Design Optimization of Splitter, Venturi Valve and Charlotte Valve Using CFD

Sudarshan B Ghotekar, Ashish Kinge, Ajay Ballewar, Amit Belvekar, Yogesh Bhalerao

Detailed Affiliations of Authors:

Sudarshan B Ghotekar
School of Mechanical & Civil Engineering,
MIT Academy of Engineering, Alandi, Pune, India

Ashish Kinge
School of Mechanical & Civil Engineering,
MIT Academy of Engineering, Alandi, Pune, India

Ajay Ballewar
School of Mechanical & Civil Engineering,
MIT Academy of Engineering, Alandi, Pune, India

Amit Belvekar
School of Mechanical & Civil Engineering,
MIT Academy of Engineering, Alandi, Pune, India

Yogesh Bhalerao
Mechanical Engineering and Design,
University of East Anglia, Norwich, UK

Abstract Ventilator valves are external attachments that are used to deliver oxygen at fixed concentrations for patients having acute respiratory distress or suffering from COVID-19. Three-dimensional printing technology can be used via a filament extrusion system or a polymer-laser powder bed fusion process to print single-use valve sets, and 3D printers can design the different elements of the valve using biomaterials such as polyamide and Poly sulfone, polycarbonate, silicone rubber, and stainless steel. Furthermore, these disposable valves eliminate time consuming sterilization.

This manuscript deals with CFD simulations and design modifications in Venturi Valve, Splitter and Charlotte Valve based on basic parameters like flow quality.

Keywords: CFD, Covid 19, Venturi valve, Splitter, Charlotte Valve

Introduction

The ongoing Covid 19 pandemic had caused surge in number of patients, that too in terms of waves of infections causing strain on healthcare system which has not adapted to deal for treating multiple patients in the limited supply of medical equipment such as ventilators for ARDS.

In the recent months of the pandemic the world has seen slowdown in the manufacturing and industrial sector which made it hard for manufacturing the parts conventionally with mold building, machining, and injection molding for plastic products. While 3D printing has emerged as the revolutionary technology for prototyping, which can be also optimized for the mass production of the plastic printable products. Many private institutions carried out their independent projects involving the concepts of optimizing the use of ventilators in the period of shortage and urgency.

Ventilator as a whole setup is a costly equipment to manufacture as well as to operate, which reduces the supply for those in market because of economic reasons, while many researchers have been developing and improving the technologies which involves making of custom parts and using them directly. Parts like Splitter, venturi valve and charlotte valve have been developed and are getting registered for legal medical use.

Researchers focusing on the increasing the capacity of ventilator like Lorenzo [2008] had conducted an experiment of ventilating four on a single full featured ventilator for 12 hours, a similar article by Grant [2020] describes ventilating two simulation lungs using Y splitter, also demonstrating the change in compliance of one lung has no effect on other. Lewith [2020] had explained concepts and mechanism of respiration like tidal volume, compliance, peak Inspiratory pressure (PIP), Positive end expiratory Pressure (PEEP). Jeremy [2020] in an experiment demonstrated on an artificial lung aimed to provide inspiratory pressure with the help of low cost and effective custom designed device helps provide the response of the ventilator data for the study in this paper.

Researchers have also studied the application of venturi air flow sensor to be used for human pulmonary ventilation measurement. Praneel [2018] given a simple design, and ease of maintenance, the venturi method provides a potentially inexpensive, reliable alternative to common methods that are prone to damage and relatively expensive to purchase and maintain. Researchers from university of Leeds, Leeds Teaching Hospital NHS Trust (LTHT) and Bradford Teaching Hospitals NHS Foundation Trust have been working to repurpose existing ventilation systems. This venturi valve works by having one end connected to the oxygen supply by a patient’s bed and the other end connected to the tubing that goes to the person’s oxygen mask.

