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Design optimization of fluid dispersion systems with value engineering and simulation

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Abstract. A key goal of engineers working on industrial fluid management systems is to balance cost and performance. This research presents a methodology for redesign of a liquid dispersion unit using value engineering (VE) concepts and simulation-based analysis. The approach identifies high-cost, low-value components through Function-Cost-Worth Analysis (FCWA) and evaluates their impact with the Function Analysis System Technique (FAST) and evaluation matrices. Results showed that the nozzle subsystem was the main limitation, as it did not cover the spray area well and fluid dynamics were unsatisfactory. To address this, several nozzle shapes and materials were examined during the creative phase. A complete cone nozzle proved the best design. Computational Fluid Dynamics (CFD) confirmed improved flow properties, while Finite Element Analysis (FEA) showed structural adequacy under operational pressures. Polypropylene was selected as the best material since it is secure and significantly less costly compared to metals like gunmetal and stainless steel. The changes increased system efficiency from 63.75% to 75.25%, an 11.5% improvement, while overall cost decreased by 2.52%. This demonstrates that integrating VE with CAD-based simulations can generate innovative, scalable designs for fluid-based industrial systems.

Keywords: computational fluid dynamics; finite element analysis; function analysis system technique; value engineering

1. Introduction

In today's industrial environment, fluid dispersion systems are essential for preserving regular operations and effective procedures [1]. Among many other disciplines, many depend on these systems: environmental control, chemical processing, and cooling technologies [2]. The increasing profile of cost control and sustainable engineering makes the optimization of these systems more crucial than ever before [3]. One typical difficulty for conventional design approaches is maximizing performance while cutting expenses [4]. VE along with simulation tools to achieve each of these two objectives concurrently [5].

VE is a methodical approach based on functional demands that promote creativity and savings. Recent CFD-based investigations have demonstrated that nozzle geometry and flow modelling

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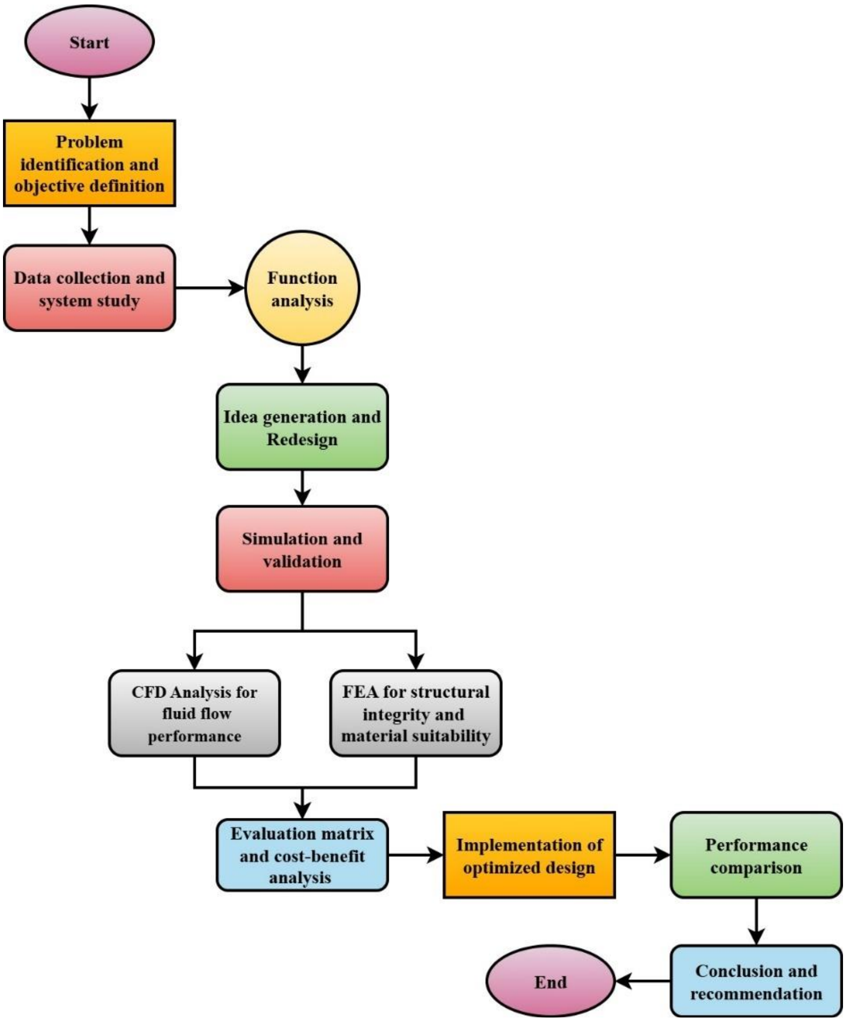


Figure 1. Computational mesh structure generated for the numerical analysis of the fluid dispersion model

significantly influence spray uniformity and stability in fluid dispersion systems [6-7]. The results show that value engineering with simulation modeling can be used to systematically redesign fluid distribution equipment. Engineers can carefully uncover design inefficiencies using tools such as the FAST and FCWA [8]. These methods help distinguish between those that are required and those that are not, therefore enabling one to measure the relative expenses of different purposes [9]. The main performance and cost limitations of the fluid dispersion unit [10]. The nozzle subsystem has been determined through the analysis as both inefficient in its functionally inefficient and economically expensive [11]. Its fluid performance was not really good and the distribution of sprays was not uniform. To overcome these drawbacks, the concept design phase involved several nozzle designs and material choices [12]. To evaluate and compare the flow properties of the proposed configurations, the simulations of the CFD were carried out [13].

This method allows measurement of spray distribution, pressure differences, and velocity distribution accurately [14-15]. The structural feasibility was determined with the help of the FEA

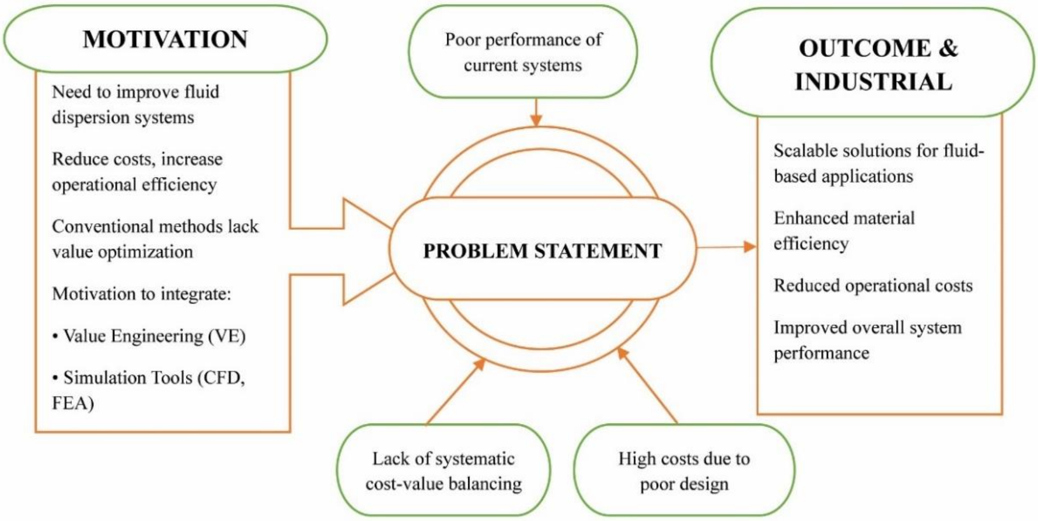


Figure 2. Conceptual representation of research motivation, problem identification, and proposed solution framework

to consider the mechanical soundness in the operational environment [16]. According to all the performance measures (both functional and structural), the full cone nozzle was the most appropriate of the options examined [17]. Polypropylene was selected as a substitute for traditional metallic materials because it is cost-effective and possessed sufficient mechanical strength. Compared to gunmetal and stainless steel, polypropylene offered the necessary corrosion protection at a much lower cost in terms of material costs [18]. After the change in configuration that was done and the redesigned configuration was implemented, the efficiency of the system went up to 75.25% as compared to 63.75%, which is an increase of 11.5 %. Also, the overall cost of the system was cut by 2.52%, which also shows the economic viability of the suggested change [19].

