forces in NC/NO valve. The pilot pressure set to 10 bars (1 MPa) the pilot piston diameter can be computed based on the force balance equation:

Equation 9

$$p_{concentrate} \times \frac{\pi}{4} d_s^{\,2} = p_{pilot} \times \frac{\pi}{4} d_{pilot}^{\,2}$$

Computing the closing force to 508 N, the pilot piston diameter for a pilot pressure of 1 MPa is d_{pilot} of 25.54 mm.

Orings on pilot piston and rod are compressed between grooves and contact surface. The oring compression stretches the ring and creates stress on the ring. This compression is generating a contact force making the ring fill the groove. This way the tightness of the valve is assured. In conclusion, the contact force of the oring fulfills an auxiliary function which is providing tightness. This is an auxiliary force. Although, this force is sealing the required chambers it is generating unwanted forces. Contact normal force engenders friction forces. Friction forces are unwanted forces. In fact, oring filling the groove resists the motion of the rod and piston by this mean. Friction is an associate force. It is creating resistance to switching of the valve. Friction opposes the valve moving parts. When pilot piston is operates the valve, friction opposes the switching. For NC valve, friction force opposes valve opening. For NC valve these forces oppose valve closing. When pilot is removed, friction prevents NC valve closing and NO valve opening. Eventually, friction forces need to be balanced. Minimization of friction force requires appropriate choice of material combination to the extent that friction coefficient is minimized.

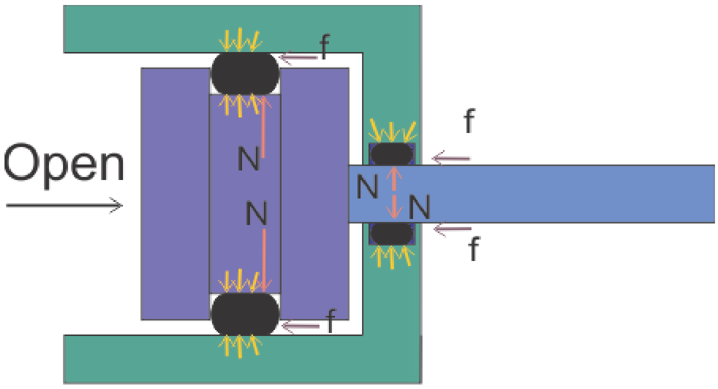


Figure 15: Friction force and normal contact force applied to the piston and rod

Normal contact force is related to friction forces with according to the following equation:

Equation 10:

$$f = \mu . N$$

The spring force is an auxiliary force. The function fulfilled of the spring is the valve switching. The spring brings poppet back to initial state once pilot flow is removed. That is the main task fulfilled by the spring. Once, hydraulic balance requirement is fulfilled in the valve, the required spring force is minimized. The friction force generated needs to be balanced by spring force. The spring rate and precompression are computed to satisfy these requirements. Spring force must overcome friction force to switch valve back to initial position.

Main mode of loading can be restricted to pressure force creating tension at the internal body of the valve. The tensile stress is stretching the valve laterally making it expand. The insert of valve body in the cartridge limit this effect. This way the expansion of internal member is subject to limitation by the valve cartridge so tension will be transformed into compression because the cartridge prevents the valve expansion. Friction force generates a shear effects at the contact area, but this effect is expected to be of small magnitude because the area under stress is large. Pilot force is mainly transmitted through the pilot piston-rod-poppet. Just the rod transmitting this force shall have an area that can withstand this effect. The pilot pressure applied to pilot housing is of low magnitude compared to working pressure. There is also no stress effect highly generated from this pressure to expect. Force of the compressed spring acts on its seat and affect the spring coil. The spring is subject to shear stress, compression and therefore it can be also prone to buckling.

D. Material Selection

Material selection characterizes mechanical design process. It is an essential step for any designer to choose the appropriate material for his proposed solution. In fact, this is a key parameter. A designer can simply fulfill multi task requirements based on his material choice. The component dimensions and size are the first to be influenced by this choice as well as its performance (Edwards, 2005). Material choice determines the maximum stress and deformation a component can withstand. This would affect component dimensions and sizing so the optimum design is directly related to this step. Also component compatibility in its working environment (corrosion, heat resistance, friction force generated, installation space and fatigue failure) is material mechanical and chemical properties dependent. Furthermore the material choice determines the possible manufacturing process of the product. Product price depends on manufacturing process, dimensions and life of a product. These criteria are functions of material. In conclusion, material choice determines the final product price. This choice comes with respect to constraints the designer defines.

Generally, the constraints are set by the product operation, working condition, component life requirement and ease of manufacturing. These are common requirements that would apply for any special case or area of application. It is recommended that chosen material suits the working environment. Also it shall allow the component to survive the life cycle required. And it allows producing the required components shape with non-complicated process for a reasonable cost. The material choice might be easier for an experienced engineer rather than for a younger one. However, the choice is always made by the mean of coupling the application requirements to the material data acquired from testing datasheets (Edwards, 2005). Wide range of material offers different possibility and a wide range of quantified properties (Hales, 2011). Existing materials are estimated to range from 40000 to 80000 materials with around 1000 processing method (Ashby M. F., 2004).

1. Material Types and Properties

In (Ashby M. F., 2004) material choice is first made in the embodiment phase based on material properties, later in detail design stage this choice can be evaluated based on production process possibility. Through iterative steps, the choice of material is corrected when production/manufacturing process confronts difficulties. Throughout iterative process, available material properties shall be provided. Material properties can be quantified (having numerical attributes) or qualified (subject to Boolean evaluation or ranks from excellent to awful) (Ashby M. F., 2004).

Type of engineering available material allows arranging them into different categories. Main material families are: metals, polymers, ceramic, and composites. Each one of these material families offers special characteristics. Metals offer good stiffness, low expansion, and ductile behavior (exhibiting yielding behavior before fracture). However there are subject to fatigue and are prone to corrosion and friction. Ceramics are hard material offering high resistance but they are brittle which means that they undergo failure without yield phase. These materials are harder than metals and have more strength in compression compared to tension about 15 times (Ashby M. F., 2013). However, they are sensitive to stress concentration feature and high contact stress.

Polymers started to compete with metals. A deep gap exists between these two families in terms of elastic modulus and expansion factor and thermal resistance. Nevertheless, polymers offer high stress resistance and variety of production technique. Polymer materials have lower density than metals therefore they offer higher strength per unit weight. This material category offer an effective alternative for metals whenever there is a corrosion, wear and friction issues. Composite material can be combination of two different materials. The characteristics of these materials depend on the components volumetric ratio and layout. The change of direction modifies the material properties. Material resistance is dependent on the loading direction. This is an anisotropic behavior.

2. Selection Process

In a multiple constraints design problem it is suggested as initial step giving the components dimensions, providing geometry and defining loading (Brechet, 2001). In fact, performance of design artefact is expressed by means of geometry, loading and material (Ashby M. F., 2000). Setting geometries and loading analysis is made through embodiment design first steps (layout and force analysis). Designer extracts essential requirements. Next, the existing solution shall be meeting several requirements (providing different criteria). This steps expresses exchange coefficient identification (Brechet, 2001). Material is selected from available material families existing or from different classes of a single material family (Ashby M. F., 2004). Material properties need to be defined from available datasheets. Finally, the choice of material is validated on basis of manufacturing process.

The widespread material used in mechanical design has been metals for long time. The class dominates the design is steel available in different size, shape, grades and properties. This is the traditional material available in engineering design with a reasonable cost. In modern industrial community, polymers start substituting metals. They are offering acceptable strength for less weight and cost. Also, this material family easy shaping and manufacturing gives it advantage over other materials in case of complicated shapes and geometries requirements.

In the current design problem, constraints and requirements have been defined through task clarification and embodiment design. First requirements that valve operating conditions impose is defined by corrosion resistance because the material flow is mainly water. Additional, constraint is to have a material easily manufactured (especially can be machined easily). It is vital to have a material offering good surface quality for low cost manufacturing process. Finally, the force analysis section provides additional requirements related to material strength, expansion rate, low friction and wear rate. All these requirements are to be considered with the respect of a low cost material.

Ordinary steel is mainly excluded from the material choice list, because it will undergo corrosion. Other ferrous material can be suggested such as stainless steel and nickel alloy provides good corrosion resistance. However, the machinability and cost of these materials makes this choice unappropriated. One of the proposed solutions is to use polymers. Although, this material family offers less strength than metals and lower stiffness (elastic modulus) it seems suitable for the current application. This material family offers types fulfilling the requirements. Regardless of the low strength of these materials, in the current application the stress is expected to be low (this proposition shall be verified in detail design through finite element study). Polymers properties depend on temperature. In this application, operation is at ambient temperature therefore there is no thermal effect altering the material properties or creating thermal stress.

The body of the valve and cartridge can be made out of plastic. The valve spring is premanufactured spring. In order to avoid corrosion the spring material shall be stainless steel. As for the poppet, it can be made extracted from ceramic ball bearing. Ceramic bearing balls have good surface quality; they require no manufacturing process. Ceramic are finding their way in several applications as substitute of metal. These application involving water, wear and corrosion issue such as valve and pumps (Fang, 1999). SKF bearing ball are made of silicon nitride. This material offers all requirements for the intended application with an exceptional fatigue resistance (Horibe, 1990).

The valve body is made out of plastic. One of the most promising solution is polyoxymethylene (acetal) commercially known as Delrin. This is a polymer providing tempting combination of properties regarding friction, wear, mechanical and chemical resistance (Lüft). It has good corrosion resistance, wear resistance, strength and machinability criteria. Also it has chemical resistance to the working environment (salt water) and low water absorption (Chen, 2017) (Sigrid, 2014). In addition it has good fatigue resistance and life cycle at low temperature (Connolly, 1985). Main, constraint restricting the use of polymer in engineering application is high temperature. This limitation does not exist in the current situation.

E. Safety Mechanism

Any mechanical design should have safety measure. These measures protect humans, environment and the working system. Safety can be direct, which means eliminating danger from outset. Or it can indirect whenever a special protection system is designed to eliminate danger. Safety measures fulfill protection function. Although, safety measure may imply some complication to the design and increase cost, it proves beneficial for long term economy (Pahl, 2013).

The RO desalination membrane might be subject to pressure fluctuation. It is expected that pressure in the membrane rise above the limits set for normal operation. This behavior is harmful for both the membrane life and system stability. The energy recovery device (valve combination) is mainly meant to hold the energy of the concentrate flow. During system operation (power stroke of the system) this device (ERD) shall maintain flow in the closed system and prevent leakage. In case the pressure rise during this phase, the closed system should be opened to tank in order to relief pressure of the system. Otherwise, it will be subject to instability. This relief requirement creates additional constraint on the directional function of the valve combination. In conclusion a direct safety measure seems difficult and complicated. In this case, designer shall recur to indirect safety where an independent safety system shall be proposed and designed.

Indirect safety requires special protective system that operates in danger (Pahl, 2013). Those systems shall operate in danger situation only. They capture danger signal as input. Next they must detect it in case of danger they need to act which means remove it as output. This function assignment defines the requirements of a protective device design. Those systems operation needs to be clear. They shall function only in danger situation and along danger period (the device should not be shut off before danger removal). Finally they must resist tampering. By this mean, the protective system action cannot be removed by unintended action.

The application of these conditions to the present system can be applied straightforward. The protective device input signal is a pressure signal. In case this signal is below a defined threshold (maximum operating pressure of 80 bars) protective system should not operate. Once the input cross the threshold limit, the system should detect it and operate in a way to remove it. This protective measure must operate as long as the pressure as high.

