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Analysis & Optimization of Weir Dimension of disk of high pressure pump recirculation valve by CFD

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Abstract : Control Valve has a large field of applications in Process Industries like Power plants, Sugar factories, Cement and Chemical industry with enormous variety of gases, pressure and suction volumes, which have low efficiency. In this paper, control valve is optimized by Cfd analysis and past experience technique. The total efficiency, which is chosen as the object function of optimization by optimizing weir dimension (depth) of disk, which is computed through CFD analysis. Since the efficiency maximization of disc is done for particular discharge rat, cavitation and exit velocity. For weir dimensional analysis and optimization, the valve inlet outlet pressure, velocity is considered and effect on the flow separation, pressure distribution and exit velocity in the disc channel is studied. The computational fluid dynamics (CFD) plays a greater role in hydrodynamic design of machinery to study complex phenomena relate to flow in valve disc. The methodology used to analysis the designed disk is CFD method. The hydrodynamic performance of disc is evaluated using Ansys CFX -14.5 software for entire analysis cycle. Designing of control valves of the tortuous path employing at right angles turns and multiple paths are presented here with improved efficiency with additional features and with past experiences and on field. The main feed pump recirculation valve is the most difficult and severe service application in a central power station. The valve must provide a controlled letdown of the pressure without excessive noise, cavitations or erosion while maintaining leak-free service when shut off. A valve design and its performance in the field is described. The design has evolved from many years of application feedback. The result is a valve which has provided trouble free and economical performance for periods in excess of two years. This compares with some plant experiences which require valve rebuilding every three to six months. The tortuous flow path takes the energy out of the fluid or gas and reduces its velocity in a controlled way, ensuring that velocities never exceeds the threshold that could impair system performance or damage valve components

Key words: **CFD, CFX-14.5, Cavitations, Tortuous path, shut off Valve, Feed pump.**

I. INTRODUCTION

This paper describes a valve design which has evolved from field experience. The design has been proven in applications with trim life in service for nearly ten years and with time between maintenance exceeding five years.

The high pressure pump recirculation application is one of the most difficult and severe duty control valve installations demanded by the power industry. There are two significant features that make this valid. First, flow must be controlled during a very high pressure drop and second, when not controlling flow a tight leak proof shut off is required. Failure to achieve either of diesel functions will quickly result in a plant shutdown or valuable loss of energy over an extended period.

The feed pump recirculation valve application has been discussed many times in the literature; Reference 1 gives a general description, discussing the merits of on-off versus modulating service.

The hope was expressed. That a valve could be designed for a five year trim life, this article presented an excellent summary of the state of the art and a description of the relationship between liquid pressure and velocity during die throttling process. The author describes the "...recirculation valve service to be die most difficult of any in the station ... The recirculation valve is the highest-technology valve in the central station today." Unfortunately, the state of the art has not changed much in me intervening years. Improvements have been slowed by the time necessary to receive feedback from the field.

The main reason for a feed water recirculation loop is to protect the pump under reduced flow conditions. For some pumps this is as low as 20 percent of the design flow but for nuclear plant pumps this can be as high as a 50 percent flow rate. Many difficult schemes have been used to try to control the pressure letdown. For example, Reference 5 mentions six different methods for just avoiding flashing in the downstream piping, although flashing may not be the worst effect of the pressure letdown. Many of these schemes are tried because a good recirculation valve has not been available.

There are many different types' tortuous path valves which differ in the manner in which pressure drop stages are achieved and the amount of division of the main flow stream.

In multi stage valves with single flow paths, the pressure drop stages are formed by a non uniform cage shape with corresponding plugs of varying cross section and the flow is parallel to the axis of the plug.

Within the area of the valve design numerous options have been attempted. One of these has been to solve the cavitations damage problem by brute force, that is, to use harder and harder materials. Material selection guidelines and valve designs are presented in Reference 6 for the classical treatments of erosion and corrosion in recirculation valves.

The design to be discussed has evolved from many trials and tests conducted over an extensive period. Many different designs features were tried and feedback from either good or bad performance integrated into an evolving solution.