The integration of simulation tools with the principles of VE offers a well organised framework of enhancing technical performance and cost effectiveness [20]. This method can be applied to the broad variety of mechanical systems based on fluid movements, and it is specifically applicable to industries where sustainability and the lack of energy were given priority [21]. A successful integration of the use of FAST, CFD and FEA will enable the making of informed decisions using quantitative measures of performance. The results reveal the feasibility of digital simulation implementation along with value-based design approaches [22-23]. In general, this research work adds to the creation of systematic approaches to the engineering optimization. Whereas CFD is used to analyze the behavior of liquids and spray coverage, FEA is used to analyze structure stability and material appropriateness at working conditions as shown in Fig. 1. After the simulation, the financial feasibility is performed through evaluation matrices and cost benefit analysis. An optimal design is then chosen and implemented and its effectiveness is evaluated with the initial setting. The new system recorded a reduction in material cost and also improved operational performance.

The interplay of VE and computational simulation models is a systematic way of optimizing fluid-based industrial systems in the area of process, energy systems, and manufacturing. The latest trends in computational design are focused on the idea of combining CAD/CAE with the methods of simulation and optimization to enhance the efficiency of engineering processes [24-25]. Such advances are within the field of the Advances in Computational Design. Fig. 2 demonstrated the motivation behind the research and formulation of the problem.

The study pursues the following objectives:

- To define and estimate elements in the fluid dispersion system that portray reduced functional performance with the help of FCWA and FAST methodologies.
- To optimize nozzle geometry and design using value-oriented design principles with an aim of coming up with a better spray cover and uniform flow.
- To analyse the performance of the modified design using both the CFD and FEA as both operational performance measures.
- To accomplish cost-saving through the use of alternative materials, which retain the structural integrity and reduce the total cost.

The paper has the following structure. Section 2 provides a literature review of past studies touching on the topic of simulation-based optimization and VE in industrial systems. Section 3 describes the FCWA-FAST approach that was taken in this work. In section 4, A comparative assessment and discussion of the proposed framework with respect to standard methods will be attempted. Section 5 is a conclusion to the study, and the likely areas of future investigation are discussed in it.

2. Related works

Recent studies on energy-efficient process design and sustainability have researched on superior optimization and simulation design within a wide variety of industrial applications. The most important ones are thermal control, fluid behaviour, ventilation efficiency and a green manufacturing system. CFD, TRNSYS, Aspen Plus, and statistical optimization models have been used as computational platforms to improve the efficiency of operations and regulate costs to facilitate data-driven engineering practices.

One of the studies by Kundu et al. [26] explored the field of simulation-based methods applicable in enhancing thermal energy systems. Their model combines the system-level simulation and the parametric analysis with thermodynamic modeling. With MATLAB co-operating with TRNSYS, the research successfully streamlined load management, design of thermal storage and optimized the design of heat exchangers, hence minimizing energy wastage and enhancing decision making in industrial thermal processes. Structured engineering approaches have also been applied to the industrial ventilation design.

In an analysis, Goodfellow and Wang [27] discussed the Industrial Ventilation System Engineering Design Concepts (IVS-EDC), with focus on the airflow modeling, empirical design techniques, and balancing measures of the system. Their method synthesizes the optimization of fans choice, the layout of the duct, and mitigation of the pollutants obtained with the aid of CFD simulations that led to the enhancement of energy efficiency and the management of indoor air quality.

Pimanov et al. [28] presented the concept of sustainable machining optimization and compared three types of methods dry cutting, cryogenic-assisted machining, and minimum quantity lubrication through the prism of multi-objective optimization. The decision-support model based on the integration of statistical analysis, artificial intelligence methods, and life cycle assessment have been implemented to minimize the material wastage and environmental impact without affecting productivity.

Simulation-based evaluation has also been used in process optimization during production of biodiesel. In the case of Pasha et al. [29], the techno-economic and sustainability assessments were carried out using Aspen Plus and SuperPro Designer. Their approach to it is to correlate process modelling to the optimization strategy in order to find economically feasible and environmentally friendly production paths.

Yang et al. [30] have also noted the previous progress in multiphase CFD modelling, especially using the discrete phase method (DPM). The method allows fine simulation of flows of particles and sprays within the framework of combustion processes and chemical processing and pharmaceutical systems. The DPM-based model enhances forecasting of equipment stability and processes.

Liu et al. [31] investigated spray-based flue gas desulfurization systems where CFD simulations were carried out in conjunction with their operation plant data to determine droplet distribution and SO 2 capture efficiency. Sensitivity analyses were also done to minimise tower geometry and nozzle orientation, leading to enhanced control of emissions and less pressure loss.

Otoko [32] suggested a multi-criteria approach to cleanroom system design that provides a trade-off between control of contamination and financial parameters, as well as sustainability. The study made layouts using the combination of Lean Six Sigma, CFD modeling and Monte Carlo simulation to ensure adherence to ISO standards and the project cost minimization.

Zadeh, Shoushtari, and Talebi [33] studied analytical decision-support approaches on industrial engineering. They involve statistical quality control, linear programming, and evolutionary algorithms in their work in terms of simulation-based process models in order to improve the accuracy of design and the operation of the manufacturing and logistic settings.

Taken together, these works point to the significance of integrating simulation instruments with systematic optimization frameworks in order to increase efficiency and sustainability of the system. Its application can be seen in thermal management and emission control, machining, and cleanroom design. The combination of CFD, multi-objective decision model, and process simulation methods can be seen to have quantifiable value of resource exploitation and operational stability. Extended computational optimization has also applied broader to biomedical and fluidic systems wherein finite element methods have been much used as well as CFD methods by Li et al. [34]. Some of the earliest efforts of employing CFD to optimize design by Knight, [35] have laid the groundwork on fundamental principles of design optimization with a CFD, whereas lattice Boltzmann methods have also been used in computing the configuration of fluid distributors by Wang et al. [36].

3. Proposed method

The balance between the system performance and financial sustainability is one of the pivotal issues that have been troubling industrial fluid distribution applications. To address this, an adapted liquid dispersion arrangement is established through combining the principles of VE with a numerical simulation technique. The application of Functional Analysis System Technique (FAST) and FCWA is used to determine parts of the performance and discussion held on imbalanced contributions to cost in the current system. Based on these outcomes, alternate design configurations are examined through CFD and FEA. The current framework helps in the reduction of cost as well as enhancement of flow behavior.