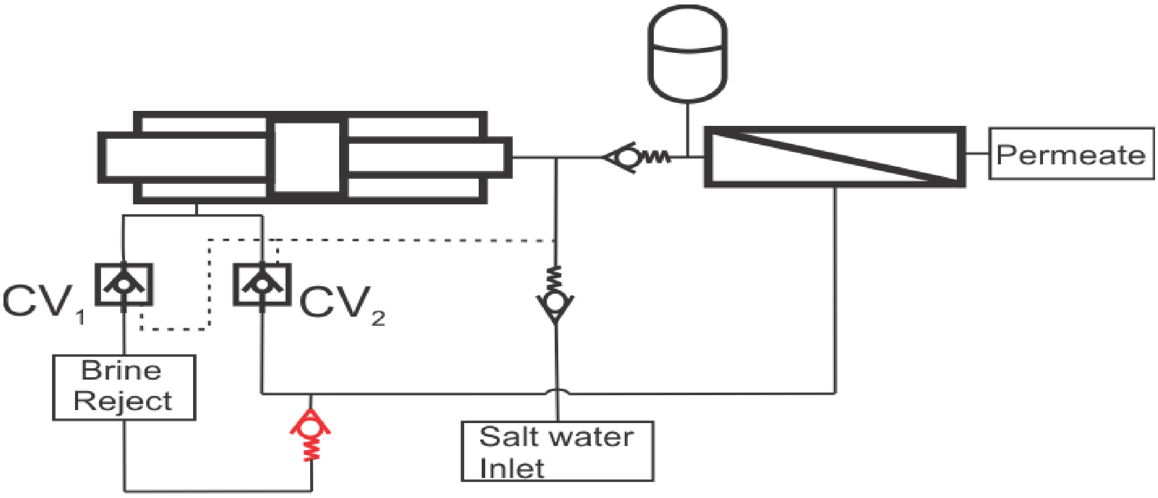


Figure 16: Wave powered system with energy recovery and safety device

The design rules also apply to the protective system. Task to be performed are similar to directional valve. In other word, the protective system to be designed should only open flow path to tank when it acquires a danger signal. Once, danger is removed, this device action stop. It shall go back to initial state closing tank path. Requirements that apply to the pilot operated check valve are identical to the safety system requirements. However, this system is only piloted by system pressure. In this case, the suitable pressure relief mechanism would be a direct operated check valve. This valve should be closing path to tank. The cracking pressure opening this valve is the maximum operating pressure of the system. Once pressure exceeds this value it opens to tank and evacuates flow to the extent that flow pressure is below cracking pressure. At this stage valve closes. Proposed system is depicted in figure 16 with the safety device in red.

CHAPTER V

DETAIL DESIGN

A. Valves Components

At this stage, after setting up all the preliminary and basics of the design. Concepts and embodiment are fully understood and settled. Designer can propose a solution. This is where a design to production is made. Designer should finalize dimensions and layout. At the end of this section a CAD model is generated and a finite element analysis can be made. The pilot piston, sleeve, spring and orings are to be determined. Proposed normally closed valve is depicted in figure 17.

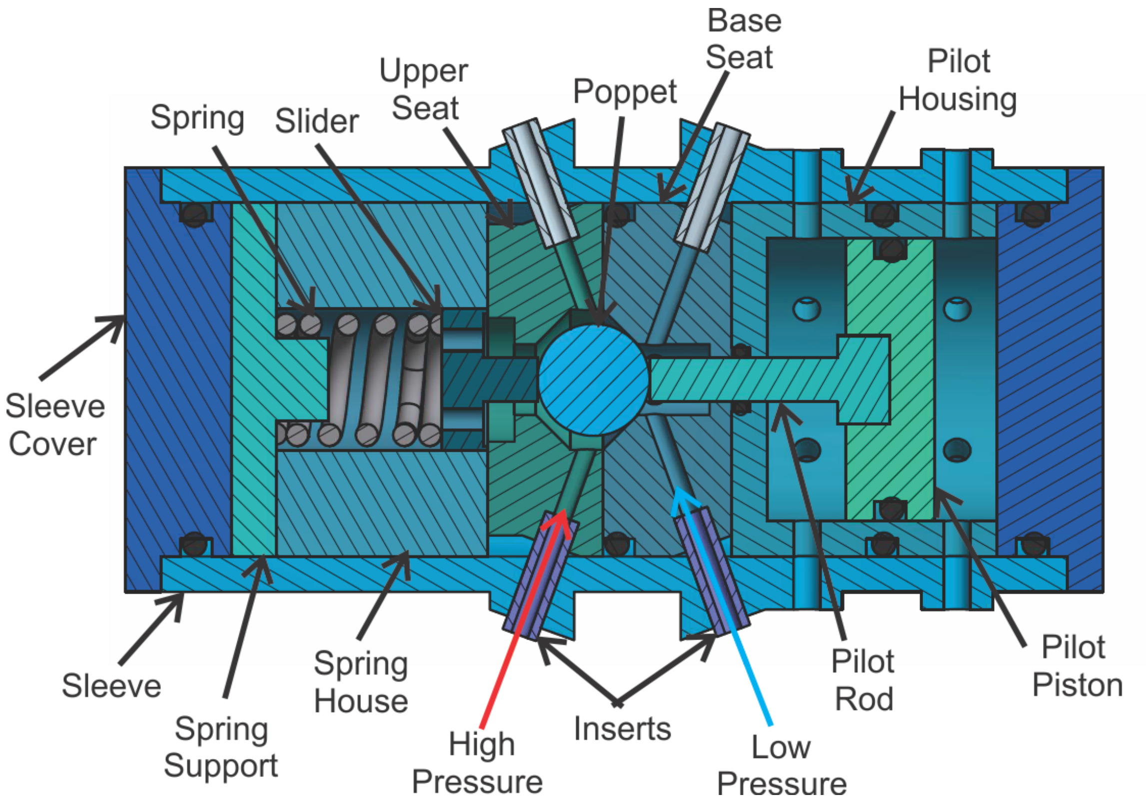


Figure 17: Normally closed valve

Proposed modification eliminates the intermediate housing. The rod oring used to seal base seat is seated in the pilot housing groove. Also, spring is seated in a separate housing and it is operated through a slider connected to poppet. The slider has holes in order to allow flow from high pressure chamber to spring housing. This would help establishing hydraulic balance on the poppet when the valve is opened. This way the spring force required to shut the valve closed will be decreased. Also, water can lubricate slider reducing friction of the slider on the spring housing.

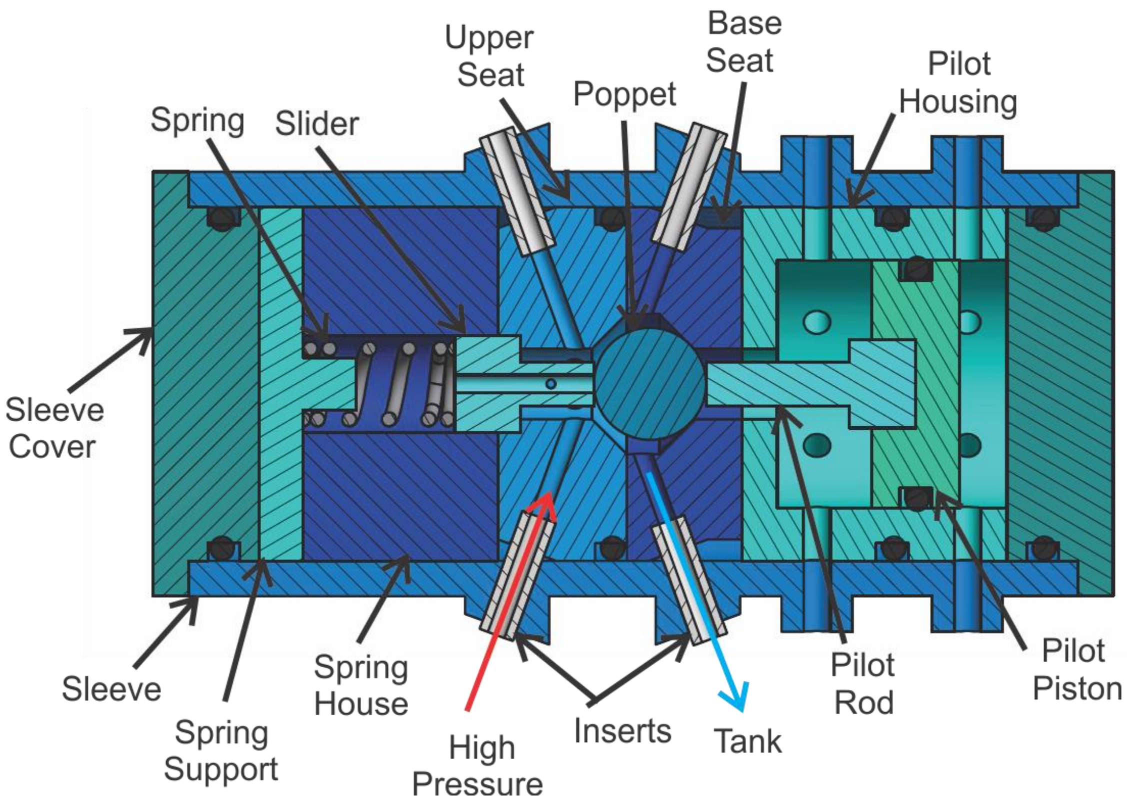


Figure 18: Normally open valve

These shapes are simple and can be produced by lathe machine. Main parameter that defines the overall dimension of the valve is the pilot housing. Pilot housing diameter is function of pilot piston diameter. Housings are recommended to additional thickness. Adding more thickness is not in this case for the sake of providing additional resistance to the components. It is required for the sake of manufacturing purposes. Delerin is machinable but it is softer than metals. Cutting tool may exert excessive force, or deviate inside the machined part. Pilot rod is threaded inside pilot piston.

The NO valve depicted in figure 18 has a similar deign to the NC valve. Only the pilot housing of this valve needs no sealing grooves to isolate base seat chamber from tank. The friction forces in this valve shall be reduced.

Chamfered seat length S and effective valve lift h, inner diameter d_i of the seat and outer diameter d_o have influence on the valve operation. Those parameters have influence on cavitation number of the valve and its stability. The outer to inner diameter ratio of the seat for a valve certain lift x affect the valve stability (MAEDA, Studies on the dynamic characteristic of a poppet valve, 1970). Valve lift higher than 1 mm and pressure higher than 80 bars can be stable for a outer to inner seat diameter higher than 1.18. In addition to this the stability regions for a flow of 300 cc and pressure of 80 kg/cm^2 requires a minimum ratio of outer to inner diameter of 1.2 (MAEDA, Studies on the dynamic characteristic of a poppet valve: 1st report, theoretical analysis, 1970). For a divergent flow in hydraulic poppet valve with a flow of Reynolds number lower than 1000, seat length to effective lift ratio should range from 1 to 2.5 in order to reduce cavitation number. Laminar flow through valve opening for chamfered seat is able to reattach (Oshima, 1985). In the case of turbulent flow, the cavitation number would be the same for a ratio marge of 1 to 5 for divergent flow (Oshima, 1985). In this case, the fluctuation of this number is limited. In Figure 19 shows geometrical parameters of the seat.