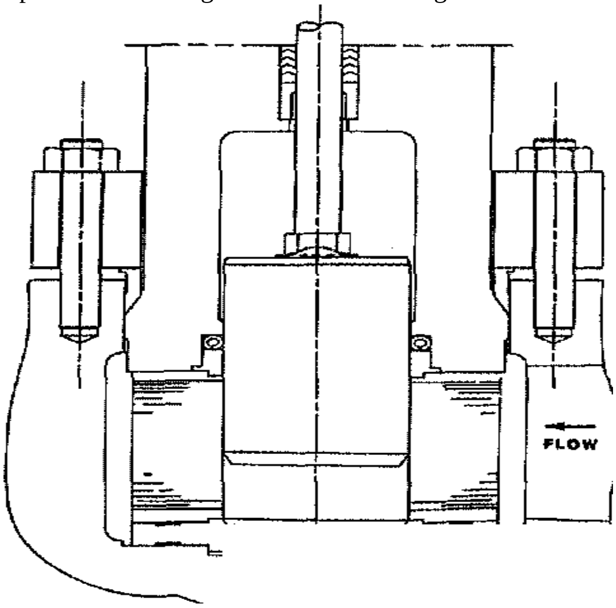

Fig 1 Valve schematic

The features of the design and installation experience are presented below. The design is indifferent as to whether the application is for an on-off or modulation service.

Improved additional Features

The recirculation valve must perform two important functions. It must control the fluid during the large pressure letdown when open at all plug positions and it must assure no leakage when the valve is closed. There is little room for error in performing these functions as any erosion or cavitations damage cascades rapidly, resulting in a very short trim life. The controlled pressure letdown features are discussed first.

A sketch of the recirculation valve is shown in Figure 1 where the flow direction and path are shown. The flow enters the tortuous path trim and flows inwardly to the plug, then past the seat ring and out. Although an angle valve configuration is shown in Figure 1 a globe body configuration is also applicable.

The tortuous path trim consists of a number of disks brazed together to form a stack as shown in Figure 2. Each of the disk outlet openings are staggered circumferentially from the disk above and below so as to develop a uniform exiting from the disk. The inside diameter of the disk stack is ground to a tight tolerance so that a minimum annular gap is available for fluid flow between the stack and the valve plug.

Each disk in the stack has a multitude of tortuous flow channels electric discharge machined into the metal. Each disk channel is independent of adjacent channels or disks. Thus each disk's flow remains constant regardless of the position of the plug once the opening is uncovered. For the recirculation valve each disk is the same so that each disk is working equally for all flows, another way to say this is that the total valve flow is directly proportional to the plug position as the disk stack has a linear characteristic.

If it is necessary that the flow resistance of the trim change with increasing stroke then each disk, or grouping of disks, would have different channels machined into their surface. A fully customized flow versus stroke stack can be characterized to meet a unique set of flow conditions.

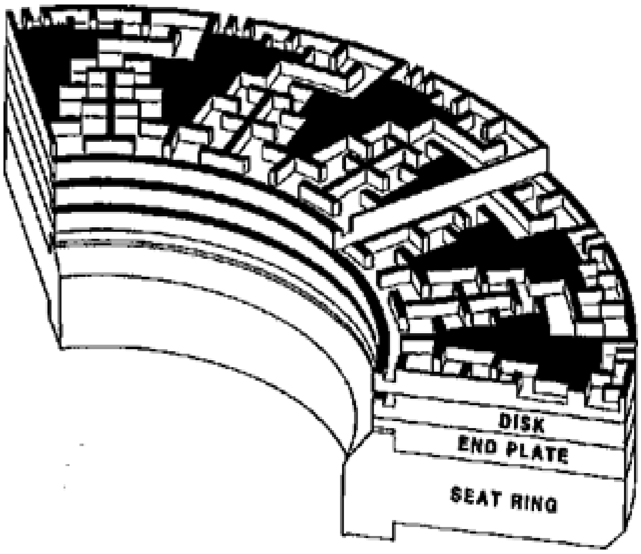

Fig 2 Disc Section

A typical disk channel is shown on Figure 3. Each flow channel consists of several right angle turns (stages), each of which account for more than one velocity head of pressure drop. This large number of stages is packaged into a radial wall as small as 1 1/8 inches (28 mm). Therefore a pressure drop of 3000 to 4000 psi (200 to 300 kg/cm^2) is achieved by each channel in a very tight space.

Figure 3 shows five significant features of each disk channel. These are:

1. Strategic Inlets *(Section 1)* which are the smallest flow channels in the path, but are significantly larger than the required flow channel after the entrance. The purpose of the dual inlets and their size is to prohibit any foreign matter such as weld rod or other trash from passing through the valve and damaging the seating surface. Particles small enough to pass through the inlets will also flow through the channel because the flow area is continually increasing. The extra flow area at the inlet will permit almost a 50 percent blocking before the flow versus pressure drop characteristic of the valve is impacted.