3.1 VE-simulation framework for fluid system optimization

The VE simulation framework suggests utilizes 'Functional' and 'non-functional' optimization model. In addition, it links the performance assessment and the data validation of fluid dispersal systems. To put it differently, the evaluation process will first identify performance and setting of measurable objectives problems. It should be noted that the available configuration's thorough workmanship is being calculated. This primarily pertains to the functionality of components and data operated through it. According to FCWA and FAST the nozzle assembly component is considered expensive and has negligible proportionality. This has to do with the system's overall functioning. Since that, inconclusive results would be analyzed further to determine reasons for second testing. The identified design alternatives are further refined using FCWA and FAST methodologies. In the end, the computations of the configuration assure that the structural soundness and satisfactory flow performance in the operating condition are obtained.

$$fi(fm) = \sum_{ct} eem_{pd}(ct) - 2^{-\frac{fr}{2}} * \partial(2^{-cs}Dn - md) \tag{1}$$

Continuity Equation ct is a principle of Fluid Mechanics for conservation of mass eem_{pd}. The mass flow rate is said to represent the mass carrying a mass unit which is entering or leaving a control volume. Moreover, the mass flow rate $_{-}2^{-\frac{fr}{2}}$ is measured in kilograms/second. As per Eq. (1) dispersive action of spray $2^{-cs}Dn$ is uniform. This is presumed for dispersal of fluid by nozzles. Thus, it becomes easy to identify that whether the new nozzle arrangement given distortion of the mass distribution of the system. The function guarantees the presence of flow parameters allowing flow models developed from the function to be used.

$$\int |PS(ff)|^2 me = \sum_{nf} \left|PS_{vy}(ped)\right|^2 +^{\sum_{on} fe} \tag{2}$$

Energy loss-deviation associated with evaluation- nozzle flow; Energy loss-deviation associated with evaluation- nozzle flow me. Bernoulli's Eq. (2) relates pressure $PS(ff)$; velocity vy and elevation within a flowing liquid ped. It implies that the energy $\sum_{on} fe$, comprised of kinetic and potential energy of the liquid mean, stays constant along the flowing liquid mean.

$$NS(fd) = \sum_{i} \left|E_{ps}(ve)\right|^2 + \phi\left(2^{-fw} et - vl\right) \tag{3}$$

CFD modeling leverages the Navier-Stokes Eq. (3), which represents the flow of $NS(fd)$ fluids. This equation considers the impact of pressure E_{ps}, viscous forces, and external forces ve. Also, it is utilized for simulating the flow in the altered design of the nozzle. The system response can further be studied linearity through the loading $\left(2^{-fw} et - vl\right)$. Its performance validation help includes turbulence, shear, and velocity gradient models. Well-informed design choices help to achieve better dispersion effectiveness and less inefficiency.

$$S'o_{(mp)i} = FE_d(ts * nm)_{mp}, fqt = 1,2,\dots,ar, sd \in \{pd\} \tag{4}$$

In structural mechanics, inserting a material's particular loading conditions into the von Mises stress $S'o_{(mp)i}$ Eq. (4) finds its yield strength. With FEA FE_d, this method assesses the tensile

Table 1. Outcome comparison table

Performance Parameters	IVS-EDC	CFD-DPM	CFD	FCWA-FAST (Proposed)
Material Efficiency (%)	52.3	68.5	61.0	78.7
System Performance Score (0–1)	0.64	0.81	0.72	0.95
Scalability (0–1)	0.58	0.74	0.66	0.91

strength of nozzle materials under pressure $ts * nm$. This ensures that the selected mp materials can withstand operational conditions fqt. This optimizes the available resources $ar$and promotes safe design. The purpose of the equation is to reduce waste while increasing efficiency sd.

$$cw(ee)_i = eu_i * lv(\prod_i) * \iint ro_i ns\,, i = 1{,}2 \tag{5}$$

The cost-worth ratio provides insight into the economic efficiency$cw(ee)_i$ of a component by evaluating its cost relative to its expected utilityeu_i. A higher percentage indicates low-value lv components and potential redesign opportunities ro_i. Within this framework, it guides the optimization of multiple elements, such as an inefficient nozzle subsystem ns. This FCWA theoretical equation is fundamental. It guarantees that redesign initiatives focus on areas with the highest potential to lower costs and improve performance in Eq. (5).

To compare IVS-EDC, CFD and CFD-DPM with the proposed FCWA-FAST approach, Table 1 shows the results depending on the key performance indicators. The FCWA-FAST method has the best values of performance among the methods that are compared. Scalability score of 0.91 implies the availability of better performance in diverse industrial environments. The material efficiency is 78.7 % that shows definitely a better use of resources. The cost of operations has been achieved at 39.6 %, which represents economic effect in measurements. The performance index of 0.95 reveals better dispersion effectiveness as compared to other methods. The proposed framework, as noted in the previous finding, is better scaled and more cost-performance than traditional procedures.

3.2 System Analysis and Functional Evaluation

The fluid dispersion system must immediately address performance and cost limitations. At this stage, objectives are clearly defined and aligned with operational requirements to ensure practical and achievable targets.

$$Fve = es\left(\sum_j rb * CO(ct)_i\right) < \left|\sum_j cr * fae(rb)_i\right| \tag{6}$$

In VE Fve, Eq. (6) plays a central role in defining es the relationship between rb the value delivered by a component and its cost $CO(ct)$. It illustrates this by comparing cr the actual cost of a system function with its functional benefit and the associated economic justification $fae(rb)$. A high ratio indicates that redesign should be given primary attention. During functional evaluations, this equation supports the prioritization of design components. Optimization efforts therefore concentrate on tasks that are costly and deliver low value.

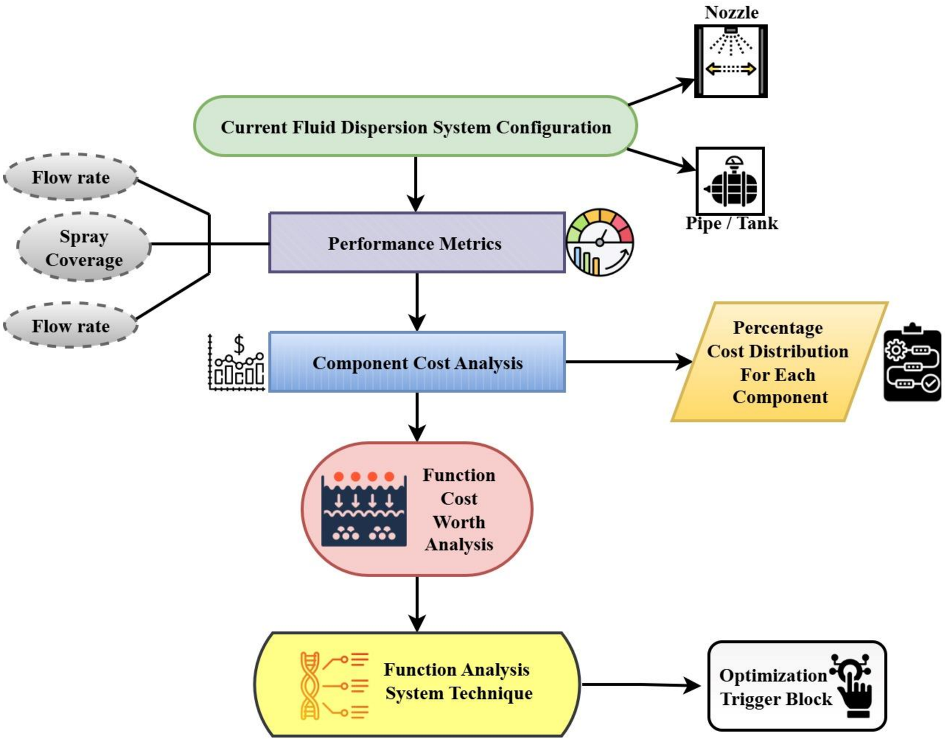


Figure 3. Functional assessment of the fluid dispersion system using FAST and FCWA methodologies

$$\partial(2^{-ee}Lb - op) = \int |SC(ot)|^2 fs\colon \rightarrow Li \tag{7}$$

Efficiency Eq. (7) establishes the relationship between a system's output performance and its inputs $\partial(2^{-ee}Lb - op)$. This statistic measures the effectiveness with which a system converts inputs into outputs like resources or energy $SC(ot)$. It helps in fluid systems fs both in terms of operational efficiency evaluation and loss identification Li. This equation contrasts present performance with standards to help with system study. This will form the basis for evaluating the success of the overhaul.