Then there's the Charlotte valve designed by an Italian team of Engineers for converting a snorkeling mask into a mask for non-invasive type ventilator applications. They have printed it and also claim to have tested it on a patient. The valve is comparatively new to the world and is yet to be certified as medically safe but the idea to convert the snorkeling mask into ventilator mask is very much serviceable and potentially an aid for this emergency. That’s why it was also included in the study.

In the present study, CFD analysis of different components of the ventilator system has been carried out aimed to determine the flow characteristics, later the designs had been modified to minimize the turbulent losses in the system. CFD analysis of the available design has been done which are available from many 3D printing institutions working on providing the modification idea for the ventilator due to the current pandemic. The splitter is use to split the flow from the ventilator to multiple patients. The charlotte valve geometry was simulated for transient conditions. There were scopes for improvement in the valve geometry and have been successfully made and demonstrated in this paper.

Methodology

Computational Fluid Dynamics is an effective method for solving complex fluid problems with iterative solver, which can perform steady as well as transient simulations. The analysis is done with the help of ANSYS Fluent 19.1.

Splitter

Design: The splitter has many designs; the model 1 is a planar splitter with inner and outer diameter 15 mm and 22 mm respectively. The Model 2 has 22 mm attachment. Model 1 and Model 2 outlet can be fitted directly in ventilator piping, while the inlet geometry of Model 2 is required to be attached with a flexible plastic coupling.

Boundary conditions and analysis settings: The data had been obtained for the pressure and mass flow rate for the ventilator generated capacity, which is obtained for PIP, PEEP applied by ventilator Lorenzo [2008] Grant [2020] Jeremy [2020]. The data is extracted from the ventilator generated graphs and the inspiratory time is set to as 1 s. The compliance condition of 20 mL/ cm H20 with PIP as 20 cm H2O and PEEP as 5 cm H2O with surface roughness of 0.4 mm. The Table 1 shows the transient flow conditions for two-way splitter. The CFD model used here if k omega SST which is ideal for flow across closed geometry having boundary interaction.

Table 1 Transient data of Inspiration

		one person	two person
	L/min	kg/s	kg/s
time	flow	m flow	m flow
0	0	0.000000	0.000000
0.1	75	0.001531	0.003063
0.2	64	0.001307	0.002613
0.3	49	0.001000	0.002001
0.4	35	0.000715	0.001429
0.5	22	0.000449	0.000898
0.6	14	0.000286	0.000572
0.7	9	0.000184	0.000368
0.8	6	0.000123	0.000245
0.9	6	0.000123	0.000245
1	5	0.000102	0.000204

Modified Geometry: Based on the analysis of streamlines, the geometry is modified to get streamlined with the flow, to make flow less turbulent. For Model 1, the edge where the flow is getting divide is made longer and blunter at corner, to divide the flow effectively reducing the backflows across adjacent cells. Modified geometry can be seen in Table 2. For the Model 2 instead of sharp triangular corners as considered in original design, a globular geometry has been tried, also the connecting edges has been highly filleted to ensure smooth flow. The globular geometry allows the flow to circulate freely without stagnating near the corners.

Venturi valve

Design: There are three main types of venturi valve designs available depending on the trajectory of the nozzle. The first type is conventional one with cone like structure having one end connected to the oxygen supply and other end connected to the corrugated tube. Near the inlet there are ports to allow atmospheric air to enter in order to dilute the 100% oxygen supply so that patient does not get neat oxygen. Other types developed include a traditional venturi like structure having converging and diverging sections. This type has two oxygen inlets, one from the side and one in the pathway. Atmospheric inlet is around the main inlet. The same model has another variant having only one oxygen inlet from the side and atmospheric inlet in the pathway. Italian engineers have devised an innovative design like the first type with an additional bleed valve in the design.

Boundary Conditions: The venturi valve has been simulated for obtaining the suction at the inlet which is open to atmosphere and the specific quantity of oxygen has been supplied through the small tube and nozzle in the throat section of the venturi valve geometry. The air inlet and outlet were kept as open to atmosphere without and fluid velocity. The oxygen inlet is given from the small tube, delivering 2 lpm and 4 lpm of oxygen, for which the models has been simulated differently. The surface roughness tolerance is kept as 0.4 mm for approximately reflecting 3D printed surface property.