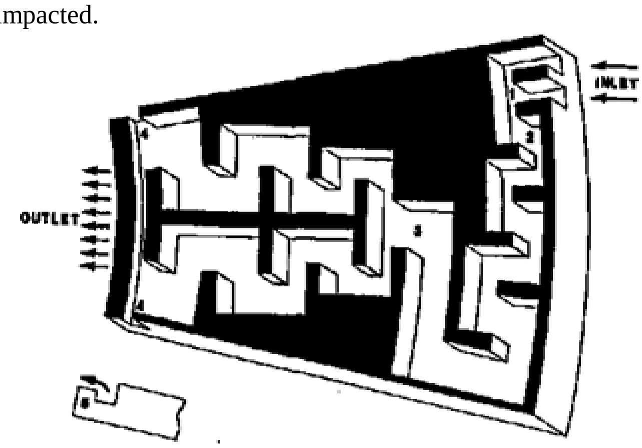

Fig 3 Flow Channels

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2. Increasing passage size *(Section 2)*, the flow area is continually increasing as the fluid pressure decreases. Thus the velocity is continuously reducing to a very low level, at-the disk outlet. As the pressure drop takes place the, velocity, is controlled by the flow area design. There are no local pressure recovery points for cavitations to take place in the trim, such-as occurs with a drilled hole type trim.

3. Increased number of stages (Section 3). Because there are 24 stages the pressure drop takes place at much Lower velocities than for designs in which there are only Three to four stages. Liquid velocities as high as180 m/s are common in most recirculation valve designs. In this the maximum liquid liquid velocity is limited to around feet per second (60 m/sec) and this only occurs for a short Period as the first expanding channel reduces the Velocity.

4. Ring (Section 4). A flow channel around the inside diameter of the disk equalizes any unbalanced pressures which may be induced by uneven velocity distribution. This pressure equalization assures that there are no unbalanced forces on the plug to cause noisy mechanical vibration.

5. Pressure reducing weir *(Section 5).* At the exit of the channel the fluid is forced over a weir. This assures a uniform sheet flow of fluid entering the plug cavity and a reduced average velocity at the weir exit. This eliminates any chance for high local velocity to cause damage. The weir exit in combination with a tight tolerance between the disk ID and the plug forms an effective labyrinth seal.

6. This minimizes any annular flow that may pass through this area and cause damage to the seat ring. The sheet flow out of the disk also intercepts any annular flow to divert it away from the sealing surfaces.

The second essential function mentioned above is to maintain a leak free valve. If a leak is allowed to develop, the high pressure, high velocity fluid quickly causes a combination of wire draw and cavitations damage to the sealing surfaces and trim. In some cases the valve body wall or downstream piping pressure integrity can be lost due to erosion or cavitations damage.

CFD Analysis

Modeling and flow domain

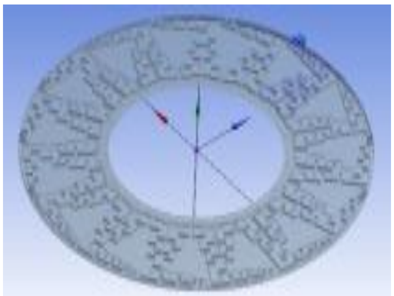

Fig 4: Actual 3D disk Modeling

The geometry model of Tortuous Path of Disk is made in CAD Package Ansys Workbench to model with exact dimensions. It mainly consists of Tortuous Fluid flow path as shown in fig 4. The geometry of Disk is imported to ANSYS ICEM-14.5 for grid generation and for defining the 3-D region and 2-D region

Grid Generation of Disk

The ANSYS ICEM is used for discrimination of domain. The mesh used for flow domain is hexahedral fine mesh for both stationary and rotating domain. A high quality hexahedral unstructured mesh is created with the appropriate y+ value in the boundary layer. This mesh gives minimum skew angle which should not be less than 18° and better maximum aspect ratio. Followings are the steps

a. Importing the Workbench file in ICEM CFD

b. Creating the Parts

c. Creating a Material Point

d. Blocking Strategy

e. Checking the Pre-Mesh Quality Histogram

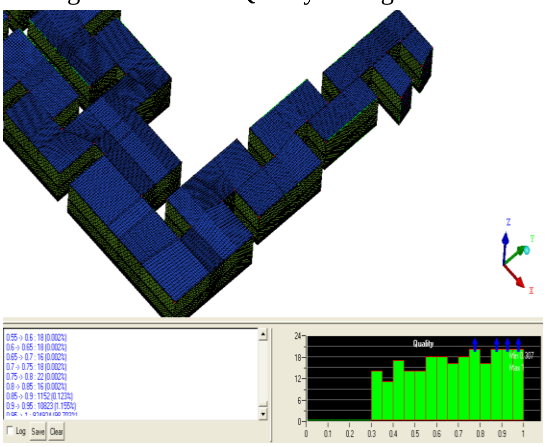

Fig 5: Meshing quality check

Mesh Independence Study

Table 1: Mesh Independence Study

Sr. No	No. of Elements (Lacs)	Pressure Drop(bar)
1	3.5	157.8
2	5	147.35
3	9.5	146.23
4	14	146.1
5	18.5	146.2

The five different hexa meshes are used for checking mesh independence from 3.5 lacs elements to 18-lakh elements. Finally the mesh element 9.5 lacs are finalized, as result. Between 9.5 lacs and 18 lacs is similar and second thing is limitation of computing power following fig shows the Pressure drop Vs No, of Mesh elements.