A detailed system analysis is carried out to check the current configurations, performance measures, and cost distribution of the elements as shown in Fig. 3. The analysis of components with a higher share of contribution to the cost than their functional output is done through the FCWA. The assessment revealed that the nozzle subsystem is a major component causing imbalance due to uneven flow behavior and insufficient spray cover. A FAST diagram is constructed to diagrammatize the functions and activities; the essential functions and the supporting activities are delineated by the diagram. This type of illustration allows one to indicate interdependencies between elements as well as to indicate areas where performance can be improved. The combination of FCWA result and FAST mapping would give guidance on redesign by matching expenditure and functional contribution. This leads to the arrangement of further modification and simulation processes based on technical performance needs as well as value-based criteria.

$$\sum_{qs=\frac{C}{lt}} be(ee):\rightarrow Hy(ts*ii)_i+\sum_j Ds*ss(id)_i \tag{8}$$

Energy balancing Eq. (8) ensures that all energy entering a system—whether stored, consumed, or lost is equal to all energy leaving it $\sum_{qs=\frac{c}{lt}} be(ee)$. A comprehensive assessment of hydraulic Hy or thermal systems has to include inefficiency detection$(ts*ii)_i$. This equation facilitates in-depth system analysis since it gauges energy changes and losses $Ds*ss(id)_i$. It can assist in identifying the causes of either too high or low energy use. It guides the allocation of resources for functional improvement.

$$\iint ff_ifr=Te_d(ds*ae)_{fds}+FR(df)_i \tag{9}$$

Flow rate $\iint ff_ifr$ represents the quantity of fluid passing through a specified area over time. Evaluating the effectiveness Te_d of fluid dispersion systems, particularly nozzle-based systems, is essential. It enables the assessment of whether, during functional review, flow delivery satisfies system requirements $(ds*ae)_{fds}$. Variations in flow rate identified in Eq. (9) are typically caused by design flaws or obstacles$FR(df)_i$. This allows for an accurate evaluation of the system's operational performance.

$$FP(re'-sp'')=(cpe-Td'')*Ft(h-mder") \tag{10}$$

A functional performance index denotes a comparative evaluation of a system's performance in relation to its intended design $FP(re'-sp'')$. Although it is not a traditional physical Eq. (10), it is applied in engineering analysis to evaluate and rank functional effectiveness $cpe-Td''$. The use of a FAST diagram supports the prioritization and organization of tasks $Ft(h-mder")$. This index guides decisions regarding redesign priorities and aligns technical performance with functional objectives.

3.3 Redesign and concept development

System redesign entails the identification of expensive and inexpensive components and coming up with new concepts to improve performance at the minimization of costs. The creative engineering and brainstorming session come up with a number of design options. Specific attention is paid to such aspects as material selections and nozzle geometry. The analysis of such options demands close consideration of such factors as the coverage of the spray, the distribution of the fluid velocity, durability, and the possibility of manufacturing.

$$SA(as-ff'')=\left(ca'-ds(rs-Ma'')\right)*If(la-sc'') \tag{11}$$

The spray angle Eq. (11) defines the angular spread of fluid from a nozzle $SA(as-ff'')$, therefore defining the coverage areaca' in a dispersion system ds. During the redesign stage, maintaining appropriate and consistent fluid distribution $(rs-Ma'')$over the intended surface is quite crucial. Though impact force can be lowered, a larger angle helps to increase spray coverage. Early phases of ideation benefit from the equation in selecting appropriate nozzle shapes $If(la-sc'')$. It ensures that functional improvements satisfy the dispersion needs.

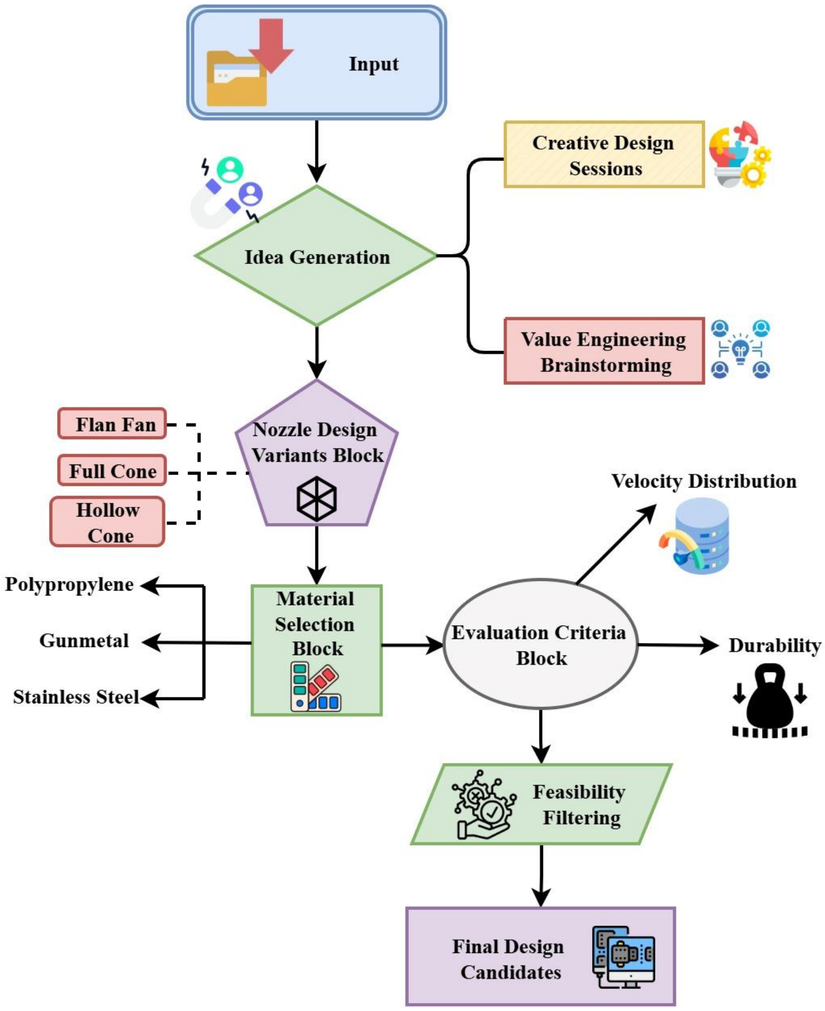


Figure 4. Comparative evaluation of alternative nozzle geometries and material options during the redesign phase

$$\sum_j fc * fc(fr)_i * \iint de_i ry + AN(tr)_i \tag{12}$$

Understanding fluid properties and flow conditions helps determine the projected flow regime, whether laminar or turbulent $\sum_j fc * fc(fr)_i$, through the dimensionless Eq. (12) known as the Reynolds number $\iint de_i ry$. During redesign, it is essential to ensure that the modified nozzle geometry promotes effective mixing and dispersion behavior. As turbulence increases, atomization can improve, although energy loss may also rise $AN(tr)_i$. The equation guides design decisions that affect fluid flow quality and confirm that the selected concepts satisfy predefined operational requirements.