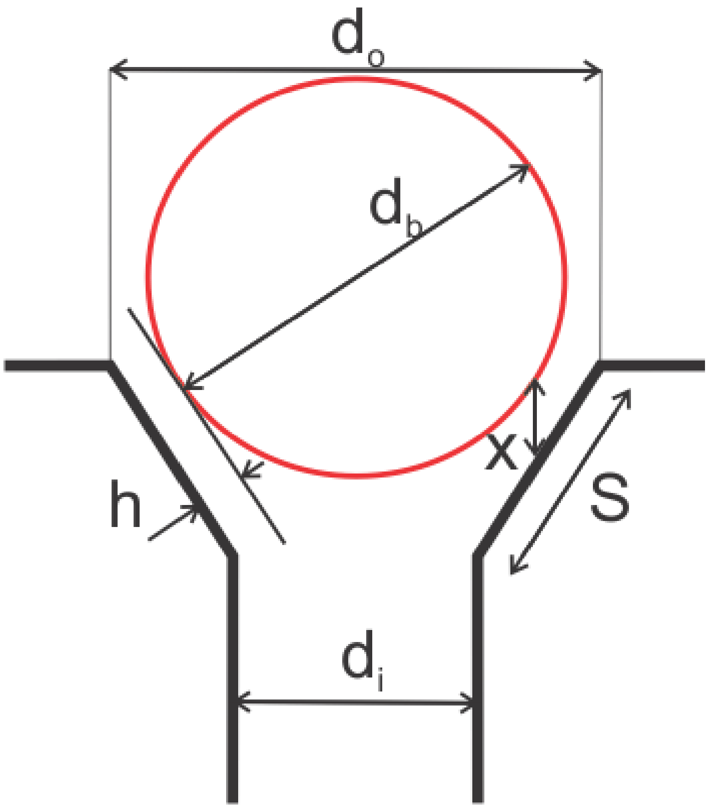


Figure 19: Seat geometry

Chosen diameter outer diameter is 15.875 mm which is larger than ball diameter. This way the poppet can freely move with no risk of having it stuck in the valve, also enough gaps for flow is available. This diameter countersink tool is available for a chamfer of 45 ^{0}. Chosen inner diameter of the valve is of 8 mm. In the current dimension outer to inner diameter ratio is equal to 1.9 which is acceptable in order to have a stable valve. Effective lift is given by equation:

Equation 11

$$h = \sqrt{x^2 + \left(\frac{d_o}{2}\right)^2 + x\sqrt{{d_o}^2 - {d_i}^2}} - \frac{d_o}{2}$$

This effective lift is h = 1.38 mm, the chamfer length is S = 5.57 mm. Which make the ratio chamfer length to effective lift of 4 which is in the range of 1 to 5.

The bearing providing balls of 12.7 mm diameter is 7209 ACD/HCP4A (Super-precision bearing). Orings are chosen from Trelleborg sealing solution. The pilot piston required diameter is 25.54 mm. Trelleborg sealing solution catalogue offers rings for two diameter 25 mm and 28 mm (Trelleborg). It is better to choose a pilot diameter higher than 25.54 mm. A diameter of 28 mm is appropriate for the application. In this case the pilot housing bore is of 28 mm. The thickness of the housing is chosen with respect to sleeve dimension, available orings for the housing and machining requirements of the housing oring groove. Groove depth is of 2 mm therefore a pilot housing thickness of 6 mm is suggested.

The pilot piston rod shall only transmit pilot force to poppet and operate it. The rod is sliding inside flow path of the valve. The flow path would be in a concentric cylinder of inner diameter that of the rod. The rod diameter chosen is of 5 mm. That way the flow area through the seat is of 30 mm^2. The oring used to seal the rod for NC valve is OR1500500 with dimension of 5mm x 1.5mm (Trelleborg). Pilot piston Oring is ORAR00119 with dimension 23.47 mm x 2.62 mm (Trelleborg). Static orings mounted on pilot housing, seat and cover have the size 34.59 mm x 2.62 mm ORAR00126 (Trelleborg). Soft seal can stretch easily and make better sealing. Harder sealing resist abrasion and extrusion. Oring suggested material is the nitrile rubber with shore 70 A which is a standard shore hardness. This material is expected to have low friction coefficient of 0.2 on Delrin after treatment of the ring with silicone oil as suggested by (Ratway, 1998). Figure 20 shows compressed Oring geometry and parameters.The contact force generated by Oring contact with the sealed surface is extracted from (Karaszkiewicz, 1990) through the following equations:

Equation 12

$$\epsilon = \frac{d - g}{d}$$

Equation 13

$$\frac{s_0}{d} = 2\epsilon + 0.13$$

Equation 14

$$\frac{\overline{\sigma_0}}{E} = \frac{\pi}{6}\,(2\epsilon + 0.13)$$

Equation 15

$$\bar{\sigma} = \overline{\sigma_0} + 0.9\,p$$

Equation 16

$$\frac{s}{d} = (2\epsilon + 0.13\,) + [0.39\,(1 - \epsilon)^{-1} - 0.5(2\epsilon + 0.13\,)]\left[1 - exp\left(\frac{-4.6p}{E}\right)\right]$$

Equation 17

$$N = \pi\,(D + d)s\,\bar{\sigma}$$

Substituting each parameter with appropriate values, the contact force of the rod inside the sealing for NC valve is of 180 N. This would make friction force of the sliding rod of 36 N. Also, these equations apply for the pilot piston of both NC and NO valve. The piston contact force is 265 N. The friction force of the piston becomes 50 N. Total friction forces in the NC valve are computed to 86 N; in the NO valve it is 50 N.

For the NC valve at closed position, the high pressure flow applied to spring slider brings additional force closing the valve. In order to reduce this force and establish a force balance on both side of the slider, a thin rim of 0.5 mm thickness is machined at the bottom of it. The additional closing force on the piston is 195 N. NC piston diameter is increased to 32 mm. The pilot force becomes 804 N. The oring used for NC pilot piston is ORAR00121 of dimension 26.64 mm x 2.62 mm. This new dimension affects slightly friction force. The friction becomes of 58 N.

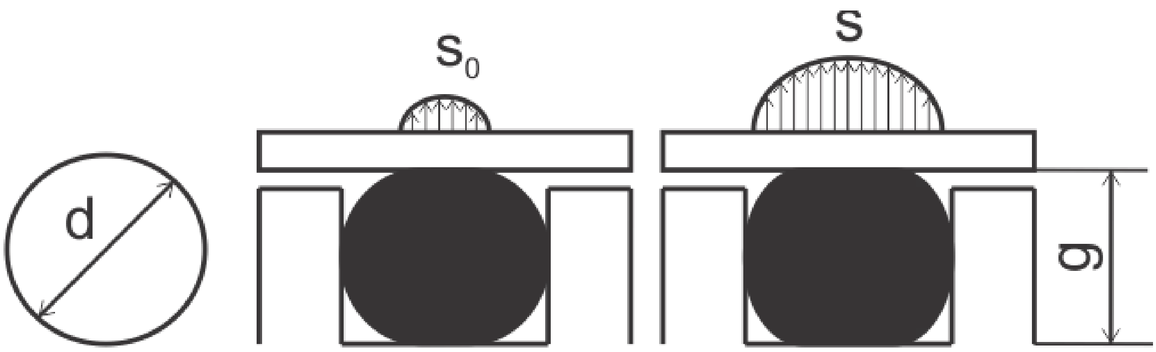


Figure 20: Oring in initial state and compression state

The spring should bring the poppet to the seat once pilot signal is removed. The spring force should overcome friction force generated by the component contact with the seal. Rated friction force is of 88 N in case of NC valve. For the NO valve it is 50 N. Spring is chosen from federnshop. This spring manufacturer offers different size and material of compression springs. Spring choice shall be made in a way that the chosen spring must have sensibility to small deflection with a small stiffness. By this mean the spring force generated at low deflection will not be high enough to resist pilot action and opening of the valve. The NC valve spring is chosen from federnshop, it has the number VD-283B. The spring rate R is equal to 50 N/mm. This spring shall be precompressed in a rate of 0.25 mm. At maximum opening of the valve the spring compression is 1.8 mm so the closing force is of 90 N can overcome the friction. The NO valve spring chosen is VD-228A. The spring rate is of 20.364 N. This spring shall be compressed length is of 1 mm. At closure of the valve the total spring compression is

2.5 mm. So the closing force is of 50.86 N. Springs dimensions define the spring housing and slider size.

Spring stress should be verified. The spring will be subject to combination of torsional shear stress and transverse shear stress (Steven R. Schmid, 2014). The shear should not exceed the strength limit of the spring. Yet, spring deflection under stress affects the spring safety. The spring length under load should not be lower than the solid length. The solid length is the parameter that set the maximum deflection the spring can undergo. In addition to these constraints, the spring subjected to compression can suffer from buckling. The buckling resistance is related to spring to spring length and mean diameter (Steven R. Schmid, 2014). The resistance of spring is computed with the following equation (Steven R. Schmid, 2014):

Equation 18:

$$S_{ut} = \frac{A_p}{{d_w}^m}$$

S_{ut} is the ultimate strength of the spring. A_p and m values are empirical. Shear strength is dependent of the ultimate strength.

Equation 19:

$$S_{sy} = 0.35\ S_{ut}$$

Shear strength of the NO valve spring is equal to 610 MPa. For NC valve it is of 571 MPa. Several factors have been suggested to account both transverse shears to torsional shears. One of those factors is the Whal factor. This is a factor used when expecting fatigue failure. The Whal factor and shear stress are given:

Equation 20:

$$C = \frac{D}{d_w}$$

Equation 21:

$$K_w = \frac{4C - 1}{4C - 4} - \frac{0.615}{C}$$

Equation 22:

$$\tau_{max} = \frac{8\,D\,K_w\,F}{\pi\,{d_w}^3}$$

Maximum shear in NC valve spring is of 216.8 MPa, in NO valve it is 246.7 MPa. So the spring design against shear is ensured. Moreover, the spring buckling resistance shall be verified. The buckling conditions are depicted in figure 21.

Maximum deflection of the NO valve spring is 2.5 mm; its free length is of 18 mm and the mean diameter is 8 mm. For the NC valve the maximum deflection is 1.8 mm; free lengths is of 19 mm and mean diameter is 12.5 mm. These dimensions are in the stable region of the plot so the spring buckling resistance is verified. In conclusion, final dimensions of the whole valve can be defined. This would help building a CAD model. The CAD model would be analyzed in FEA software in order to verify the strength of the valve. Once the dimensions are verified to be suitable for the application, a production drawing should be made to give the final design details. In the final stage comes the design of the safety mechanism.

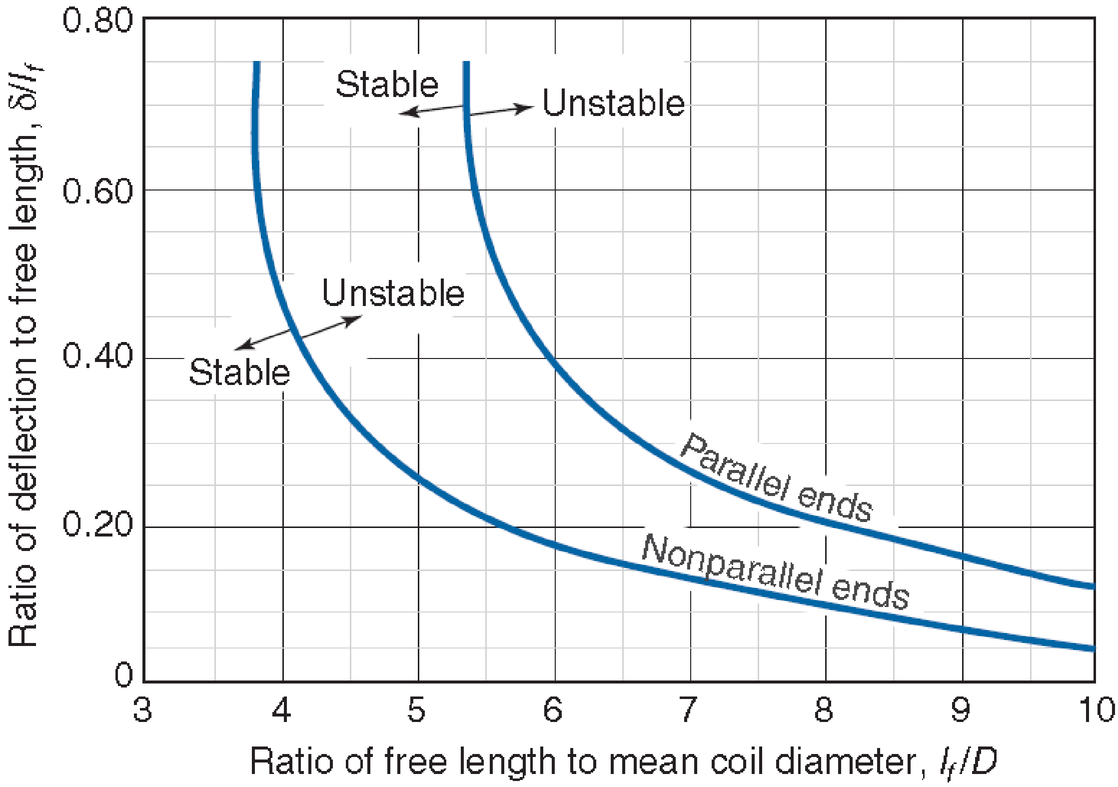


Figure 21: Spring buckling and stable conditions (Steven R. Schmid, 2014)

B. Finite Element Design

Finite element is a numerical method used as tool for engineering analysis. It solves structural and energy problem in engineering. These numerical methods basically divide the whole body into small components (grids) and apply the appropriate physics law. The basics of a successful model reside in assigning right physical constraint and condition to the body subject to analysis. Also, an appropriate mesh shall be chosen in order to guarantee acceptable results. One of the widely used software for FEA is Workbench ANSYS. The normally closed valve at open position is subject to highest load and stress so this valve is to be checked. Results are presented in figure 22 and 23. Delrin ultimate strength is of 69 MPa and strain limit is 12.5 %. The results show a strain of 1.3 % and a maximum stress of 44 MPa. So the valve design is safe. The safety factor is 1.5.