Charlotte valve

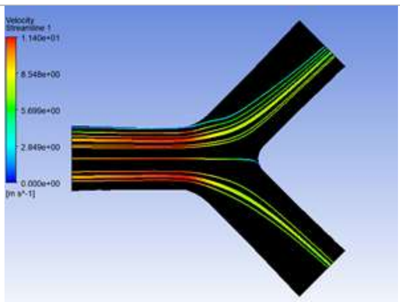
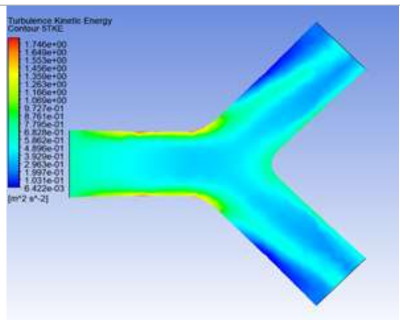
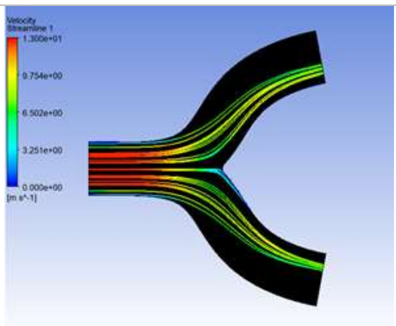
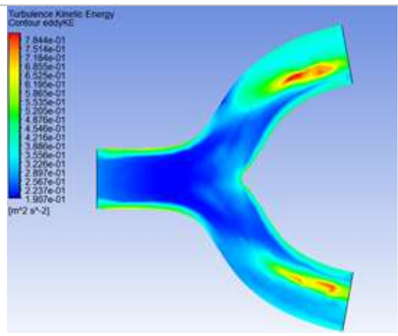
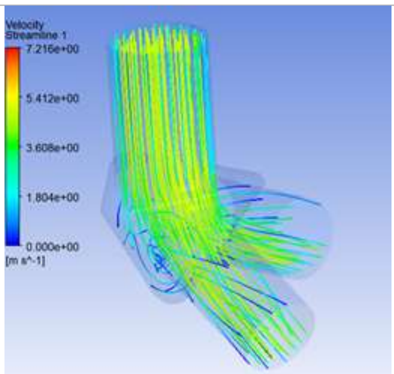
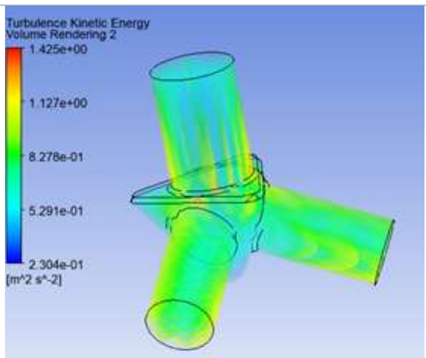
The charlotte valve geometry obtained from the Isinnova team was first analyzed for non-invasive same transient conditions of a normal breathing mass as that used for the splitter. It showed turbulence due to two sharp 90 deg turns as shown in Fig. 4 a then using CATIA the design is modified to make the flow streamlined.

Results

Splitter In the results the streamline and turbulent kinetic energy of fluid has been analyzed which helps to determine the location of possible eddies formation in the flow. The effect of the direction change can on the flow can be seen in comparison with both original and updated designs.

Venturi valve The CFD results has been visualized in Table 3 and Table 4 showing streamlines and Volume Fraction. Table 5 summarizes the results obtained for original and modified design while changing oxygen flow rates.