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Final mesh parameter for disk for a tortuous path

No. of Hexa Elements: 937000
Minimum angle: 36°
Aspect ratio: 1.1
Quality: 0.3

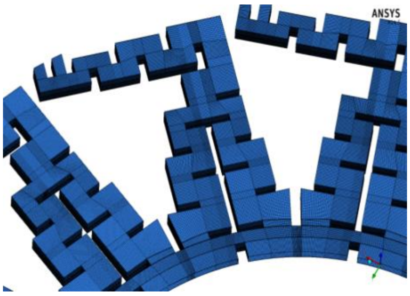

Fig 6: Meshing of Disk (Details view)

Physics of the Simulation in Ansys- Cfx (CFX -PRE)

The Problem is solved using ANSYS CFX-14.5 which is pressure based solver.

The water liquid is used as fluid flowing at inlet temperature 102.5 °C & water vapor at 100 Degree for cavitation Study

1Turbulence model

The SST (Shear Stress Transport) model is used for CFD Analysis.

Cavitation model

To model the Cavitations, the homogeneous model has been used for interphase mass transfer with the Rayleigh Plesset Mode

Boundary conditions

Multiphase Model: Homogenous model

Heat Transfer Model: Isothermal with 102.5 degree C

Turbulence Model: Shear Stress Transport model (SST)

Cavitation Model: Rayleigh Plesset Model with saturation pressure as 1.12 bar

Inlet Boundary Conditions

Bulk Mass Flow rate at Inlet: 0.14208 Kg/s with water volume fraction as 1

Outlet Boundary Conditions

Outlet Static Pressure: 12.34 bar

Solver parameter

Table 2: Simulation Parameters

Parameter	*ANSYS CFX B.C.*
Domain of simulation	Default Domain
Mesh Size	Unstructured 950000
Inlet	Bulk Mass flow rate
Outlet	Static pressure
Interface	Periodic Interface (Rotational)
Turbulence model	SST
Heat Transfer Model	Isothermal
Multiphase Model	Homogenous with Cavitations with Rayleigh Plesset Model
Advection scheme	High resolution

Assumptions in CFD model

Uniform flow at the inlet
Tortuous path wall as smooth wall

Iterative solution (CFX Solver Manager)

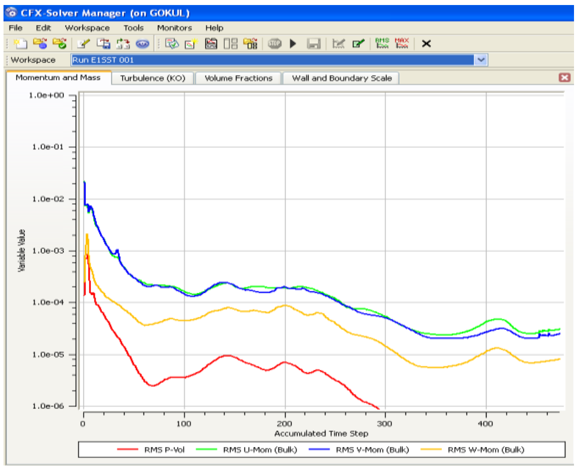

Fig 7: CFX Solver Manager Convergence graph

The CFX pre file (.def) is run in CFX solver which solve the Mass, momentum and energy turbulence & volume fractions equations up to 10^{-4}
After Convergence of the CFX solver results, it creates a result file with extension as .res, which can be visualized in CFD Post

Weir Depth Analysis

Case 1: Tortuous Path without weir

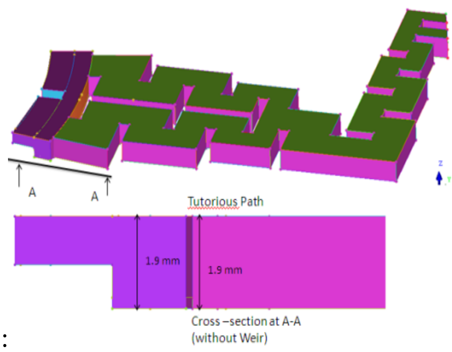

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Fig 8: Disk without weir

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Case 2: Tortuous Path with Weir Depth 1 mm