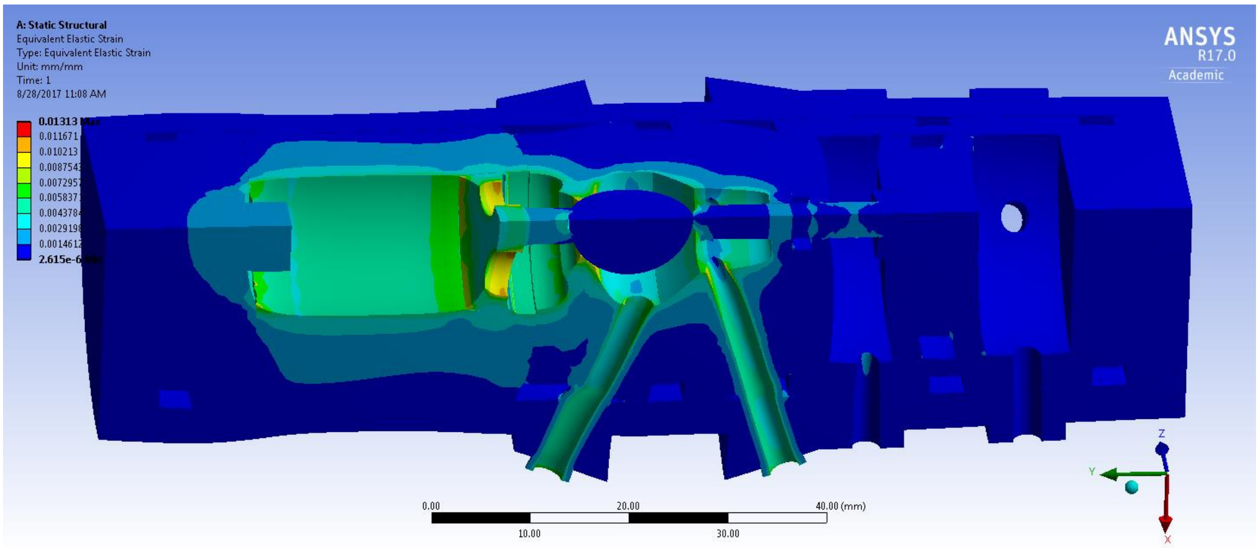


Figure 22: NC open valve strain results using ANSYS

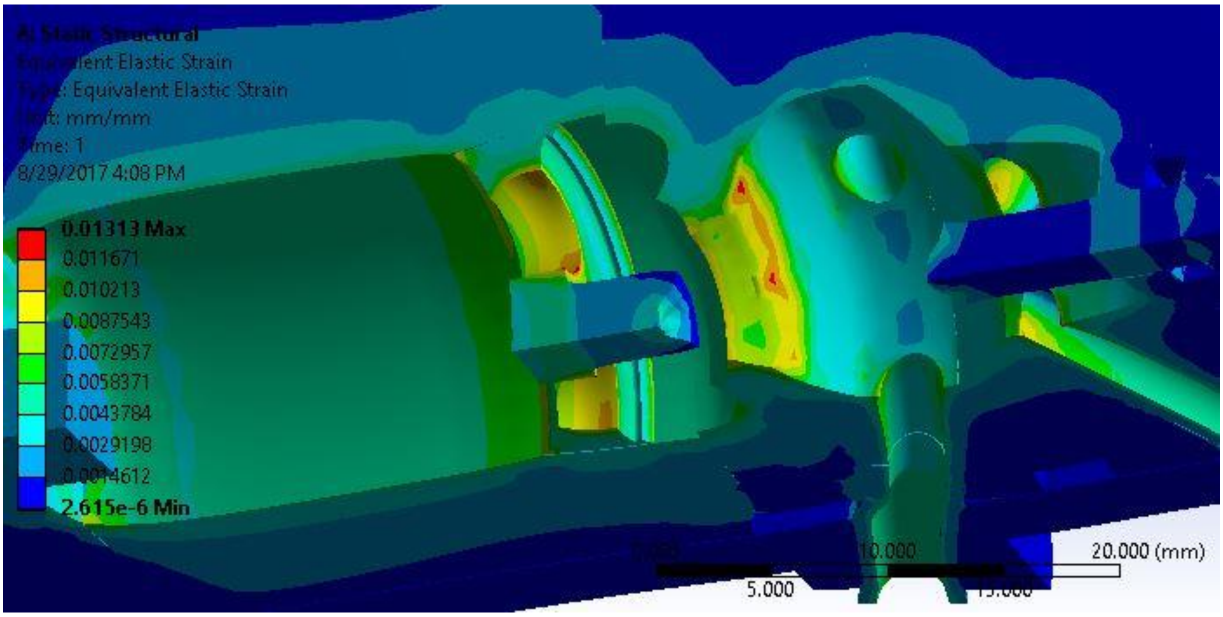


Figure 23: NC open valve maximum stress results using ANSYS

C. Safety Mechanism

Safety mechanism as mentioned in embodiment design is an essential element in the design process. It might not fulfill tasks or functions directly related to system operation. However, it proves to play vital role in system protection whenever hazardous situation occurs. Major problem that exists in fluid power circuit comes originally from the tendency of power circuit pressure to fluctuate. Excessive pressure in these circuit produce excessive stress generated. In such case it is advisable to connect flow to tank. By this mean the flow pressure starts decreasing. Pressure drop is limited by a certain threshold. Below the threshold connection to tank should be cut off or else there will be energy loss in the power circuit.

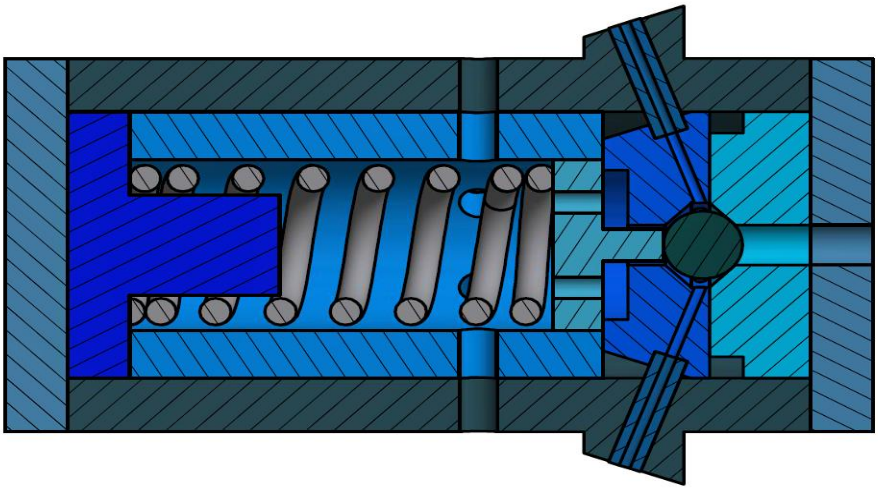


Figure 24: direct operated check valve used as safety mechanism

The description of such behavior is similar to the performance of a direct operated check valve. It only opens at a certain threshold. Once pressure drops below this limit the valve is closed. The design of this device is similar to the pilot operated check valve but it is directly actuated there is no need for pilot signal. In order to reduce cracking force required the ball diameter and seat is minimized. Also, it is recommended to have short lift so the valve can act quickly at pressure rise. These conditions affect the flow area and minimize it. The best solution to this minimum flow area is to make several components (3 valves) identical, fulfilling the same function. Valve design is depicted in figure 24.

The ball diameter is 6.35 mm; the angle seat is of 90^0 with a lift of 0.39 mm. The valve flow area at full open is of 3.8 mm^2. The rated flow is of 7.25 L/min for a pressure difference of 5 bars. So the total outflow through the 3 valves is of 21.75 L/min. The cracking pressure shall be set to 80 bars so the required force is of 126 N. The spring required for this operation shall close the valve at 80 bars and keep it open below this value. It should have low sensitivity because the lift is so small (0.39 mm).

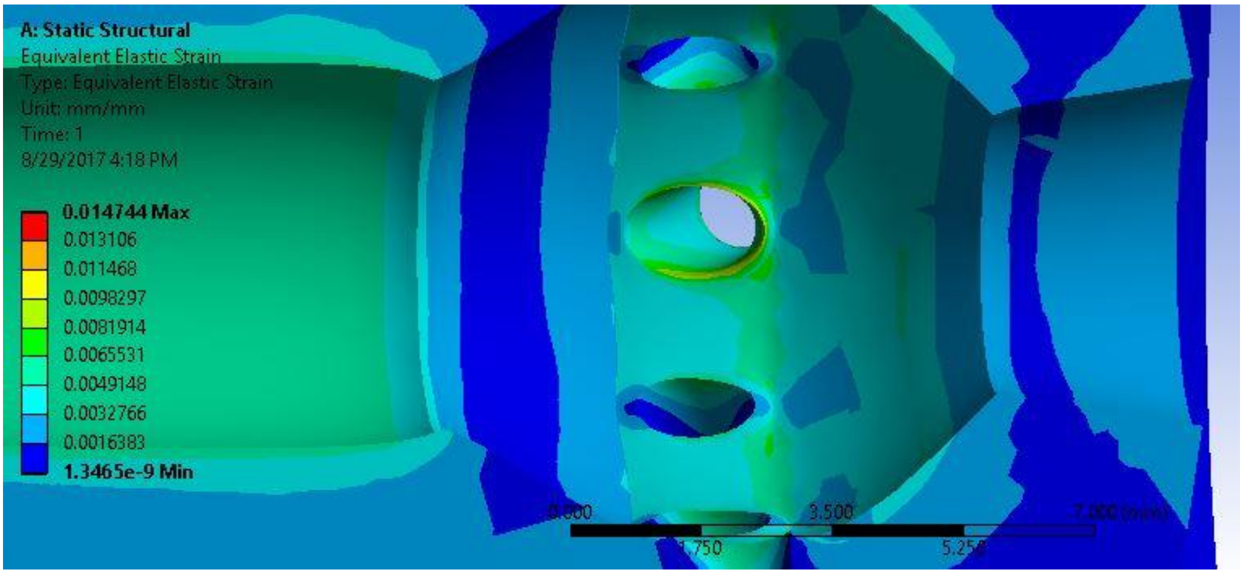


Figure 25: Safety mechanism strain analysis

Proposed spring has stiffness of 20.588 N/mm compressed initially by 6.1 mm. At 85 bars closing force of spring is 133.6 N lower than flow opening force which is equal to 134.5 N. The safety mechanism has a ceramic poppet and a plastic body made of Delrin. The strength of this component is verified and shown in figures 25 and 26. Strain rated at 85 bars is of 1.4 % with an equivalent stress of 42 MPa.