Table 2 Ventilator splitter CFD results

Model	Streamlines	Turbulent kinetic energy contour
 Model 1	 **Fig. 1 a** Model 1 (Original)	 **Fig. 1 b** Model 1 (Original)
 Model 1 Modified	 **Fig. 1 c** Model 1 (Modified)	 **Fig. 1 d** Model 1 (Modified)
 Model 2	 **Fig. 1 e** Model 2 (Original)	 **Fig. 1 f** Model 2 (Original)

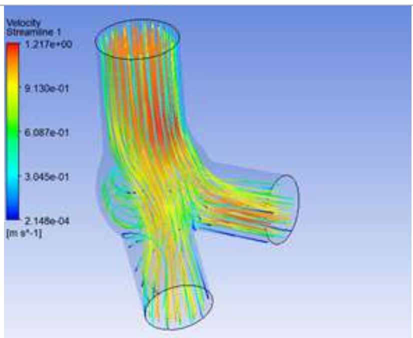
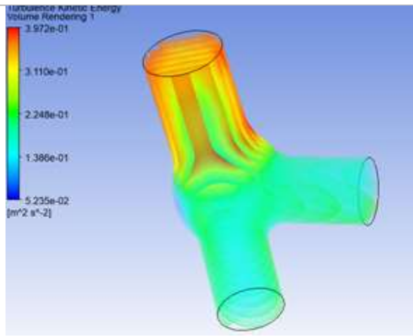
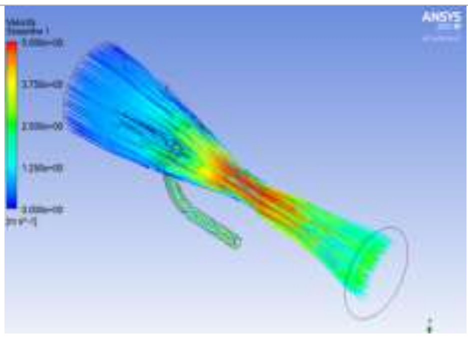
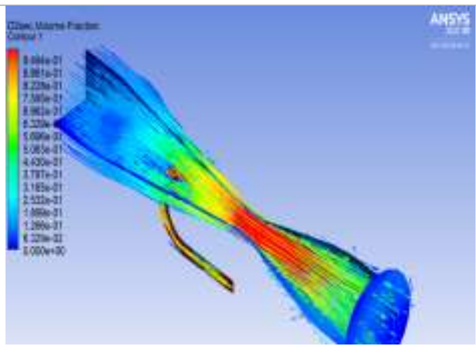
 Model 2 modified	 **Fig. 1 g** Model 2 (Modified)	 **Fig. 1 h** Model 2 (Modified)

Table 3 Venturi Valve CFD results for 2 lpm

Model	Streamlines	Volume fraction and velocity vectors
 Venturi valve 1	 **Fig. 2 a** Venturi valve 1 streamlines	 **Fig. 2 b** Venturi valve 1 volume fraction