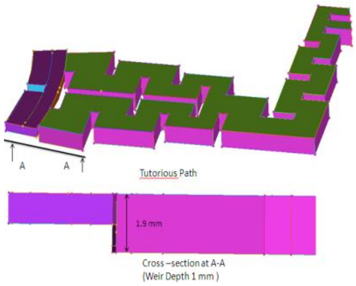

Fig 9: Weir 1 mm depth (From Top)

Case 3: Tortuous Path Weir with Depth 1.24 mm

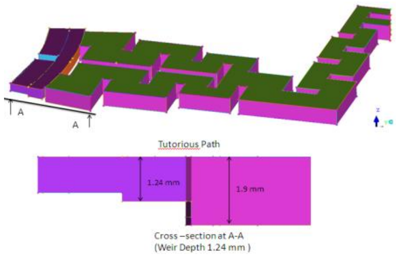

Fig 10: Weir 1.24 mm depth (From Top)

Case 4:Tortuous Path with Weir Depth 1.68 mm

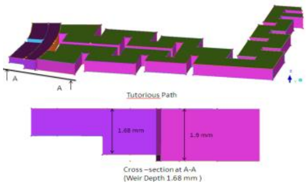

Fig 11: Weir 1.68 mm depth (From Top)

Case 5: Tortuous Path with Weir Depth 2.12 mm

Fig 12: Weir 2.12 mm depth (From Top)

Case 6: Tortuous Path with Weir Depth 2.56 mm

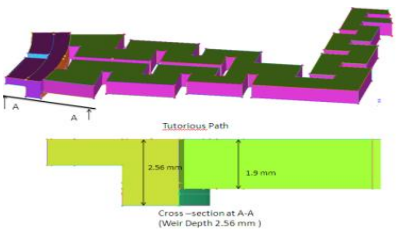

Fig 13: Weir 2.56 mm depth (From Top)

II. RESULTS AND DISCUSSION

Case I: Study of Performance of Tortuous Path without Weir

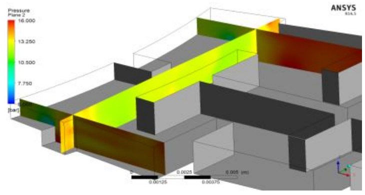

Fig 14: pressure Plot at the weir on a plane

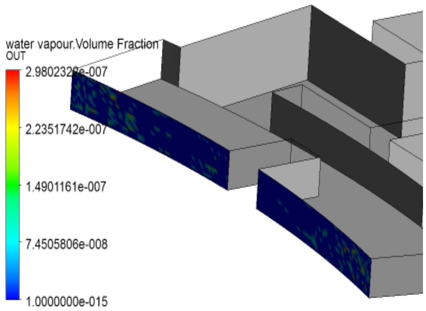

Fig 15: Water Vapor Volume fraction at Exit

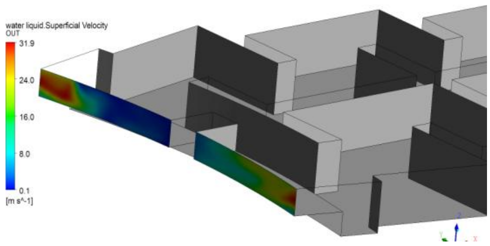

Fig 16: Velocity Plot at the exit

Case II: Cfd Results of Tortuous Path of Weir Depth 1 MM

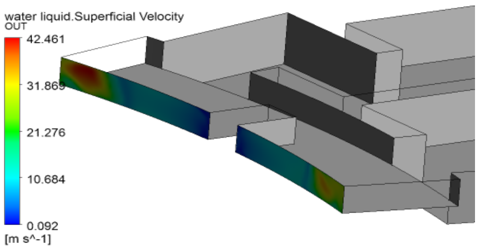

Fig 17 : Velocity Plot at the exit

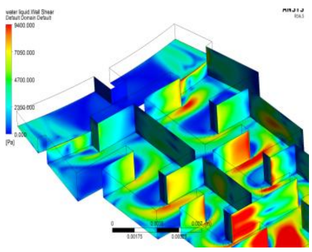

Fig 18: Tortuous path Wall shear at the Weir location

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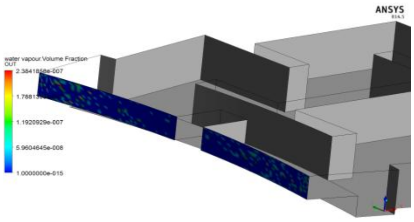