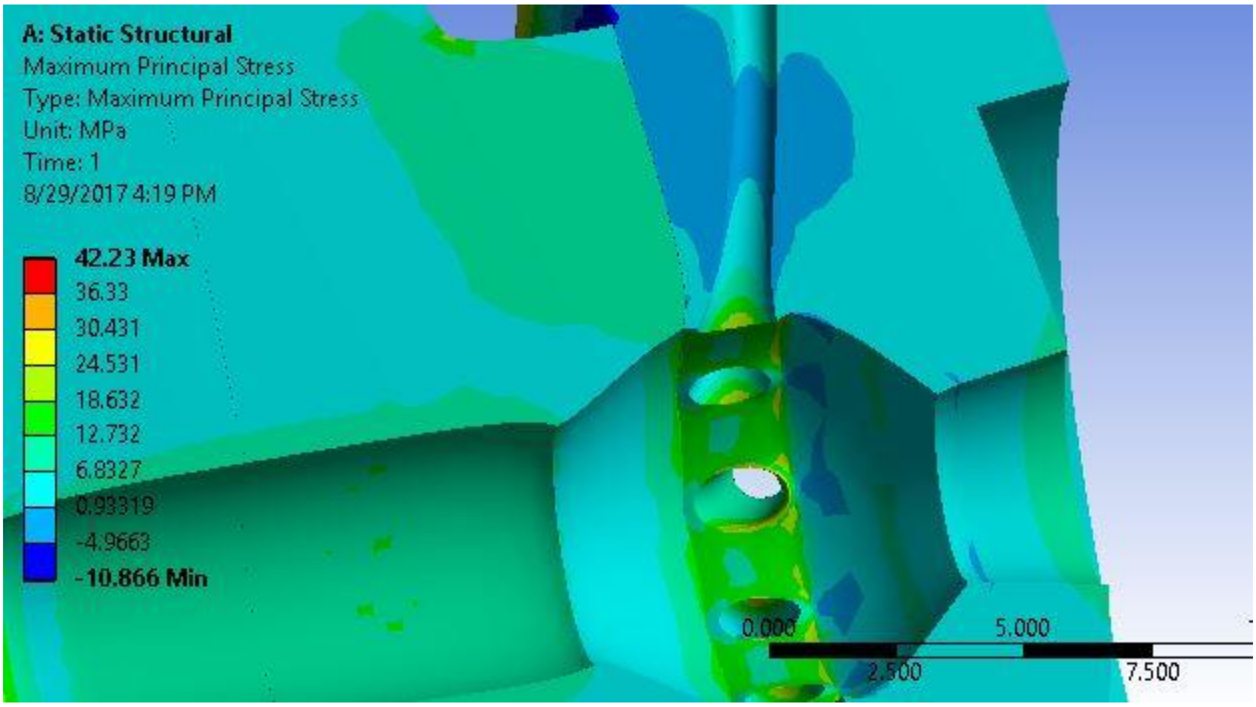


Figure 26: Safety mechanism maximum stress analysis

CHAPTER VI

CONCLUSION

Design is an important aspect in engineering duties. It emphasizes problem solving, critical and analytical thinking. An energy recovery device design problem is presented in this dissertation. It proposes making flow control device by modifying existing product. The proposed design proved through analysis to be suitable for the intended application. It benefits from new existing plastic material in order to form design object components.

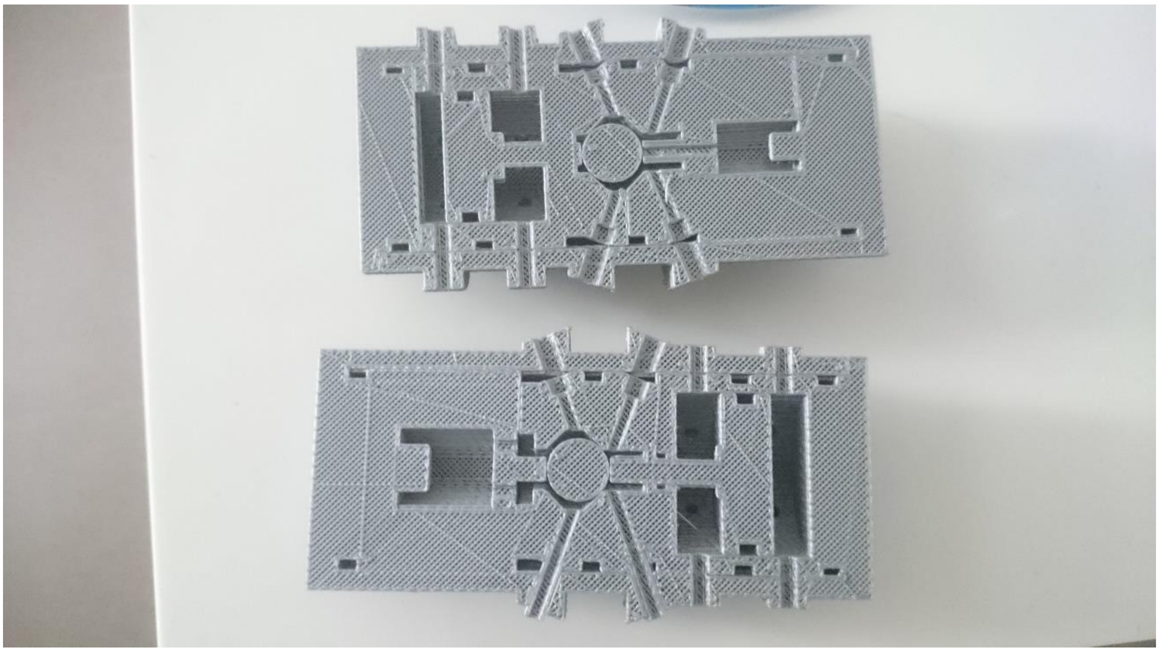


Figure 27: 3d Printed model of NC and NO valve

An explicit explanation for the choice made is presented. Explicit analysis and description is presented. The design steps, requirements and results are clarified. The solution proposed is simple, reliable and comes with a reasonable cost. These characteristics come in accordance with design philosophy requirements. The proposed product shall meet the requirements. A 3d printed model visualizes the solution.

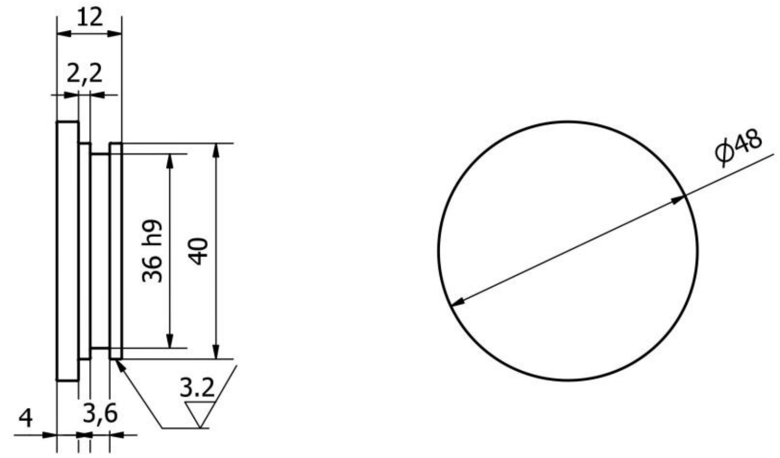
Finally, a production drawing of each component is made. It shows size, tolerances, material and roughness of each component. Valve body components (except for poppet) can be machined on a lathe. Only moving parts require special roughness in order to reduce friction between them. Material properties and production drawing comes in the appendix.

Appendix

DATASHEET AND DRAWINGS

Mechanical properties	Value	Unit
ISO Data		
Tensile Modulus	3100	MPa
Yield stress	71	MPa
Yield strain	17	%
Nominal strain at break	30	%
Tensile creep modulus, 1h	2800	MPa
Tensile creep modulus, 1000h	1600	MPa
Charpy impact strength, +23°C	320	kJ/m^2
Charpy impact strength, -30°C	280	kJ/m^2
Charpy notched impact strength, +23°C	9	kJ/m^2
Charpy notched impact strength, -30°C	8	kJ/m^2
Puncture - maximum force, +23°C	2000	N
Puncture energy, +23°C	3	J
ASTM Data		
Tensile Modulus	3250	MPa
Tensile Strength	68	MPa
Tensile Strength at Yield	68	MPa
Elongation at Yield	15	%
Elongation at Break	40	%
Flexural Modulus	3100	MPa
Rockwell Hardness	R 120	-
Izod Impact notched, 1/8 in	0.075	kJ/m

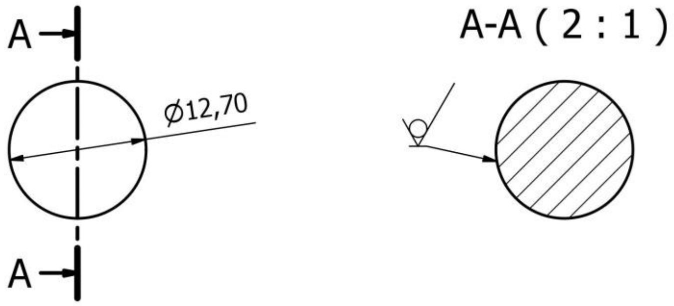
Figure 28: Delrin 500 properties (DuPont)



Designed by	Do not scale	Quantity	Material	General Tolerances	Edge and Corner
Mohamad Sleiman	Drawing	4	Acetal/Delrin	ISO 2768-mk	ISO 13715