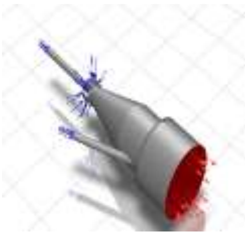
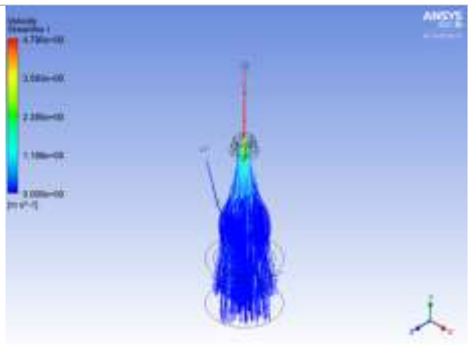
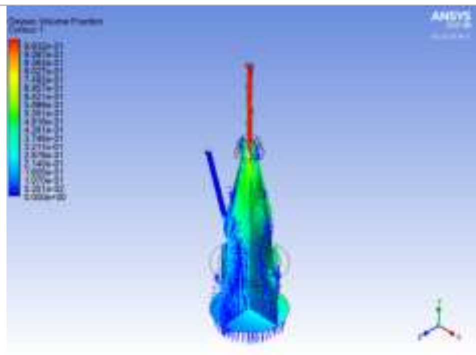
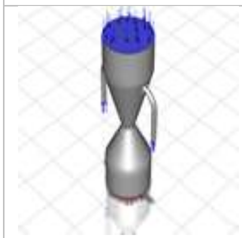
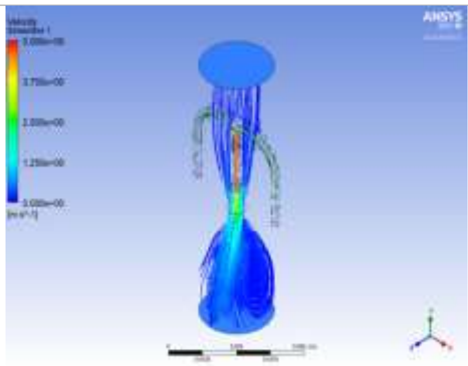
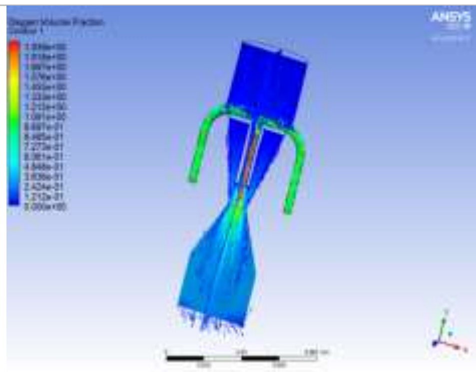
 Venturi valve 2	 **Fig. 2 c** Venturi valve 2 streamlines	 **Fig. 2 d** Venturi valve 2 volume fraction
 Venturi valve 3	 **Fig. 2 e** Venturi valve 3 streamlines	 **Fig. 2 f** Venturi valve 3 volume fraction