Fig 19: Water Vapor Volume fraction at Exit

Case III: Cfd Results of Tortuous Path of Weir Depth 1.24 Mm

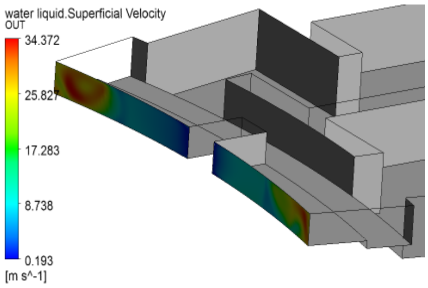

Fig 20: Velocity Plot at the exit

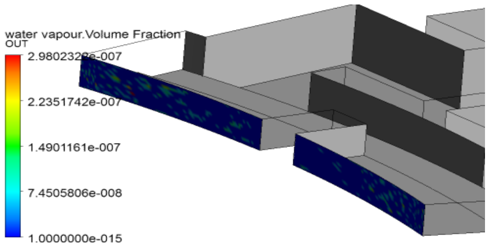

Fig 21: Water Vapor Volume fraction at Exit

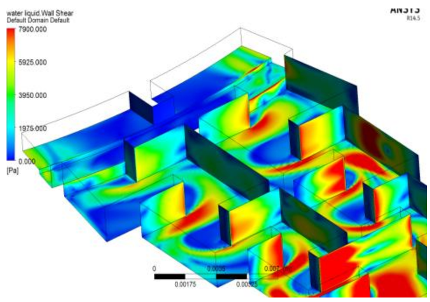

Fig 22: Wall shear at the Weir location

Case IV: Cfd Results of Tortuous Path of Weir Depth 1.68 Mm

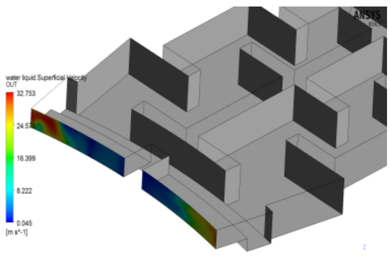

Fig 23: Tortuous Path Velocity Plot at the exit

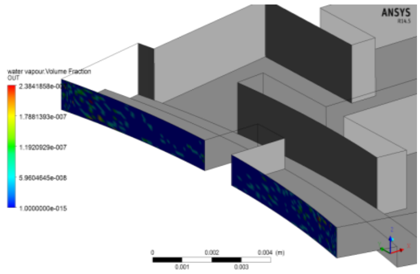

Fig 24: Water Vapor Volume fraction at Exit

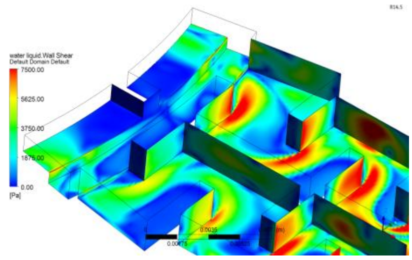

Fig 25: Wall shear at the Weir location

Case V: Cfd Results of Tortuous Path of Weir Depth 2.12 Mm

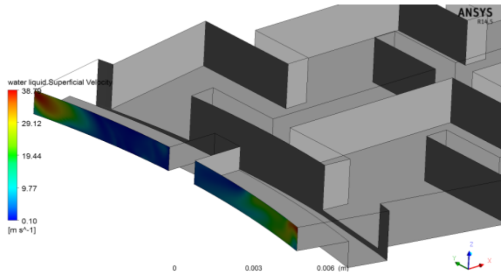

Fig 26: Velocity Plot at the exit

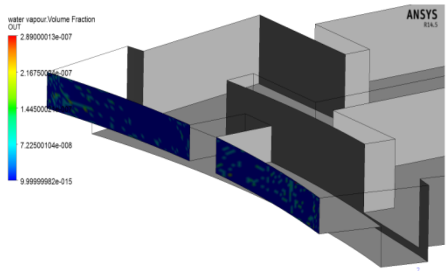

Fig 27: Water Vapor Volume fraction at Exit

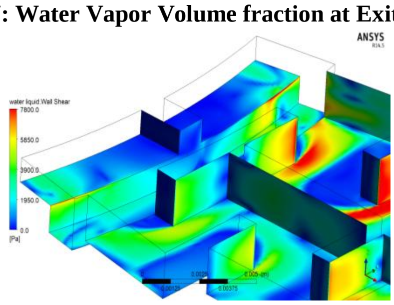

Fig 28: Wall shear at the Weir location

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Case VI: Cfd Results of Tortuous Path of Weir Depth 2.56 Mm