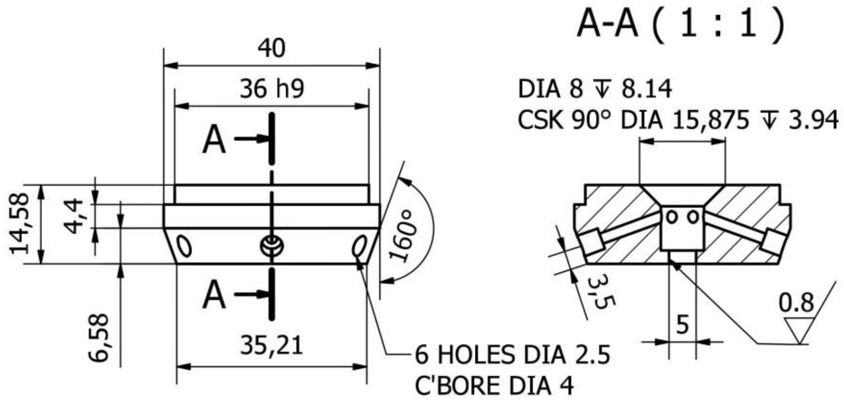
Pilot Operated Check Valve

	Scale	Sheet
Sleeve Cover	1 : 1	1 / 1



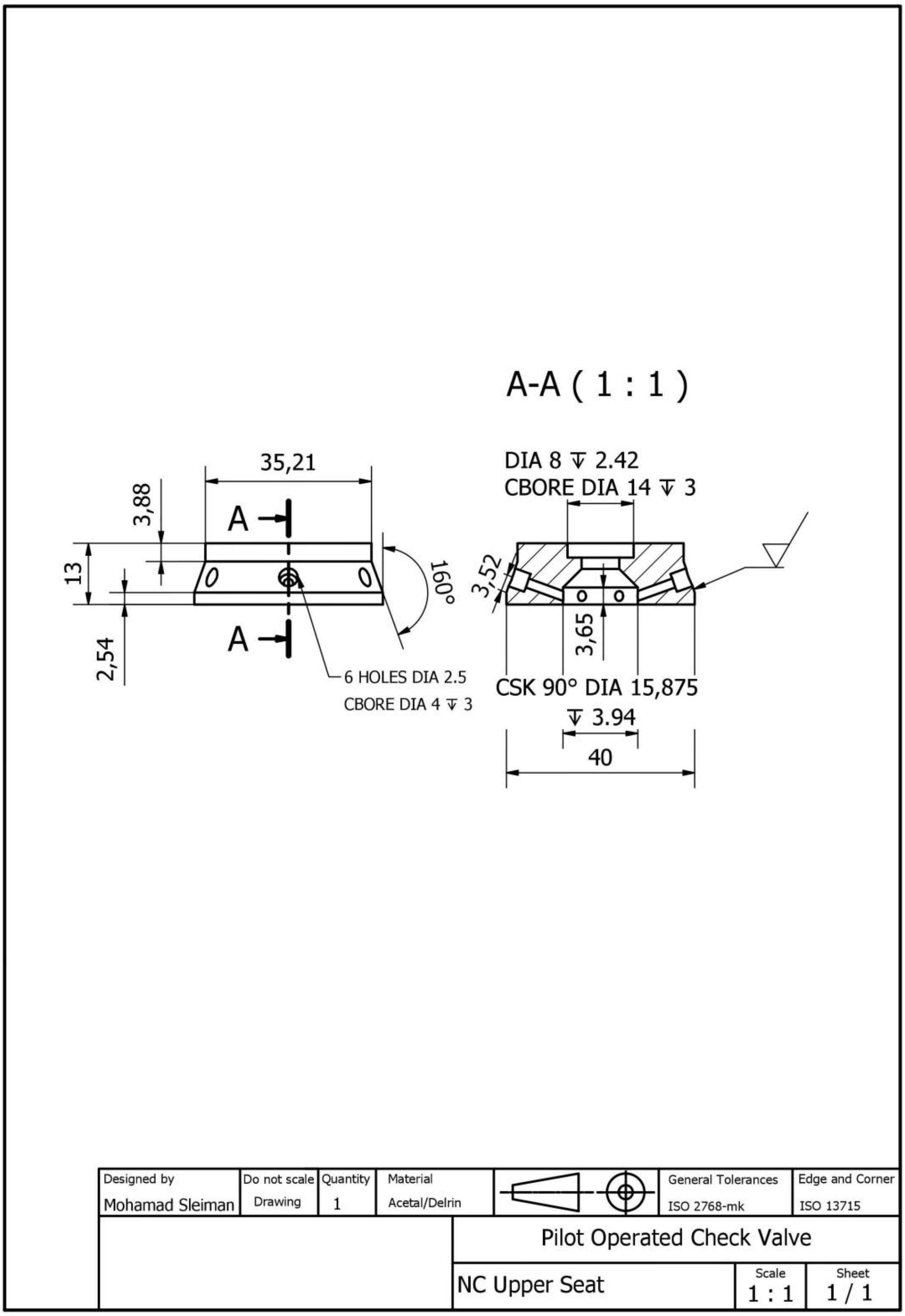
Designed by	Do not scale	Quantity	Material		General Tolerances	Edge and Corner
Mohamad Sleiman	Drawing	2	Silicon Nitride		ISO 2768-mk	ISO 13715

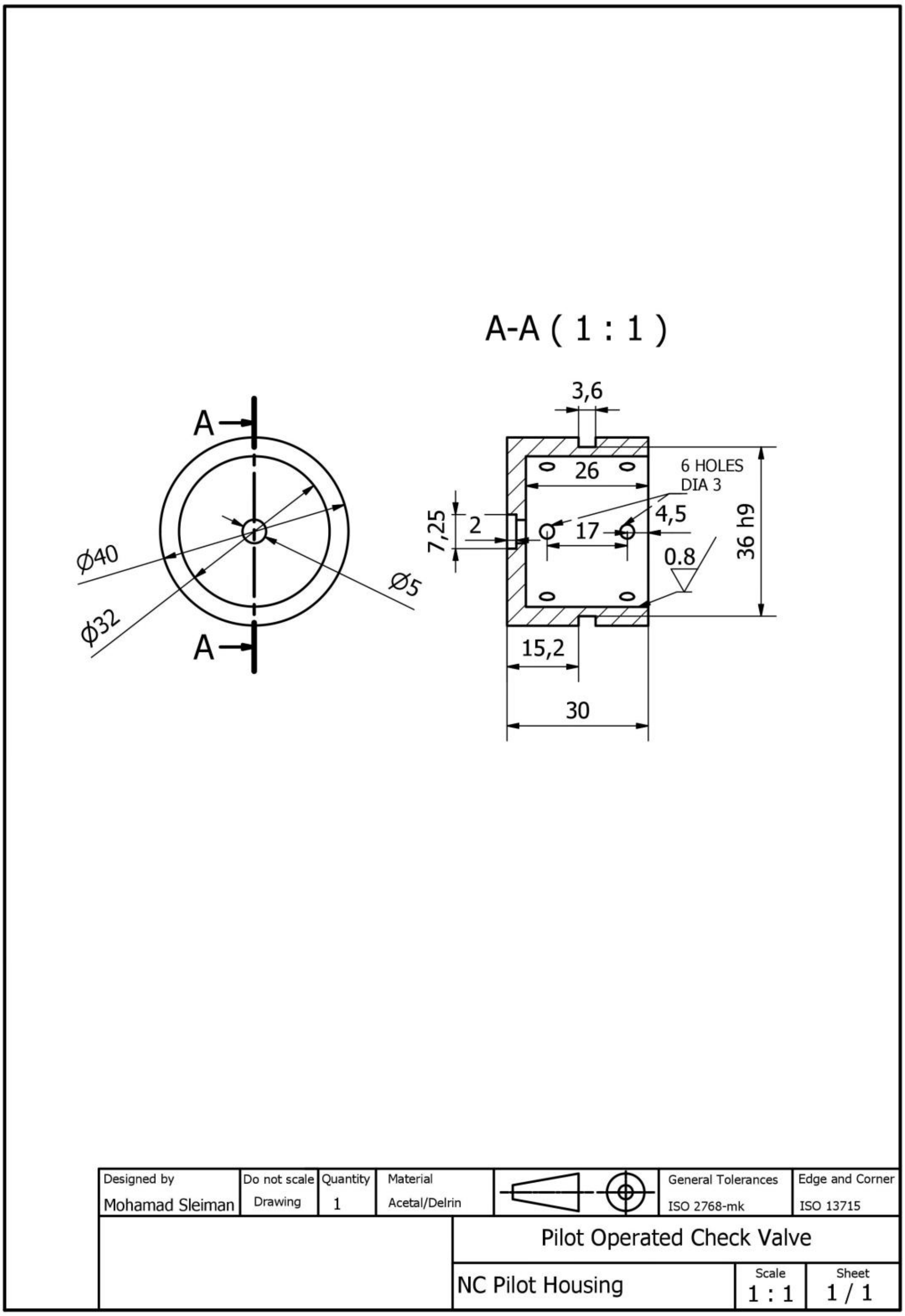
Pilot Operated Check Valve		
Poppet	Scale 2 : 1	Sheet 1 / 1

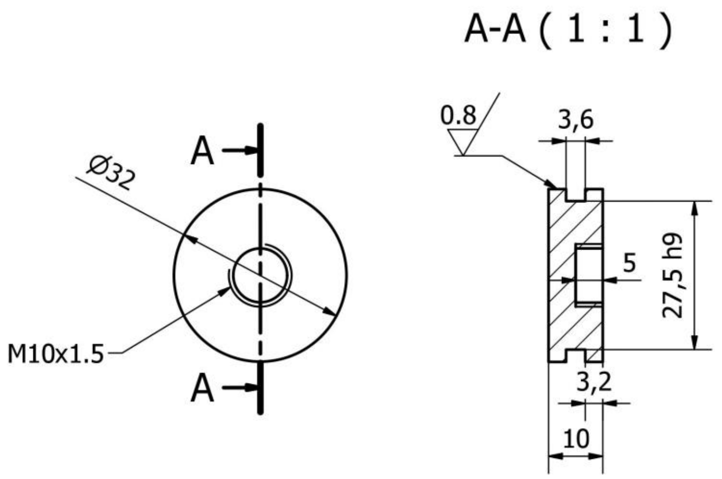


Designed by	Do not scale	Quantity	Material	General Tolerances	Edge and Corner
Mohamad Sleiman	Drawing	1	Acetal/Delrin	ISO 2768-mk	ISO 13715

Pilot Operated Check Valve		
NC Base Seat	Scale 1 : 1	Sheet 1 / 1


A-A (1 : 1)
35,21
3,88
13
2,54
A
A
160°
6 HOLES DIA 2.5
CBORE DIA 4 ↧ 3
DIA 8 ↧ 2.42
CBORE DIA 14 ↧ 3
3,52
3,65
CSK 90° DIA 15,875
↧ 3.94
40
Designed by
Mohamad Sleiman
Do not scale
Drawing
Quantity
1
Material
Acetal/Delrin
General Tolerances
ISO 2768-mk
Edge and Corner
ISO 13715
Pilot Operated Check Valve
NC Upper Seat
Scale
1 : 1
Sheet
1 / 1

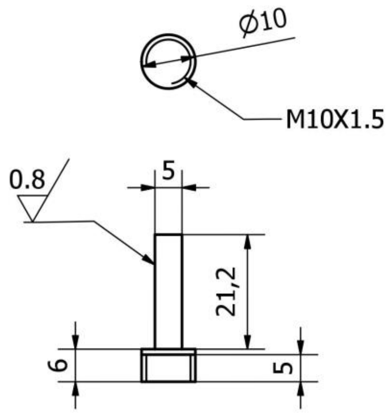

A-A (1 : 1)
3,6
26
6 HOLES
DIA 3
4,5
7,25
2
17
0.8
36 h9
15,2
30
A
A
Ø40
Ø32
Ø5
Designed by
Mohamad Sleiman
Do not scale
Drawing
Quantity
1
Material
Acetal/Delrin
General Tolerances
ISO 2768-mk
Edge and Corner
ISO 13715
Pilot Operated Check Valve
NC Pilot Housing
Scale
1 : 1
Sheet
1 / 1



Designed by	Do not scale	Quantity	Material		General Tolerances	Edge and Corner
Mohamad Sleiman	Drawing	1	Acetal/Delrin		ISO 2768-mk	ISO 13715