Table 4 Venturi Valve CFD Results for 4 lpm

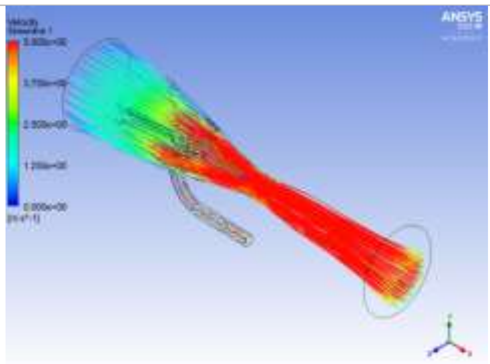
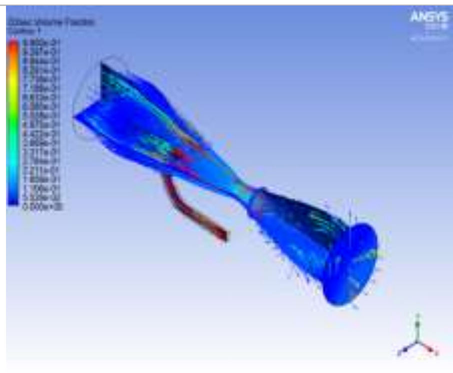
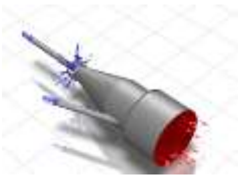
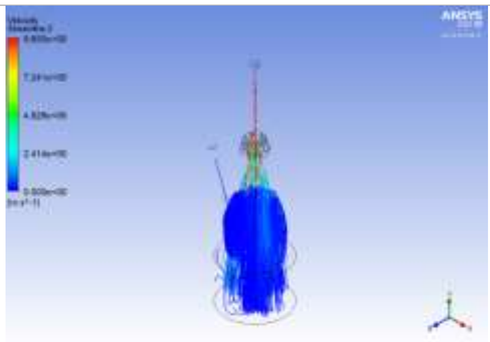
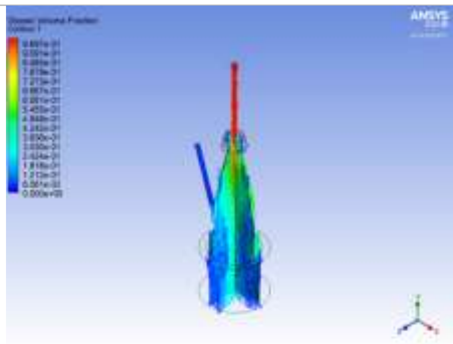
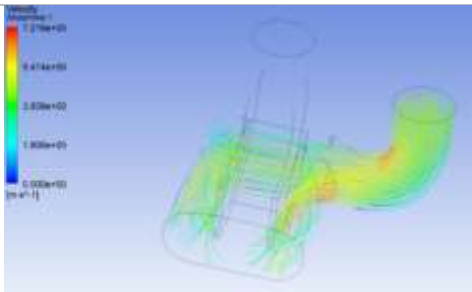
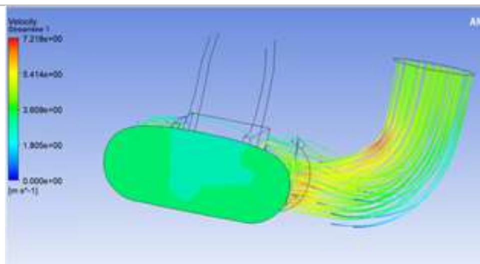
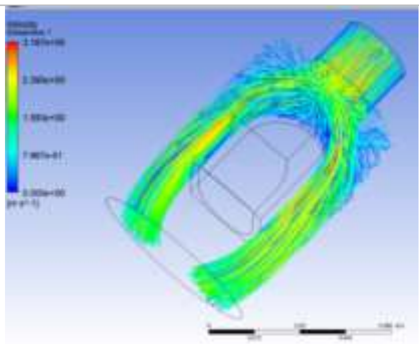
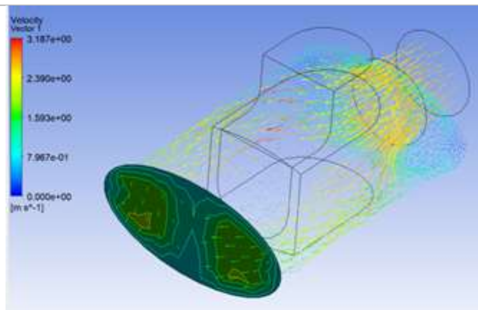
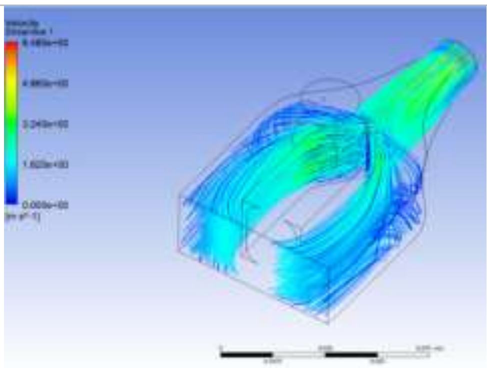
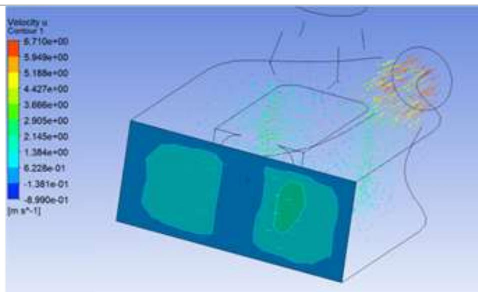
Model	**Streamline flow**	**Volume fraction**
 Venturi Valve 1	 **Fig. 3 a** Venturi valve 1 streamlines	 **Fig. 3 b** Venturi valve 1 volume fraction
 Venturi Valve 2	 **Fig. 3 c** Venturi valve 2 streamlines	 **Fig. 3 d** Venturi valve 2 volume fraction