To analyze the fluid dispersion, hollow cone, full cone, and flat fan are studied as depicted in Fig. 4. The evaluation is based on the cost, structural stability and resistance to corrosion of

Algorithm 1. Optimized nozzle selection based on simulation and cost parameters

```
Inputs:
efficiency → (Simulated spray performance expressed in %) cost → (Overall manufacturing cost in USD)
Material code → (1 = Polypropylene, 2 = Stainless Steel, 3 = Gunmetal)
design_code → (1 = Full Cone, 2 = Hollow Cone, 3 = Flat Fan)
START
INPUT efficiency, cost, material_code, design_code
IF efficiency >= 75 AND cost <= 150 THEN
  status ← "Accepted Design"
  IF material_code == 1 THEN
    selected_material ← "Polypropylene"
  ELSE IF material_code == 2 THEN
    selected_material ← "Stainless Steel"
  ELSE
    selected_material ← "Gunmetal"
  ENDIF
  IF design_code == 1 THEN
    selected_design ← "Full Cone"
  ELSE IF design_code == 2 THEN
    selected_design ← "Hollow Cone"
  ELSE
    selected_design ← "Flat Fan"
  ENDIF
ELSE
  status ← "Rejected Design"
  selected_material ← "N/A"
  selected_design ← "N/A"
ENDIF
DISPLAY status, selected_material, selected_design
END
Outputs:
status → ("Accepted Design", "Rejected Design")
selected_material
selected_design
```

polypropylene, gunmetal, and stainless steel. The aim is to find out the most appropriate combinations that minimize the manufacturing and maintenance costs and not compromise high performance. The first step is an initial feasibility screening where the field is reduced to the most simulation worthy designs. This stage focuses on the idea generation based on the engineering principles and VE concepts. The functional knowledge is converted to practical design decisions, which connects the analysis of the problem to the validation of the technical solution. The optimized designs are then subjected to elaborate computational analysis to ensure that there is structural integrity and working efficiency.

The efficiency of the nozzle design as an output parameter is computed using the input parameters of production cost and efficiency in the simulation as shown in Algorithm 1 to determine whether the nozzle design is feasible. It perceives or discards designs based on user-specified criteria based on if-then logic. After the materials and the types of nozzles have been approved, the system assigns them different numbers. The method eases the burdensome selection of optimal design by integrating both performance and cost measures and thus helps in making effective engineering decisions.

$$cm(id' - mds) = Rm(mp - uc) * dc(IS'' - mds) \tag{13}$$

Incorporating mechanical properties, including modulus, density, and strength, into Eq. (13) is a common practice $cm(id' - mds)$; this method classifies materials according to mechanical performance per unit cost $Rm(mp - uc)$. During concept development dc, it supports the selection of cost-effective IS, and structurally adequate nozzle materials. The equation assists in identifying the optimal balance where economic feasibility and performance coexist mds. It shines while testing non-metal replacements, including plastics. Design choices that are both cost-effective and environmentally sustainable provide long-term benefits.

$$df_e - fe(fo - to'){:}\rightarrow ni * Md(pl.ief') \tag{14}$$

The drag force Eq. (14) df_e allows one to determine the resistance fluid experiences fe when flowing over or through an object $fo - to'$, such as an altered nozzle interior ni. Minimizing drag Md will greatly help to reduce pressure loss and ineffective flow. This equation is helpful for evaluating the influence of new geometries on fluid resistance. Generally speaking, designs with less drag increase system responsiveness and energy efficiency $pl.ief'$. Drag plays a significant role in fluid performance and energy efficiency.

3.4 Simulation-based validation

This phase employs numerical simulation methods to validate the redesigned configuration. Computer-assisted designs of the nozzles are done using CFD to determine the flow properties of the new nozzle designs. Such parameters as velocity vectors, spray distribution, pressure variation, and turbulence intensity are evaluated in order to evaluate uniformity and performance of flow under working conditions.

The full cone nozzle configuration offers better distribution of the flow and coverage of the surface compared to the rest of the measured configurations as illustrated in Fig. 5. FEA is conducted in order to measure structural response when subjected to operating pressure and thermal loading conditions. The hybrid CFD and FEA analysis eases the process of choosing materials depending on structural sufficiency and cost factors. Polypropylene is a material of choice as it has an equal strength-cost property and resistance to corrosion.

The results of the simulation are compared to the functional targets that were set during the analytical stage. Both CFD and FEA validation proves that the chosen configuration meets the requirements of both performance and the structure. This combined assessment eliminates the use of physical prototyping and helps analyze the cost-performance viability to implement it in practice.

$$Nrs(pe - v\,s) = ss(em - fp(cg')) * [dv' - dtf] \tag{15}$$

Navier–Stokes Eq. (15) expresses the balance among inertial Nrs, pressure, viscous, and external forces governing fluid motion $pe - v\,s$. Within CFD analysis, it is used to model flow behavior in complex geometries $ss(em - fp(cg'))$. Application during validation dv' prime enables evaluation of velocity fields, pressure distribution, and turbulence effects in the modified

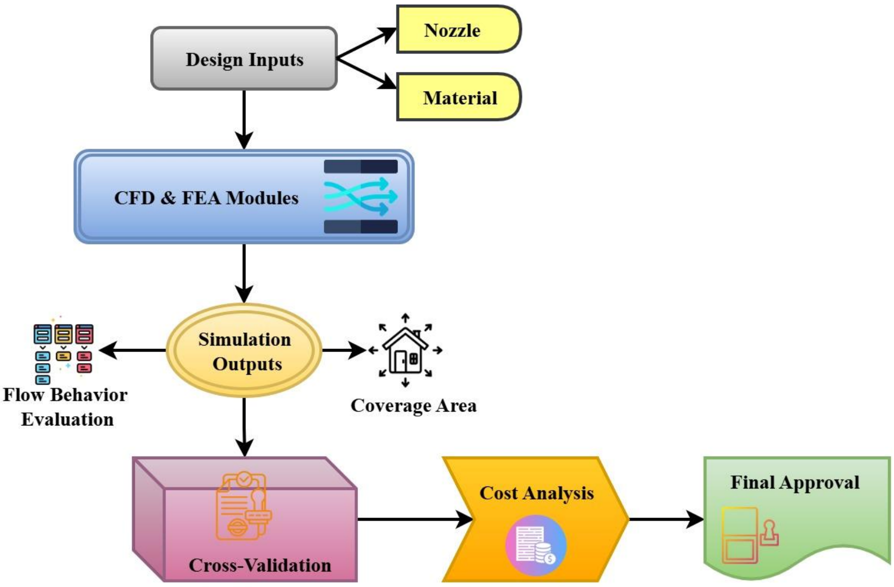


Figure 5. CFD-based flow distribution analysis and structural validation of the optimized nozzle configuration

nozzle design. The formulation provides a basis for assessing dispersion characteristics and flow stability dtf under representative operating conditions.