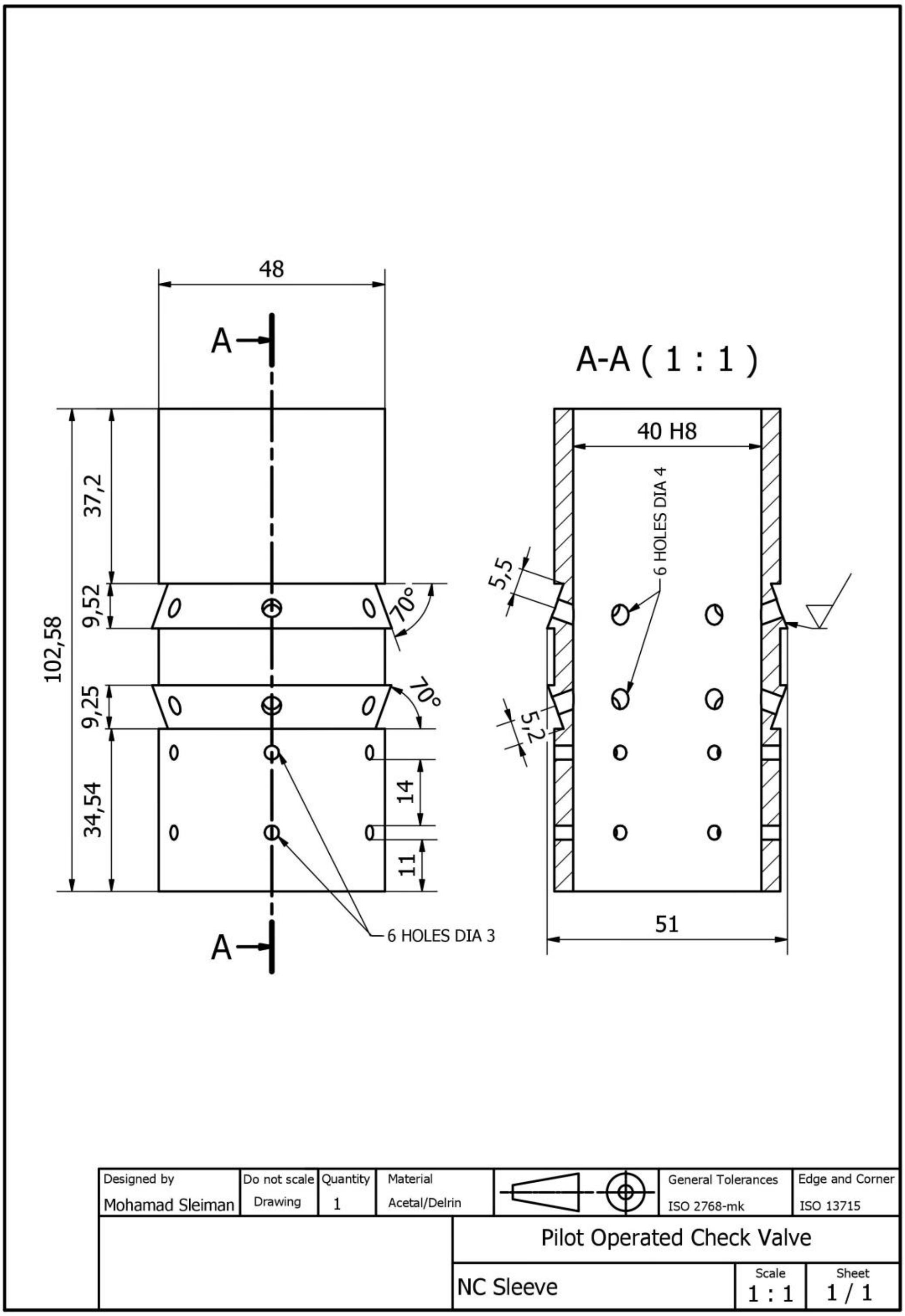
Pilot Operated Check Valve

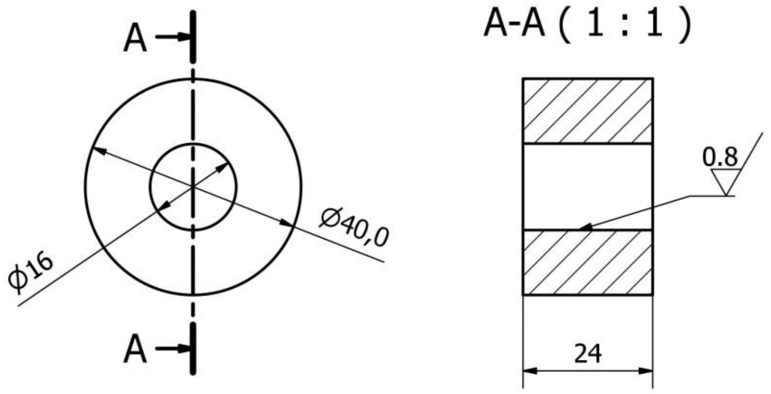
NC Pilot Piston	Scale 1 : 1	Sheet 1 / 1



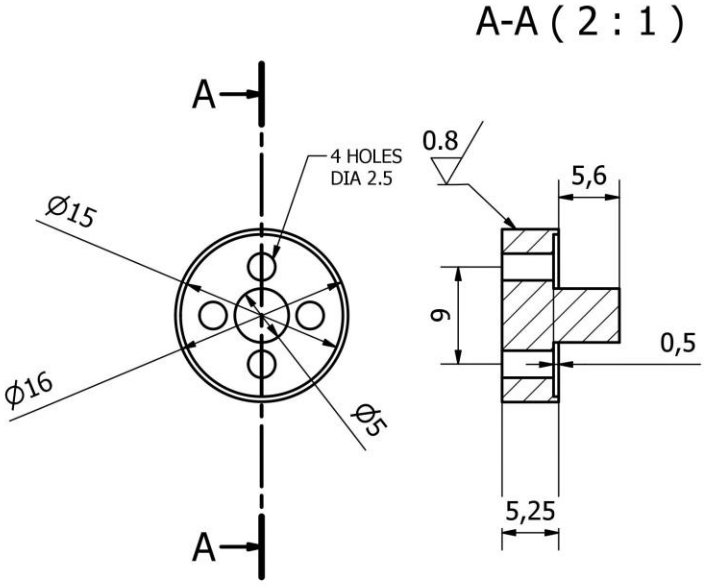
Designed by	Do not scale	Quantity	Material		General Tolerances	Edge and Corner
Mohamad Sleiman	Drawing	1	Acetal/Delrin		ISO 2768-mk	ISO 13715

Pilot Operated Check Valve		
NC Pilot Rod	Scale 1 : 1	Sheet 1 / 1

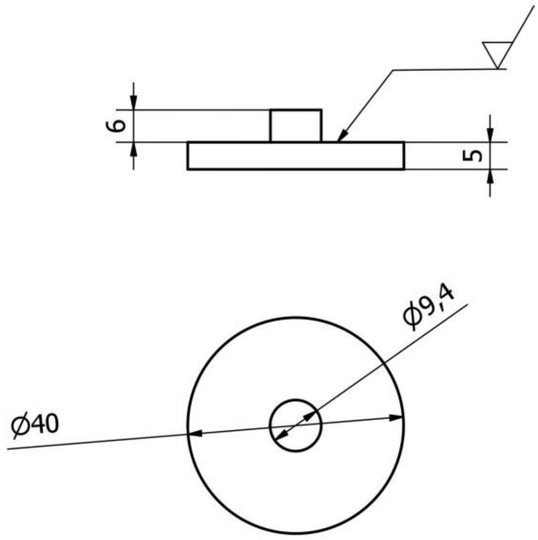

48
A
A-A (1 : 1)
40 H8
37,2
9,52
102,58
9,25
34,54
70°
70°
5,5
5,2
6 HOLES DIA 4
14
11
6 HOLES DIA 3
51
Designed by
Mohamad Sleiman
Do not scale
Drawing
Quantity
1
Material
Acetal/Delrin
General Tolerances
ISO 2768-mk
Edge and Corner
ISO 13715
Pilot Operated Check Valve
NC Sleeve
Scale
1 : 1
Sheet
1 / 1



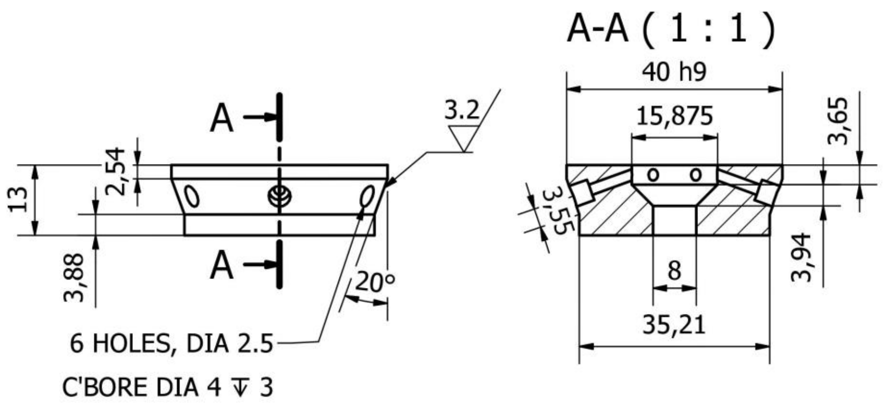
Designed by Mohamad Sleiman	Do not scale Drawing	Quantity 1	Material Acetal/Delrin		General Tolerances ISO 2768-mk	Edge and Corner ISO 13715
				Pilot Operated Check Valve		
				NC Spring House	Scale 1 : 1	Sheet 1 / 1



Designed by	Do not scale	Quantity	Material		General Tolerances	Edge and Corner
Mohamad Sleiman	Drawing	1	Acetal/Delrin		ISO 2768-mk	ISO 13715
				Pilot Operated Check Valve		
				NC Spring Slider	Scale 2 : 1	Sheet 1 / 1



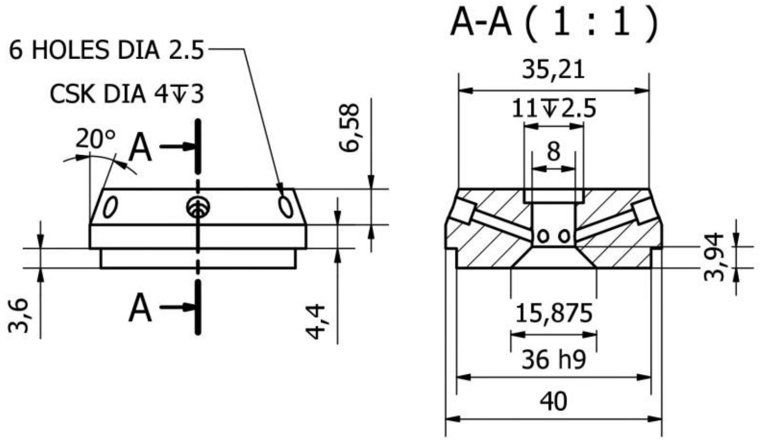
Designed by	Do not scale	Quantity	Material		General Tolerances	Edge and Corner
Mohamad Sleiman	Drawing	1	Acetal/Delrin		ISO 2768-mk	ISO 13715
			Pilot Operated Check Valve			
			NC Spring Support		Scale 1 : 1	Sheet 1 / 1



Designed by	Do not scale	Quantity	Material		General Tolerances	Edge and Corner
Mohamad Sleiman	Drawing	1	Acetal/Delrin		ISO 2768-mk	ISO 13715

Pilot Operated Check Valve

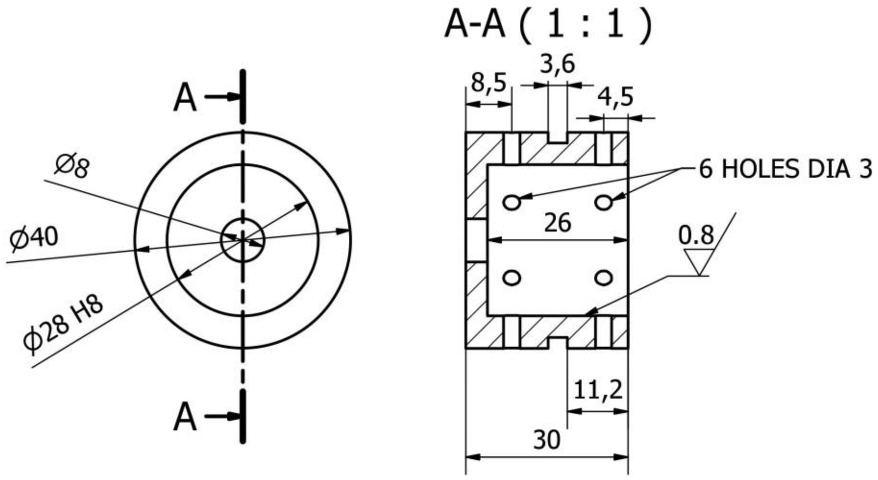
NO Base Seat	Scale 1 : 1	Sheet 1 / 1



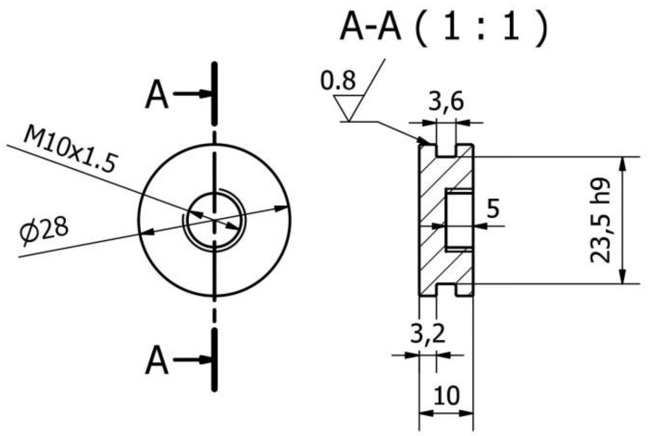
Designed by	Do not scale	Quantity	Material		General Tolerances	Edge and Corner
Mohamad Sleiman	Drawing	1	Acetal/Delrin		ISO 2768-mk	ISO 13715