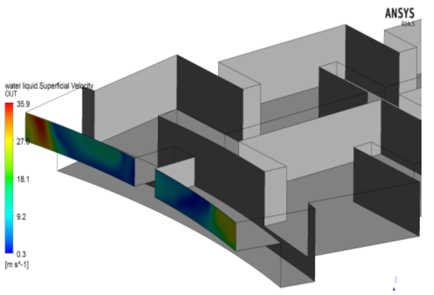

Fig 29: Tortuous Path Velocity Plot at the exit

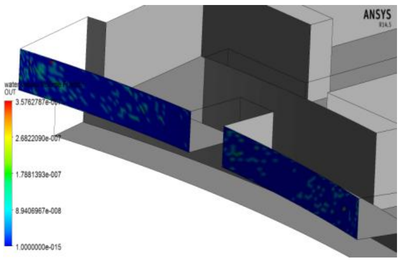

Fig 30: Water Vapor Volume fraction at Exit

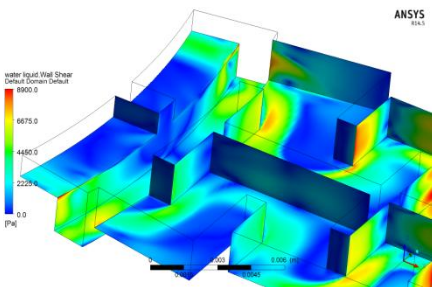

Fig 31(A): Tortuous path Wall shear at the Weir location.

Table 3: Weir Depth & CFD Parameters

Sr. no.	Dimension Cases (Depth)	Pressure drop (Bar)	Max. Velocity at Outlet m/s	Wall Shear at the Weir Pa	Cavitation
1	Weir Depth 1 mm	149.41	42.46	9400	0.2384
2	Weir Depth 1.24 mm	147.96	34.37	7900	0.298
3	Weir Depth 1.68 mm	146.23	32.75	7500	0.238
4	Without Weir 1.9mm	152.49	31.9	10400	0.298
5	Weir Depth 2.12 mm	152.55	38.79	7800	0.289
6	Weir Depth 2.56 mm	155.82	35.89	8900	0.357

From CFD analysis of above 6 cases the table has been tabulated for Pressure drop, Max velocity at Outlet, Wall Shear at the Weir wall & Cavitation in terms of water vapor Volume Fraction.

Table show the values of weir depth along with pressure drop, max velocity at out let of weir, wall shear at the weir, cavitation at weir.

From above values we can draw graphs to find out the relation between weir depth and pressure drop, exit velocity and cavitation at weir.

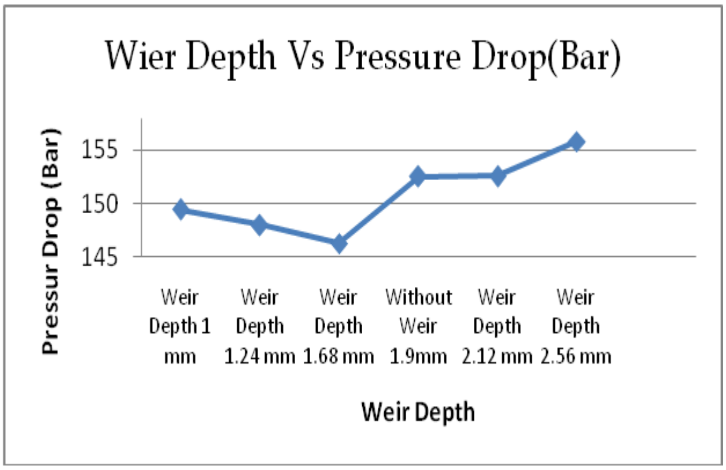

Fig 31(B): Pressure Drop Vs Weir Depth

From Fig 31when Pressure drop is 149.41 bar for Weir Depth of 1 mm, as weir depth goes on increasing the pressure drop reduces due to reducing area in case of 1.24 weir depth and 1.68 mm weir depth. But at weir depth 1.9 mm the pressure drop increases as area increases. Also flow separation, flow turbulence factors comes in picture.

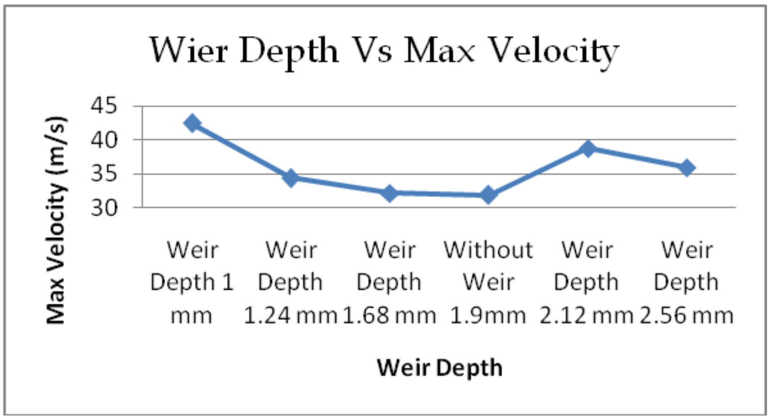

Fig 32: Max. Velocity at Outlet Vs Weir Depth

From fig 32 max. Velocity at exit should be 30 m/s in ideal case to avoid erosion, vibration & pitting etc in Valve which is our objective. Graph plotted shows how velocity varies along with various weir depths.