$$(DS - Sv'') = tb(ke' - tf) * ed\{ti\colon \rightarrow sp' = 0\} \tag{16}$$

In cases where direct CFD computation demands high computational effort $(DS - Sv'')$, Eq. (16), based on turbulence models such as the k–epsilon formulation, is employed to approximate turbulent flow behavior $tb(ke' - tf)$. The model accounts for turbulence intensity and energy dissipation to estimate mixing and dispersion characteristics. Validation through simulation evaluates whether the modified nozzle configuration produces stable spray distribution and consistent atomization $ed\{ti\colon \rightarrow sp' = 0\}$. They are essential for evaluating performance under various flow conditions. The use of these simulations enhances the reliability of virtual testing results.

$$[V.MS(F' - d.uc'')] = Er' - FC(mr - xe) \tag{17}$$

Using FEA and the Von Mises stress Eq. (17) $V.MS$ helps one to forecast the yielding of ductile materials under complex loads $(F' - d.uc'')$. It helps to evaluate, in real-world environments Er', the functional dependability of modified components such as nozzles. This equation helps one ascertain the failure or capacity of the material to remain within elastic constraints $FC(mr - xe)$. This guarantees that, mechanically, the design is possible. For this reason, it is a necessary test guaranteeing dependability and security.

$$H\{dt.ccr''\} = Fs'' < ts - mpcc'' >* \{dt(Fs - ryt'c)\} \tag{18}$$

Eq. (18) for heat transfer describes changes in heat flow through a material by conduction, convection, or radiation $H\{dt.ccr''\}$. As a result, it enables simulation in fluid systems Fs'' of the effects of thermal stresses on material performance and fluid behavior $ts - mpcc''$. It is

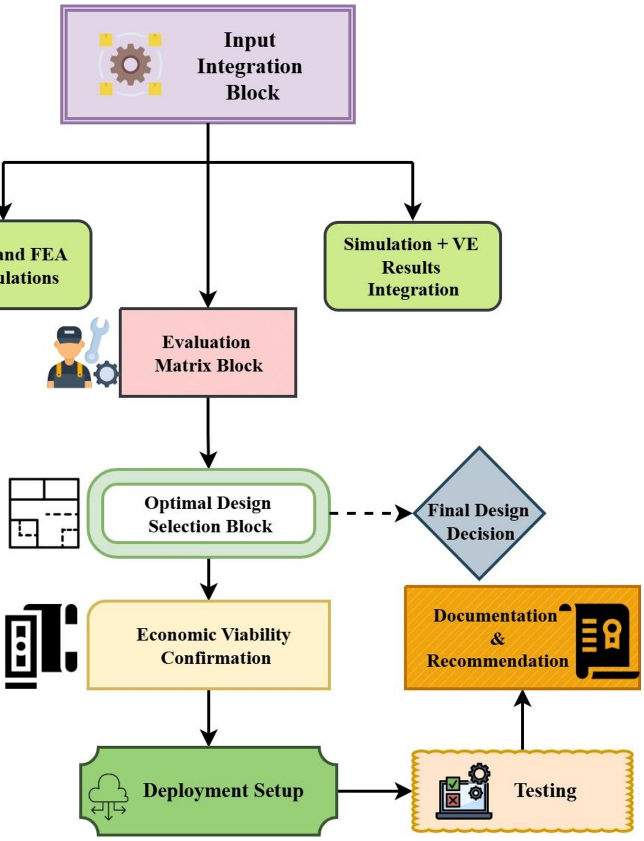


Figure 6. Decision framework combining simulation results and VE for design selection

particularly useful in high-temperature operations, allowing evaluation of how heat buildup influences system stability $dt(Fs - ryt'c)$. Adjusting temperature distributions ensures the thermal robustness of the design. The formulation provides a basis for evaluating operational safety and system reliability.

3.5 Design refinement and deployment

VE is used to supplement design selection using simulation results. A comparison of alternatives by structural integrity, fluid performance, manufacturing cost, production feasibility and the consideration of maintenance is made using an evaluation matrix which is shown in Fig. 6. A cost-benefit analysis is conducted to assess the performance of the new system financially as compared to the initial system. The full cone nozzle made of polypropylene enhanced the efficiency of the total by 11.5% and also cut costs down by 2.52%. Once selected, operational verification was done via comparative testing of the efficiency, spray distribution and reliability parameters. The findings show that performance improvements that can be measured with respect to the integrated evaluation process are positive. Last minute documentation and implementation guidelines were made ready to enable the application of the design in similar fluid dispersion systems. The stage is a step forward after analytical assessment through proven operational performance based on a combination of both simulation and value analysis techniques.

$$[we' - cpd].qe(sy - ro') + \iint dm_i cd \qquad (19)$$

Multi-Criteria Decision-Making (MCDM) Eq. (19) ranks design alternatives using weighted parameters such as manufacturing capability $[we' - cpd]$, cost, reliability, and performance. Each criterion is quantified to enable structured comparison among redesign options $qe(sy - ro')$. The formulation provides a basis for selecting configurations that satisfy predefined technical and economic conditions $dm_i cd$. This procedure facilitates consistent and transparent design selection.

$$cb\{ff\!:\to ps' = c(pe - wi'')\}\!:\to e\{fd.rae''\} \qquad (20)$$

Cost–benefit cb ratio Eq. (20) expresses the relationship between total anticipated benefits and associated costs $ff\!:\to ps'$. During optimization $c(pe - wi'')$, the ratio is used to assess whether performance gains offset implementation expenditure. The formulation provides a quantitative basis for judging economic feasibility $e\{fd.rae''\}$. A value greater than one indicates that projected benefits exceed costs, supporting objective financial evaluation prior to deployment.

$$\iint SE_i pp = sg_a(nc * ot)_{fee} + CP(ao)_i \qquad (21)$$

System efficiency gain Eq. (21) quantifies the percentage variation in output performance after design optimization $SE_i pp$. The parameter reflects changes in throughput, fluid distribution, and energy utilization $sg_a(nc * ot)_{fee}$ _fee associated with the modified configuration. The formulation enables comparison of operational performance before and after implementation $CP(ao)_i$. This comparison provides a measurable basis for evaluating the impact of the redesign.

$$Pr(mt' - bf'') = (gti - Fc'') * LT(p - ltsd") \qquad (22)$$

Reliability Eq. (22), commonly represented through Mean Time Between Failures (MTBF), quantifies expected service life and operational stability $Pr(mt' - bf'')$. The formulation is applied to evaluate component performance during implementation $gti - Fc''$. It provides a basis for estimating long-term behavior under standard operating conditions and supports lifecycle cost analysis as well as maintenance scheduling. Assessment of projected service life prior to deployment informs design verification $LT(p - ltsd")$.

This method was proposed in order to improve a commercial fluid dispersion system with VE and simulation-based tools. This method demonstrates that the primary limitation to performance was the nozzle subsystem. Several designs were considered and CFD ensured enhanced flow characteristics with the full cone nozzle design, whereas FEA ensured its structural soundness under the working condition. Polypropylene was chosen as an economic material because it has appropriate mechanical characteristics. Due to this simulation-based VE approach, there was an increase in the system efficiency by 11.5%, and system overall cost was also decreased by 2.52%. These results prove the efficiency of integrating the functional assessment and engineering simulation to practice the optimization of the system.