Pilot Operated Check Valve

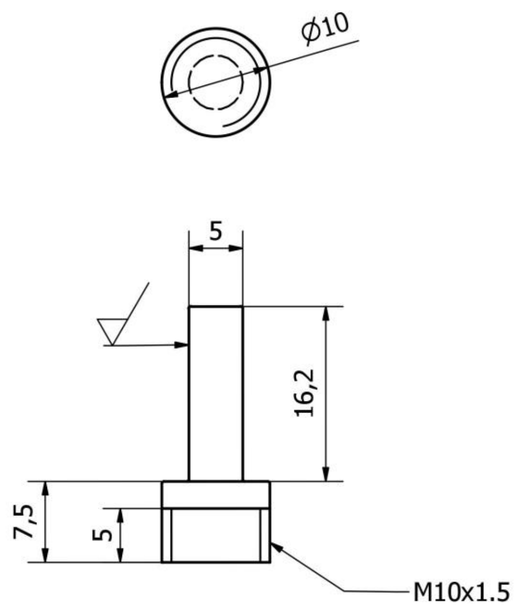
NO Upper Seat	Scale 1 : 1	Sheet 1 / 1



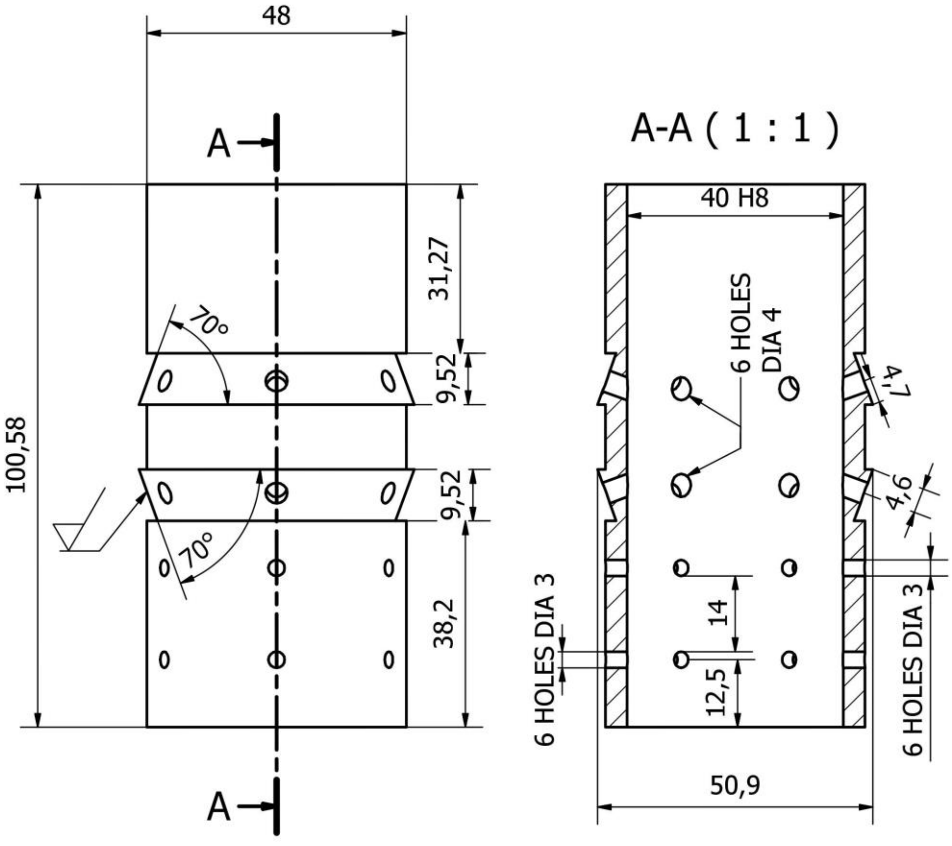
Designed by	Do not scale	Quantity	Material		General Tolerances	Edge and Corner
Mohamad Sleiman	Drawing	1	Acetal/Delrin		ISO 2768-mk	ISO 13715
			Pilot Operated Check Valve			
			NO Pilot Housing		Scale 1 : 1	Sheet 1 / 1



Designed by	Do not scale	Quantity	Material	General Tolerances	Edge and Corner
Mohamad Sleiman	Drawing	1	Acetal/Delrin	ISO 2768-mk	ISO 13715
			Pilot Operated Check Valve		
			NO Pilot Piston	Scale 1 : 1	Sheet 1 / 1

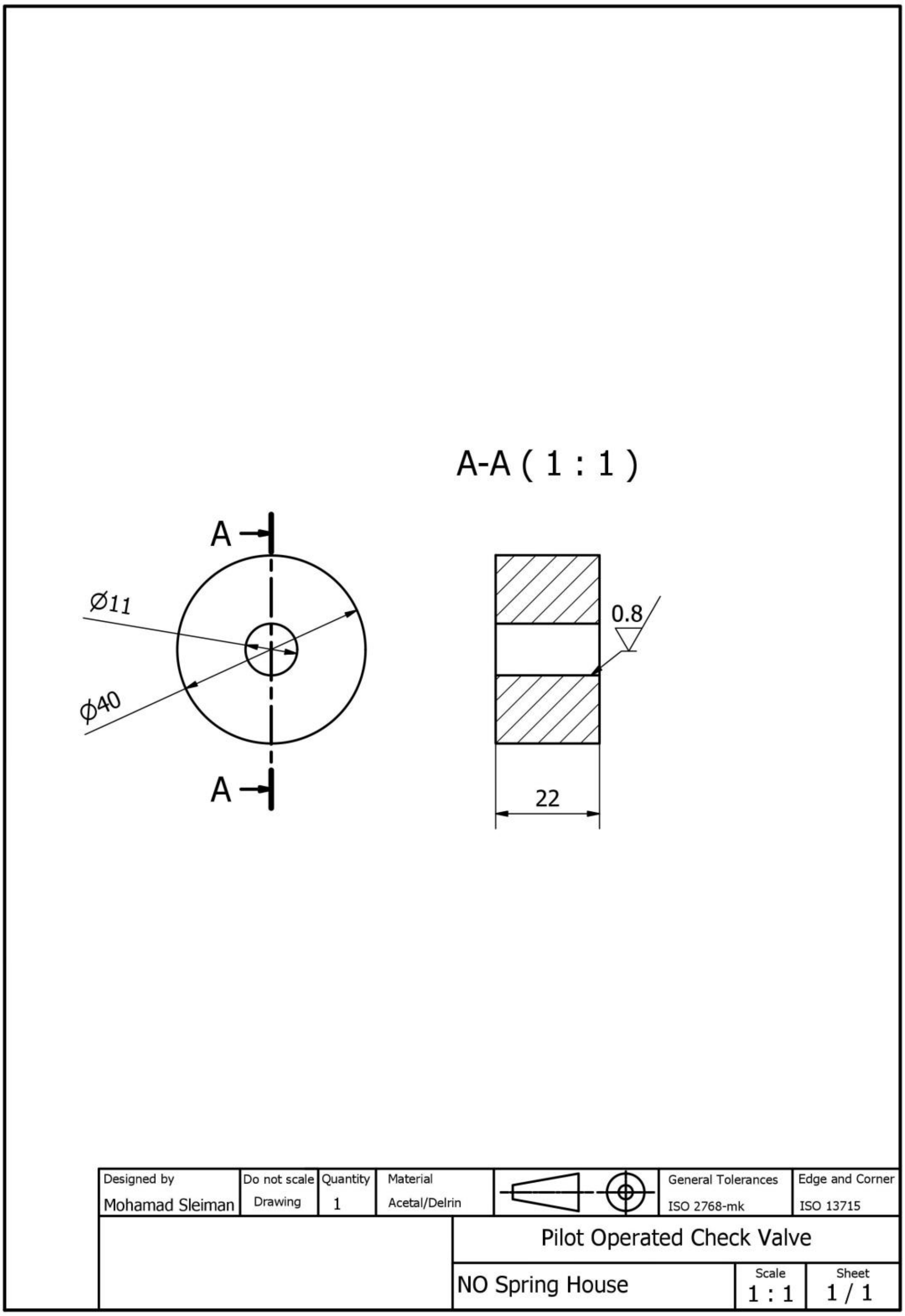


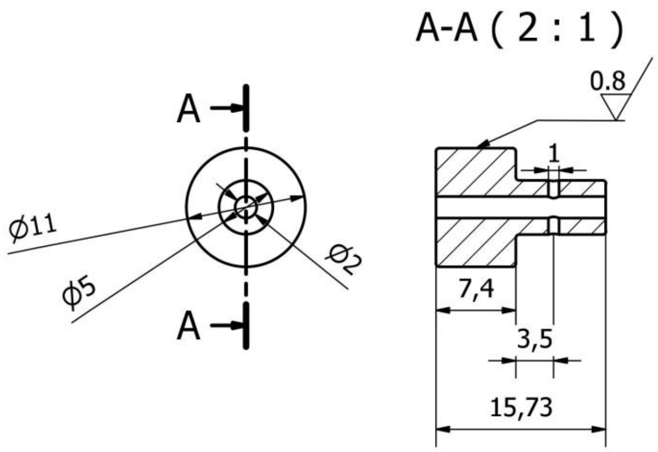
Designed by	Do not scale	Quantity	Material		General Tolerances	Edge and Corner
Mohamad Sleiman	Drawing	1	Acetal/Delrin		ISO 2768-mk	ISO 13715
			Pilot Operated Check Valve			
			NO Pilot Rod		Scale 2 : 1	Sheet 1 / 1



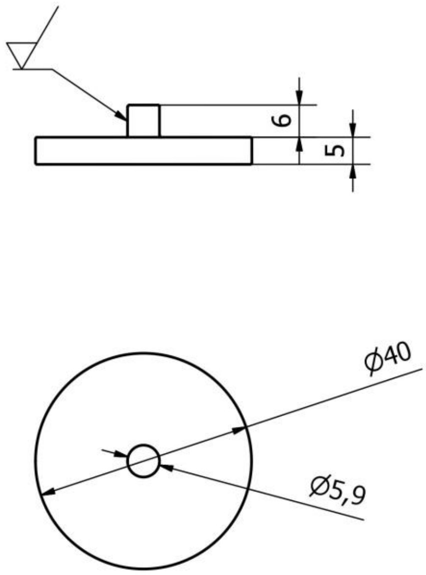
Designed by	Do not scale	Quantity	Material	General Tolerances	Edge and Corner
Mohamad Sleiman	Drawing	1	Acetal/Delrin	ISO 2768-mk	ISO 13715

Pilot Operated Check Valve		
NO Sleeve	Scale 1 : 1	Sheet 1 / 1


A-A (1 : 1)
A
A
Ø11
Ø40
0.8
22
Designed by
Mohamad Sleiman
Do not scale
Drawing
Quantity
1
Material
Acetal/Delrin
General Tolerances
ISO 2768-mk
Edge and Corner
ISO 13715
Pilot Operated Check Valve
NO Spring House
Scale
1 : 1
Sheet
1 / 1



Designed by	Do not scale	Quantity	Material		General Tolerances	Edge and Corner
Mohamad Sleiman	Drawing	1	Acetal/Delrin		ISO 2768-mk	ISO 13715
			Pilot Operated Check Valve			
			NO Spring Slider		Scale 2 : 1	Sheet 1 / 1



Designed by	Do not scale	Quantity	Material		General Tolerances	Edge and Corner
Mohamad Sleiman	Drawing	1	Acetal/Delrin		ISO 2768-mk	ISO 13715
			Pilot Operated Check Valve			
			NO Spring Support		Scale 1 : 1	Sheet 1 / 1

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