Cavity Sprayer Flow optimization for Medical devices Industry

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Abstract: Globally, in Otolaryngology industry, Sinusitis is one of the most common diseases related to nose. Sinusitis is caused when the cilia fail to move the mucus resulting sinus tissue infection that leads to blockage of the sinuses. All the sinusitis cannot be cured through drugs. Some cases may require surgery. When a sinus cavity is subjected to a nasal endoscopic surgical procedure, one of the preferred methods, to avoid infection after surgery is to provide a degradable polymer-based medicinal coating on the sinus cavity through a sprayer. The sprayer helps in keeping the surgical wounds moist, disinfected, and protected from seepage of internal fluids to ensure rapid healing. The main challenge in the sprayer process is to ensure that the sprayer movement inside the sinus cavity to fully coat the walls should be minimal. As part of product development, Finite Element Analysis (FEA) techniques are used as design direction tools for quick turnaround time in meeting competitive market needs. To optimize the design parameters and reduce the design cycle time, COMSOL multiphysics is used as a numerical solver.

Keywords: Sprayer, optimization, mass flow rate, and angle of spray.

1. Introduction

In general, a sprayer can be used to mix four phases of medication fluids that react to form a single phase. This will be sprayed through the nozzle on to the sinus cavity by means of pressurized air supplied from an external source.

In this study, a typical multi-hole sprayer is used for the fluid flow simulation. This sprayer is intended to optimize the mass flow rate and angle of spray at each hole to cover the desired sinus cavity. In order to simplify the physics, only the thick medication fluid was considered and assumed to be laminar in nature. Design optimization were carried out considering different design variable of sprayer and giving inputs as dynamic viscosity of the fluid, inlet and outlet pressure. A flow simulation was carried out using COMSOL software and Minitab for Design of Experiment (DoE) principle.

This paper does not deal with the chemical reaction between fluids and turbulent effect of air with fluids.

2. Mathematical Model

In this study, nozzle model **Figure 1** was meshed with linear tetrahedral elements using COMSOL. To simplify the problem, fluid part of the nozzle was taken for analysis and quarter-symmetry model was used to take advantage of the symmetry.

The basic steps involved in this study are:

- Setting up initial physics in FEA for the simplified model and correlation of FEA results with physical testing results.
- Identification of critical influencing factor through Sensitivity Study using DOE approach.
- Simulation process development for sprayer in building a numerical model of the flow domain, capable of creating a transfer function to evaluate the existing design and new design (with similar technology and similar sprayer design).

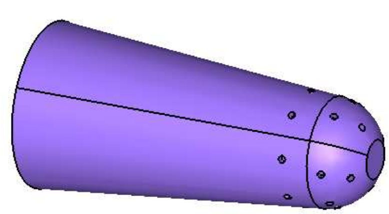


Figure 1. Nozzle

2.1 Governing Equations

The basic equations that are used to identify the nature of flow are as follows:

2.1.1 Bernoulli's Equation

$$\frac{v^2}{2} + gz + \frac{p}{\rho} = constant$$

Where:

v is the fluid flow speed at a point on a streamline

g is the acceleration due to gravity

z is the elevation of the point above a reference plane

ρ is the density of the fluid

2.1.2 Reynolds Number

$$Re = \frac{\rho V D}{\mu}$$

Where:

ρ is the density of the fluid

V is the velocity of the fluid

D is the diameter of nozzle

μ is the dynamic viscosity

2.2 Theoretical Calculations

Given data

Inlet pressure (p_1) = 0.184 MPa
Inlet Velocity (v_1) = 0.15 m/s
Outlet Pressure (p_2) = 0.1MPa

Outlet Velocity (v_2) = $\sqrt{\left(\frac{{V_1}^2}{2} + \frac{P_1}{\rho} - \frac{P_2}{\rho}\right) * 2}$
= 13.37 m/s

Density of the fluid (ρ) = 940 kg/m^3
Inlet diameter = 0 .005m
Outlet diameter = 0 .003m

Reynolds number at inlet = 1.08
Reynolds number at outlet = 58.03

Reynolds numbers at both the inlet and the outlet of the sprayer indicate that the flow is well within the laminar region. It should be noted that the effective area of the cross-section of outlet is much more than that is considered (due to the presence of multiple outlets). Therefore, the Reynolds number at the outlet should be much lower than the value that is calculated. Therefore, the flow can be considered to be laminar throughout.