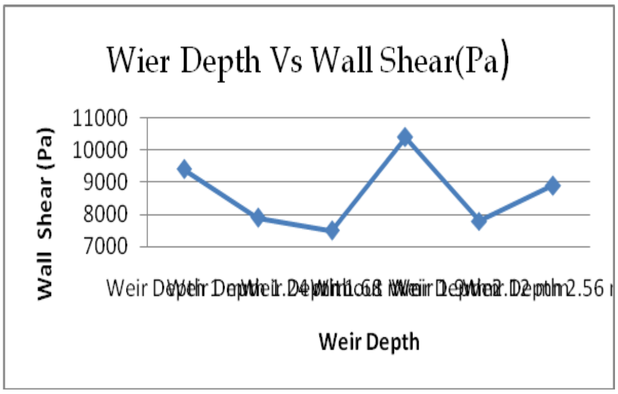

Fig 33: Wall Shear Vs Weir Depth

Wall Shear stress is directly proportional to the shear stress developed in the material from Fig 33 it can be observed that the minimum shear at the weir depth 1.68 mm is 7500 Pa. As the weir depth goes on decreasing the shear value goes on increasing also as weir depth goes on increasing the Wall shear goes on increasing.

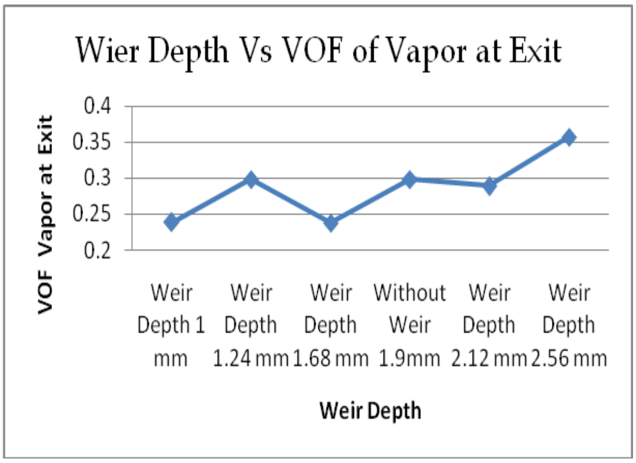

Fig 34: VOF water Vapor at Outlet Vs Weir Depth

From Fig 34, it can be observe that the cavitation is minimum at the weir depth 1.68 mm, still the value of water vapor volume fraction is very negligible, at weir depth 1.68 mm it shows minimum.

III. CONCLUSION

In conclusion, severe service applications must be treated differently from general service control valves. In addition, different severe service applications have their own specific set of requirements for high performance. The performance limits of a control valve in such services is clearly a function of the technologies it features

A proven high pressure pump recirculation valve design has been described. The valve performs the necessary dual functions of controlling fluid velocities during the pressure letdown and provides tight shutoff when closed. The fluid velocity is controlled via a 24 stage tortuous vector disk. The weir in the vector disk assures a uniform sheet flow of fluid entering the plug cavity and a reduced average velocity at the weir exit. This eliminates any chance for high local velocity to cause damage to the trim parts. The calculated and computational investigation provided a satisfactory tool to capture the complex velocity, pressure distribution pattern in vector disk, still there is slight variation in calculated and the CFD results. From above study & CFD Analysis & fit can found for Weir Depth of 1.68 the Max velocity is 32.15 m/s which very near to the Actual ideal value which is 30 m/s.

For Weir depth of 1.68 mm, the pressure drop is minimum s well as the wall shear value is minimum compare to the other cases. There is no cavitation found in the tortuous path, still here is very minute cavitation found at the exit & minimum cavitation found for the weir Depth of 1.68 mm.

Hence the Disk has been manufactured with the weir depth of 1.68 mm & used in the control valve & the results in actual condition found very satisfactory.

The pressure drop across a restriction is proportional to the square of the average velocity. The proportionality constant is a function of the fluid density and the nature of the restriction. Ignoring the minor differences between various restrictions the influence of the number of pressure loss stages on velocity can be established for comparative purposes.

IV. FUTURE SCOPE

The results obtained from CFD analysis can be used for FEA analysis to determine the stress concentration at weir exit. By fine tuning the preprocessor and boundary conditions we can reduces the variation in experimental and the CFD results.

The work on this project is by no means complete Designing and performance improvement of valve can go a long way. The further studies in control valve are is to identify the noise level & vibration by FEA method as well as metallurgical study for more performance improvements.

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