4. Results and discussion

The performance assessment of the revised fluid dispersion system is given in the results as

Table 2. The simulation environment

S. No.	Metric	Description
1	Simulation Tool (CFD)	Applied to evaluate fluid flow behavior and spray distribution patterns in nozzle configurations.
2	Simulation Tool (FEA)	Utilized for structural assessment of nozzle materials under operating pressure conditions.
3	Mesh Size	Specifies the resolution level of the computational grid employed in CFD and FEA analyses.
4	Boundary Conditions	Defined at the inlet, outlet, and wall surfaces to replicate real-world flow scenarios.
5	Turbulence Model	Models such as k-ε or k-ω are applied to simulate turbulent flow within the nozzle.
6	Material Properties	Mechanical and thermal properties of nozzle materials (e.g., polypropylene).
7	Operating Pressure	Simulated inlet pressure reflecting real fluid system conditions.
8	Spray Coverage Metric	Measures the area evenly covered by the spray jet.
9	Flow Rate	The volume or mass of fluid passing through the nozzle per unit time.
10	Stress Distribution	Evaluates material deformation and stress distributions based on FEA results.

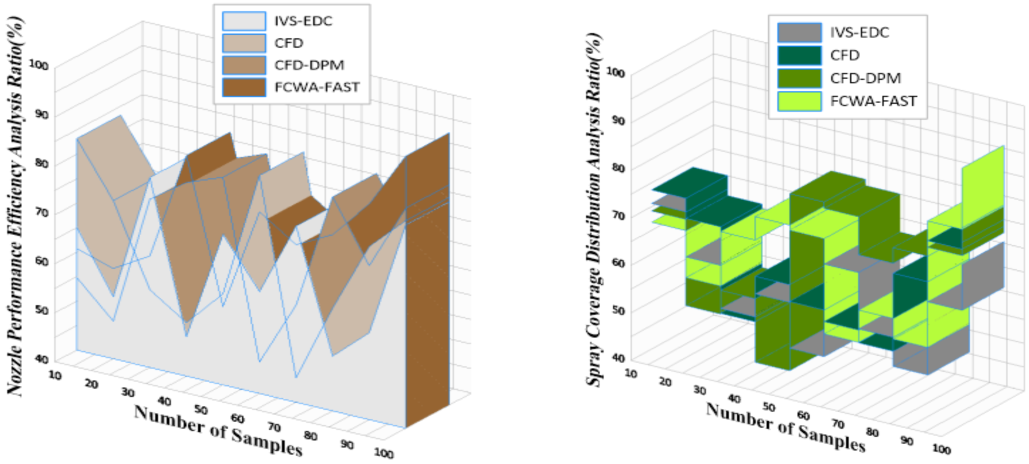
presented below. The method incorporates VE and computer simulation methods like CFD and FEA. Changes were made to the nozzle subsystem to accommodate uneven spray distribution and unfavorable flow behaviour. To strike a balance between cost and operation aspects, several nozzle designs and materials were considered. Simulation validation Justification Numerical validation of the system provides evidence of the stability of the system at typical operating conditions.

4.1 Dataset description

Experimental reference is taken using Electrical Arc Shock Tube (EAST) data sets which was offered by NASA Ames Research Center and can be accessed on the NASA Open Data Portal. The EAST plant produces shock-heated gas conditions of high enthalpy that are similar to hypersonic flow conditions. The data set comprises of experimentation records of the shots, velocity, instrumentation records, and quality measures. The spectral measurements include information on wavelength, spatial position and intensity with the assistance of cross-section files and MATLAB-based parsing tools to handle the data. Table 2 Shows the simulation environment.

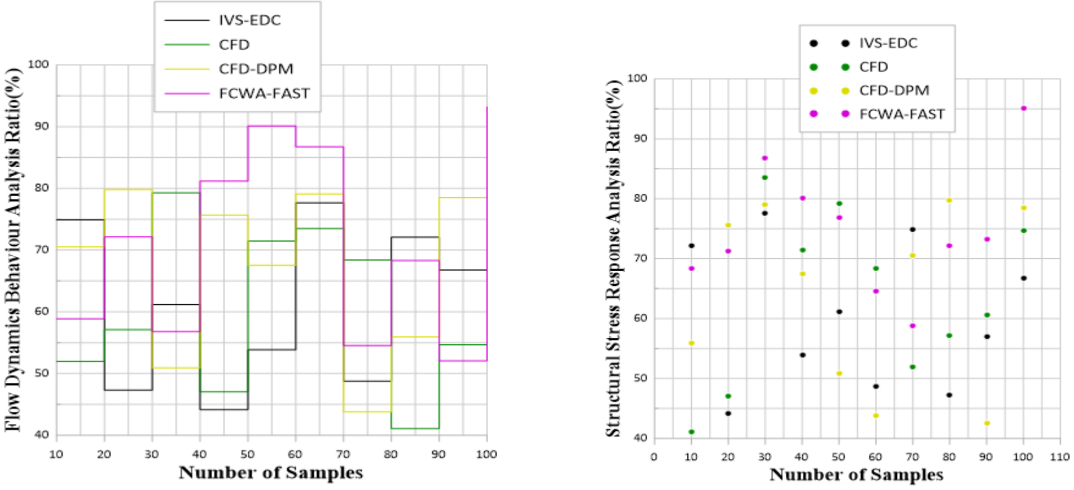
These experiments are taken to validate CFD and FEA simulations. The comparison facilitates the evaluation of the discharge behavior, thermal loading effects as well as the structural response under the real operating conditions. Simulation results combined with the experimental data that is available helps in the assessment of the redesigned nozzle design at high-energy flow conditions.

The test is aimed at flow uniformity and discharge capacity of the modified nozzle. Simulations FD were conducted to study discharge rate and homogeneity of the fluid as depicted in Fig. 7(a). The findings show that there is the improvement of efficiency of the system after the geometric modification. The new arrangement exhibits a better dispersion behavior control in different operating conditions. The properties of spray distribution were also considered to evaluate the consistency of the cover. The spray angle and impact distribution were simulated, which allowed determining areas with a high accumulation level and incomplete dispersion. The geometry of the



(a) Nozzle Performance Efficiency (b) Spray Coverage Distribution

Figure 7. CFD simulation results showing nozzle efficiency and spray uniformity improvements

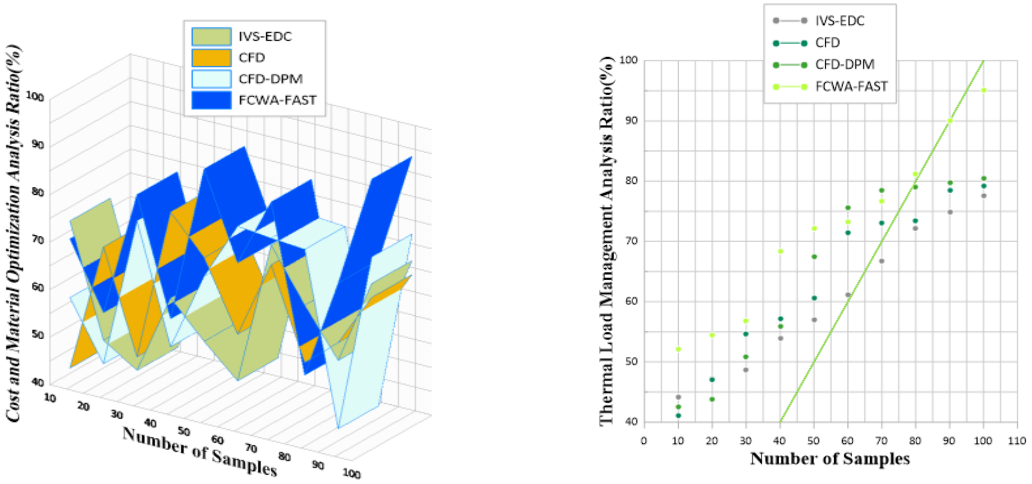


(a) Flow Dynamics Behavior (b) Structural Stress Response

Figure 8. CFD and FEA results showing flow dynamics and stress distribution in polypropylene nozzle

cone was optimized which enhanced the coverage of the target surface. The improved design ensures better uniformity in space distribution as shown in Fig. 7(b) and this is necessary in industrial fluid processes.