2.3 Sensitivity Study through DoE

The sensitivity study is done to understand the effect of various design parameters of the sprayer on the flow rate and angle of spray of the fluid through the nozzle. Sensitivity analysis will help in determining the contribution of each design parameter that influences the responses of flow rate and angle of spray. The goal is to develop a relationship between the different design parameters and the responses in the form of a transfer function. Typical DoE table used for the study is shown in **Table-1**.

	Angle of Hole (°)			Hole position(°)			Number of Holes		
Concept	Min	Normal	Max	Min	Normal	Max	Min	Normal	Max
1	0			0			16		
2			35	0			16		
3	0					15	16		
4			35			15	16		
5	0			0					24
6			35	0					24
7	0					15			24
8			35			15			24
9		22.5			7.5			20	

Table-1: Typical DoE table

3. Use of COMSOL Multiphysics

In this study, we used chemical engineering module - 3D Momentum transport - Laminar flow - Non Newtonian flow - Steady state application mode.

3.1 Meshing

In this study, the work was accomplished exclusively with default mesh settings. Iterative trials were performed to determine the element size and number of elements to achieve equilibrium condition in mass flow rate.

3.2 Boundary Conditions

The inner wall of the nozzle that interacts with fluid was modeled as the rigid wall. Pressure boundary condition was applied on the inlet and outlet of the nozzle. Symmetry boundary condition was applied on the faces shown in **Figure 2**. Viscosity of the fluid was defined as the function of the shear rate.

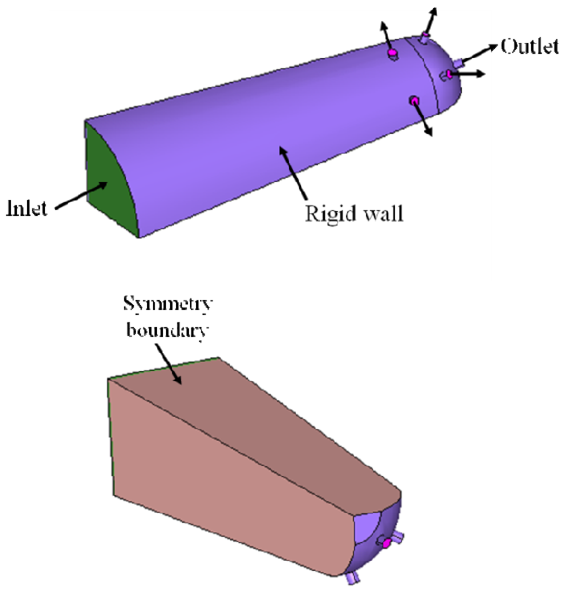


Figure 2. Boundary condition details

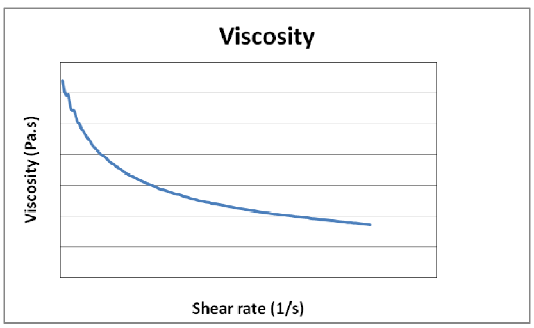


Figure 3. Typical viscosity graph for shear thinning fluid

3.3 Solver Parameters

Settings used for the study:

Solver mode : Direct (PARDISO)
Matrix symmetry : Nonsymmetric

In linear solver settings, the tolerance values are adjusted to ease the convergence of the simulation.