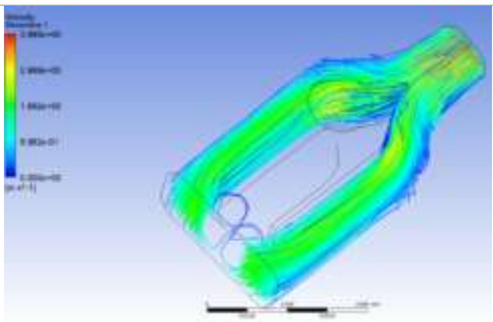
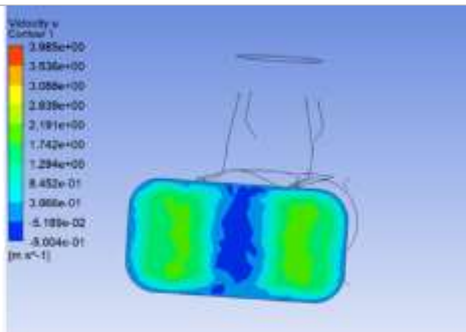
Table 5: Venturi Valve Results of oxygen percentage and outlet mass flow

Model	2 lpm		4 lpm	
	Oxygen %	Mass flow outlet (lpm)	Oxygen %	Mass flow outlet (lpm)
Venturi Valve 1	24	55	23	56
Venturi Valve 2	40	3.58	36	7.21
Venturi Valve 3	33	16	-	-

Charlotte Valve The charlotte valve design obtained from Isinnova Engineers as shown in Table 6 (Model 1) has some imperfections which led to these iterations. The part had some inward facing dents on the inside; the particular reason for this circumstance is merging of two curve surfaces. In the second model, i.e. Table 6 (Model 2) those dents have been taken care of along with making the flow streamlined. The streamlined flow is desirable so that moist air doesn't condense in the valve. Hence as shown in Fig. 4 g, the valve is flowing full and the outlet velocity is also higher than others along with least turbulence

Table 6 Charlotte valve CFD results

Sr. No.	Model	Streamlines	Velocity Contour at Exit
1	 Model 1	 **Fig. 4 a** Model 1 Streamlines	 **Fig. 4 b** Model 1 Velocity Contour (exit) with streamlines from PEEP connector
2	 Model 2	 **Fig. 4 c** Model 2 Streamlines	 **Fig. 4 d** Model 2 Velocity Contour (exit) with vectors from inlet
3	 Model 3	 **Fig. 4 e** Model 3 Streamlines	 **Fig. 4 f** Model 3 Velocity Contour (exit) with vectors from inlet

4.	 Model 4	 **Fig. 4 g** Model 4 Streamlines	 **Fig. 4 h** Model 4 Velocity Contour (exit)

Conclusion

Finally, we have come up with a 3D printable model of all the three valves which can replace the already existing valves without any difficulty and are more efficient. They also can easily be modified for custom requirements.

For the splitter, two models have been modified and optimized to their respective better versions. Turbulence zone formed between the high velocity streamlined flow and the low velocity boundary layer flow near the outer wall has been dealt with using curvature implementation. For Model 2, the turbulent kinetic energy has been found to be less and flow to be more organized than model 1. The acceptance of globular geometry instead of pyramidal has minimized the turbulence further.

The venturi valves in operation have particular combination of flow rate (lpm) and Fi02 (in %). The output flow rate depends on the diameter of the nozzle, suction pressure at vena contracta and length of the pipe. By varying the above parameters, we are able to obtain different combinations of flow rate and Fi02. During the analysis, we have also discovered the dependence of various parameters on output. Finally, we have successfully achieved a 3D printable streamline designs for venturi valve.

The charlotte valve needs to be streamlined which is successfully achieved at the end of the iterations and losses have been reduced by 3 to 4 percent.

3D printing technology has already been integrated in the medical domain but low-cost desktop 3D printers have fewer quality approvals. So, this research is pre-eminent for hospitals that are yet to implement 3D printing facilities.

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