The behavior of internal flow was measured on velocity profiles, turbulence intensity and pressure variation of the redesigned nozzle. Fig. 8(a) CFD results indicate that the flow arrangement is more stable and less irregular. The geometric adjustments helped to reduce the resistance of flow and reduce the number of vortices. The changes enhanced discharge efficiency and minimized the energy dissipation. FEA was employed in studying the structural response under conditions of representative pressure and loading. The analysis of stress distribution, shown



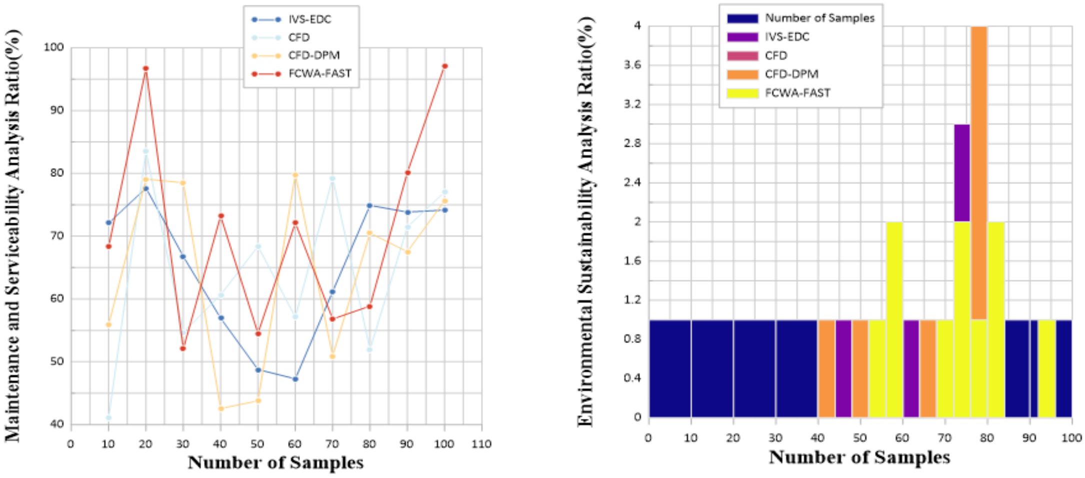
(a) Cost and Material Optimization (b) Thermal Load Management

Figure 9. Optimization study comparing material cost with thermal performance for different nozzle designs

in Fig. 8(b) revealed concentration foci points that were concentrated to determine material adequacy. The polypropylene construction has withstood stress limits which means that when used in fluid dispersion systems, the polypropylene is mechanically suitable when used in the long-term.

Both the before and after redesign configuration was compared against production and material costs. FCWA shows that Polypropylene nozzle has low material expenditure as compared to metallic ones. As shown in Fig. 9(a), cost reduction does not have a negative impact on functional performance. The outcomes show that the economic efficiency is enhanced without any quantifiable decrease in the effectiveness of the system. According to the principle of cost-performance optimization, the combination of VE and simulation-based design contributes to optimization of the cost of industrial fluid systems. Nozzle and housing materials were also studied in terms of their thermal characteristics as was demonstrated in Fig. 9(b). The thermal conductivity, expansion behavior, and deformation were tested in high temperature environment. Constant thermal performance is required to ensure a consistent performance in high temperatures. It is shown that the chosen materials do not exceed the tolerable structural level, and there are few chances of heat-based degradation over an extended period of operation.

Serviceability was considered by looking into the accessibility, modularity and disassembly needs of the nozzle components as shown in Fig. 10(a). The evaluation takes into account the possible maintenance time and parts change process. Cleaning and repair facilitating design provisions leads to the operation availability and life cycle control costs that are sustainable. When it comes to design, maintenance factors are included too, to address the reliability issue in industrial settings that demand durability and low downtime. Assessment of the manufacturing process, energy consumption, and material characteristics as shown in Fig. 10(b) has a focus on environmental performance. Consideration was given to their recyclability, potential as a carbon reduction solution, as well as compatible with sustainable manufacturing. Conforming to environmental standards will help to comply with regulatory requirements and sustain operational,



(a) Maintenance and Serviceability (b) Environmental Sustainability

Figure 10. Analysis of redesigned nozzle highlighting maintenance benefits and reduced environmental impact

economic target. The system efficiency improved from 63.75% to 75.25%. Flow distribution in the CFD results improved with the use of full cone nozzle geometry. FEA of the structural analysis confirmed that the polypropylene material was structurally safe under operational load. The design revisions cut total system costs by 2.52% The findings indicated that VE and the simulation tools can be used together to improve performance and control the cost. Various CFD-based studies have reported improved spray uniformity and flow stability with optimized nozzle geometry [6]. Simulation-driven design approaches also show that appropriate nozzle configuration and material selection can enhance fluid distribution efficiency while reducing cost [7]. The consistency of the present findings with these reported trends confirms the practical applicability of the proposed VE–simulation framework for fluid dispersion optimization.

5. Conclusions

The study presented a value-engineering-based redesign of an industrial dispersion system supported by CFD and FEA analysis. Functional evaluations conducted using FCWA and FAST indicated that the nozzle subsystem is the main source of performance imbalance and cost inefficiency. The optimal configuration was identified as a polypropylene full-cone nozzle through simulation-assisted redesign. The updated system achieved dispersion efficiency of 75.25% at 2.52% lower total cost than the existing system. The analysis through CFD confirmed that the spray distribution was more uniform and the flow behaviour was stable. Similarly, results from the FEA indicated that the structure was safe under operating pressure for the selected material. The numerical improvements clearly demonstrate that value engineering integrated with simulation is a practical and reliable means of optimizing fluid dispersion equipment. This framework can be applied to an industrial fluid handling system to achieve the performance-cost balance.

Even though the suggested VE and simulation-based framework improved system efficiency and reduced cost, certain limitations remain. The study considered steady, single-phase flow conditions. It was primarily validated through CFD and FEA simulations, with limited large-scale experimental validation. The evaluation of the materials was limited to polypropylene, stainless steel and gunmetal. Also, the economic study did not include full lifecycle costing or environmental impact analysis. With more extensive experimental validation across a range of operating situations, future research can expand the framework to incorporate multiphase and transient flow behavior. To improve system sustainability and applicability, future research may also look at substitute materials and include full lifecycle costing and environmental effect assessment.

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