3.4 Expressions

COMSOL leverages to the user to write expressions that are required to achieve the expected output. In this study, in order to measure the angle of spray with respect to the hole surface normal and mass flow rate, the following expressions are used:

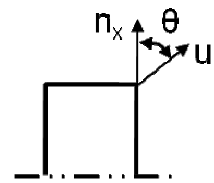


Figure 4. Angle between surface normal and velocity component

$$Angle, \theta = (acos(abs((\frac{u}{\sqrt{(u^2+v^2+w^2)}} * \frac{n_x}{\sqrt{({n_x}^2+{n_y}^2+{n_z}^2)}}) + (\frac{v}{\sqrt{(u^2+v^2+w^2)}} * \frac{n_y}{\sqrt{({n_x}^2+{n_y}^2+{n_z}^2)}}) + (\frac{w}{\sqrt{(u^2+v^2+w^2)}} * \frac{n_z}{\sqrt{({n_x}^2+{n_y}^2+{n_z}^2)}}))))$$

Where:
n_x, n_y, and n_z are normal vectors to the hole surface in X, Y, and Z directions respectively.
u, v, and w are velocity components in X, Y, and Z directions respectively.

Mass flow rate = U_Chns*rho*Area

Where:
U_Chns is the velocity of the fluid, and
rho is the density of the fluid
Area is the hole area

4. Results and Discussions

A typical mass flow rate and angle of spray plot of the nozzle hole are shown in **Figure-5** and **Figure-6** respectively. The mass flow - arrow plot and velocity stream line are shown in the **Figure-7** and **Figure-8** respectively.

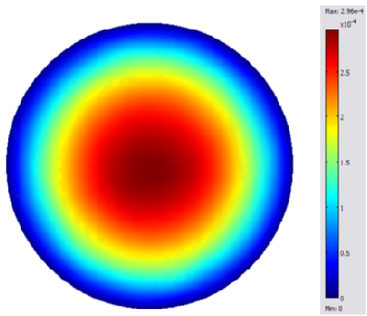


Figure 5. Mass flow rate plot

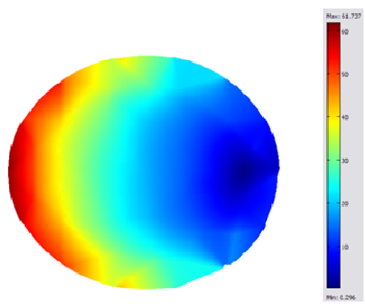


Figure 6. Angle of spray plot

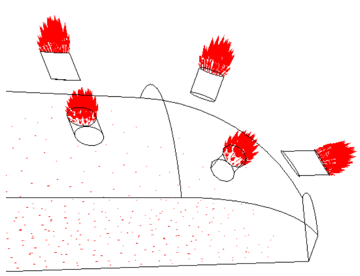


Figure 7. Mass flow rate arrow plot

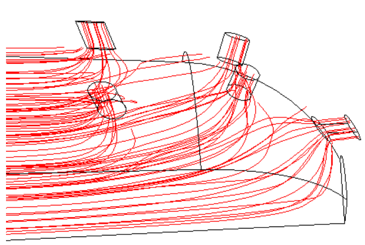


Figure 8. Velocity streamline plot

The results summary for different configurations is shown in the **Table -2**.

Description		Hole-A1	Hole-A2	Hole-B1	Hole-B2	Hole-C1	Total mass flow rate of nozzle (kg/s)
Concept-1	Total mass flow rate (kg/s)	1.258E-03	1.261E-03	1.179E-03	1.176E-03	NA	4.874E-03
	Max. spray angle (deg)	43.25	42.41	35.24	35.15	NA	NA
Concept-4	Total mass flow rate (kg/s)	1.263E-03	1.260E-03	1.188E-03	1.175E-03	NA	4.886E-03
	Max. spray angle (deg)	45.01	43.48	35.66	34.81	NA	NA
Concept-6	Total mass flow rate (kg/s)	1.372E-03	1.373E-03	1.176E-03	1.184E-03	1.427E-03	6.533E-03
	Max. spray angle (deg)	61.63	61.74	32.93	33.55	62.34	NA
Concept-8	Total mass flow rate (kg/s)	1.363E-03	1.373E-03	1.194E-03	1.203E-03	1.203E-03	6.337E-03
	Max. spray angle (deg)	64.31	62.94	32.65	33.3	32.83	NA
Concept-9	Total mass flow rate (kg/s)	1.246E-03	1.266E-03	1.172E-03	1.174E-03	1.426E-03	6.283E-03
	Max. spray angle (deg)	44.28	43.52	35.73	34.77	62.43	NA

Table 2: Result comparison

From **Table-2** we could clearly see that the total mass flow rate of the nozzle increases with increasing number of holes and increasing number of holes does not affect the individual hole mass flow rate significantly.

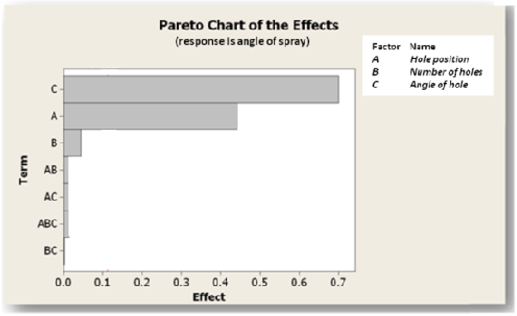
For better wound management, the maximum angle of spray is a prime response. This is achieved by having holes at a critical inclination with respect to the surface. From numerical studies of various concepts with combination of influencing parameters, design directions suggested.

4.1 Response Analysis and Transfer Function: Optimization

Response Optimization was performed using Minitab, which provides us with an optimal solution for the input design parameter combinations and optimization plot. The optimization plot is interactive and can adjust the input variable settings on the plot to search for more desirable solutions. From the response optimizer, the optimized design parameter was arrived for the required angle of spray and flow rate.

The response optimizer or Pareto chart plot provides the information on percentage influence of each design parameter for the response variable (angle of spray). With this information a "Transfer Function" was written for the required angle of spray.

Transfer function = 58.4 (C) + 37.6 (A) + 4 (B)



Factors	Influence on Angle of spray
Hole position (A)	37.6%
Number of holes (B)	4.0%
Angle of hole(C)	58.4%

Figure 9. Pareto chart for angle of spray

5. Benefits Summary

Usage of COMSOL has specifically reduced the turnaround time due to its intuitive and transparent architecture, adaptive meshing capability that relieves the analyst from the hassle of manual meshing, and providing flexibility of enter pre-processing parameters and extract post-processing data in the form of powerful expressions. This approach taken by COMSOL architecture has enabled us to easily play around with the problem, effortlessly extract the desired results, and arrive at well-informed engineering decisions.

6. Challenges

With a constant drive for product innovation, cost, and weight reduction, the medical industry is highly competitive with the challenge of continuously updating products in a very short design cycle. Reliability is one of the major challenges for medical products. The principal challenge in terms of FEA was to arrive at the proper combination of material property inputs, boundary conditions, mesh density, solver selection, and solver parameters to ensure solution convergence.

7. Conclusion

In this study, COMSOL along with Minitab has been used to achieve an optimized fluid flow through nozzle. Further study on flexible nozzles for certain endoscopic wound management requirements can be performed because of the versatility of COMSOL with multiphysics capability.

8. Acknowledgements

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9. References

COMSOL Multiphysics Help Manual