Foam-Based Fire-Fighting system for the Cessna 208 Caravan: Design and Simulation

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ABSTRACT

This review involves making a foam-based fire-fighting system for the Cessna 208 Caravan, a small general-aviation cargo plane using Low expansion AR-AFFF 3%C6 (Alcohol-Resistant Aqueous film-forming foam with six-carbon chain) using CAD designing, and FEA / CFD simulations and validation of the design by comparing with, and adhering to international standards of FAA, EASA, along with NFPA. This research is important as it sets a template based on which a system can be designed for any aircraft, be it a Boeing 747 or an Embraer business jet. A system was made that can fit in the cabin or fuselage of a plane, which is the biggest challenge, both in terms of weight and space. The system replaced Halon with the most environmentally-friendly version of AFFF possible. Coming to future areas, Fluorine-Free Foams (F3) can be used to make the project more environmentally friendly.

Keywords: Foam, AFFF, Fire-fighting, system, general aviation, FEA, CFD, cargo plane

1. Introduction:

The use of Halon by the aviation sector as a fire suppressing agent ended with the end of its manufacturing in 1994 as part of the Montreal Protocol, leaving a safety and regulatory gap. It is very serious in general aviation, where experience shows post-impact fires are disproportionately deadly, accounting for 22% of deaths from only 3.8% of accidents [7] [1] [8]. The threat of modern cargo fires, including lithium-ion batteries, adds to this issue [2]. It is difficult to make a solution because small aircraft have specific constraints, such as tight restrictions on weight, volume, and cost [3]. This project shows that an up-to-date, foam-based system [9] [12] [13] is a practical and efficient solution [4]. Firefighting foam [10] offers a strong suppression action by cooling, putting out the fire, and forming a vapor-suppressing seal over the fuel source [5][9]. Although shown in ground-based air uses, applying foam technology to onboard use on small aircraft is an innovative contribution [6]. This review highlights the methodology for designing and showing such a system, using engineering tools to transfer a proven technology to a vital, under-served application for safety. [4]

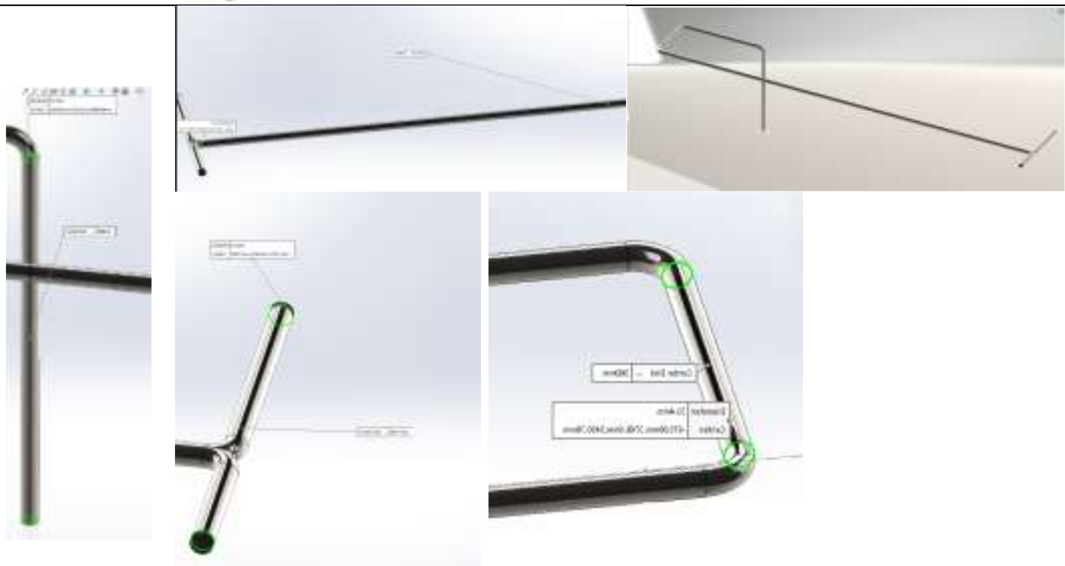
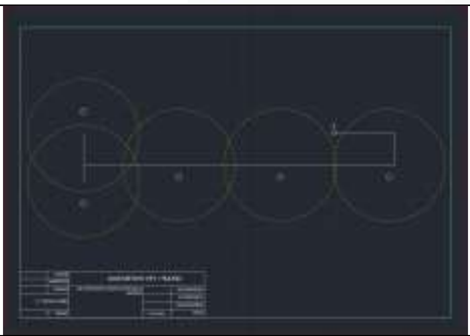
2. Methodology:

Everything started with a market study and a literature review, to decide technical specifications and justify the project's scope [7]. This guided the design phase in which a concept was generated using CAD tools with a focus on modularity and light weighting. A simulation-based process, using Computational Fluid Dynamics (CFD) [24] [25] [26] [27] to model and optimize foam dispersion [11] within the cargo bay of a Cessna 208 Caravan, was used. Finite Element Analysis (FEA) [28] was used to ensure the structural integrity of each part under simulated flight loads for ruggedness. In the end, a system level itemized cost-estimation [7] was done to ensure feasibility of system as a final product that can be made and brought to the market.

3. Problem Statement:

To design a foam-based fire-fighting system for the Cessna 208 Caravan cargo aircraft and create a template, a platform which can help in making a foam-based fire-suppression system for various aircraft.

4. Design, Analysis, Calculations, Results, and Cost-Estimation:

<table>
<tr><td>Design and Assembly of foam-based fire-fighting system using SolidWorks</td><td></td></tr>
<tr><td>Design of High-Pressure Pipeline using SolidWorks</td><td></td></tr>
<tr><td>Design of Nozzles, and HPP (High-Pressure Pipeline)</td><td>
<table>
<tr><th>NODES</th><th>GPM</th><th>PIPE DIA (mm)</th><th>LENGTH (mm)</th><th>REQUIRED PRESSURE (PSI)</th></tr>
<tr><td>4, 5</td><td>2.12</td><td>25</td><td>610</td><td>145.03</td></tr>
<tr><td>3</td><td>4.4</td><td>25</td><td>0</td><td></td></tr>
<tr><td>2</td><td>6.6</td><td>25</td><td>0</td><td></td></tr>
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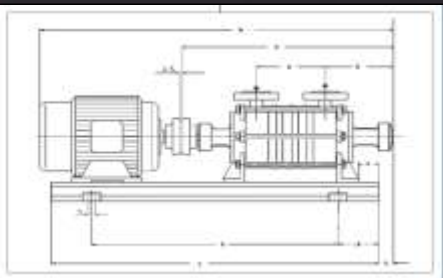
<tr><td>Pump Design, courtesy Kirloskar</td><td></td></tr>
<tr><td>Design of water tank using SolidWorks</td><td></td></tr>
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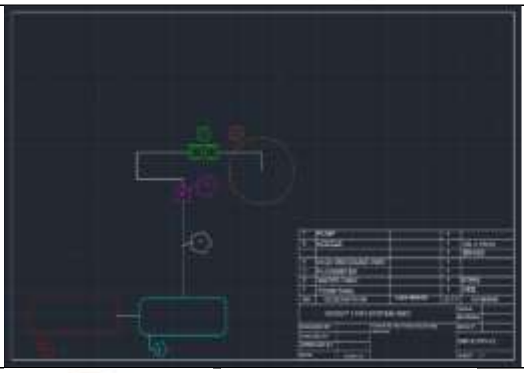
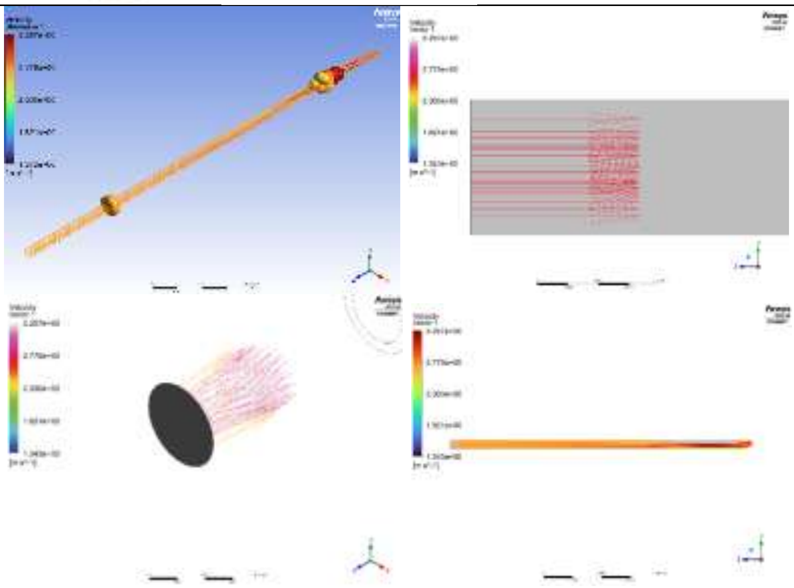
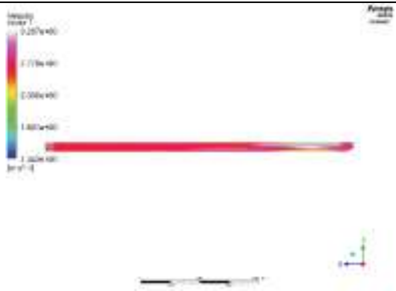
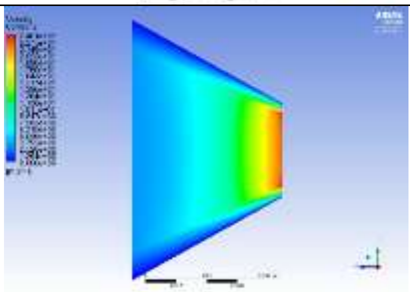
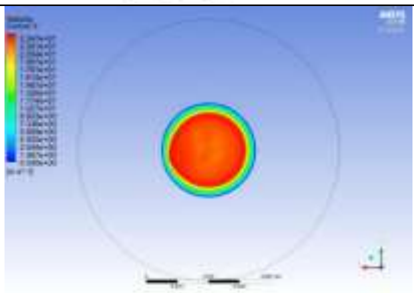
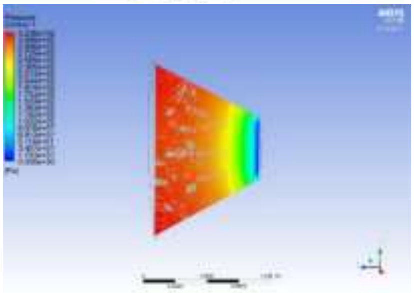
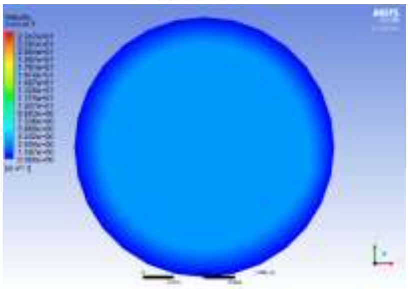
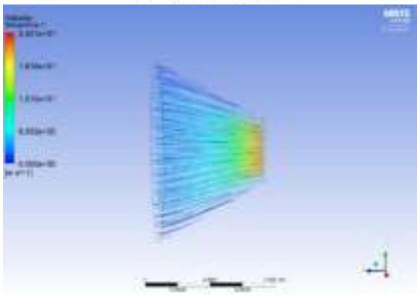
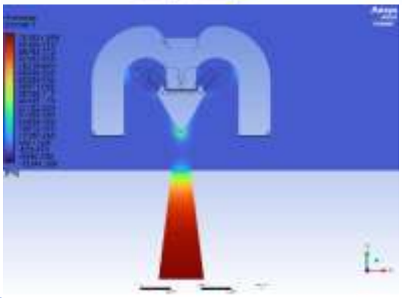
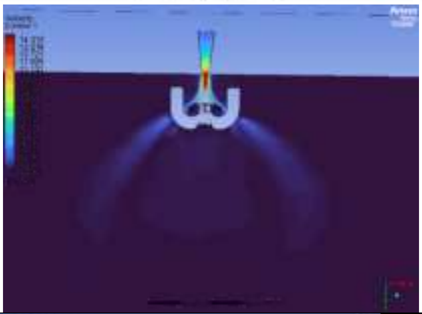
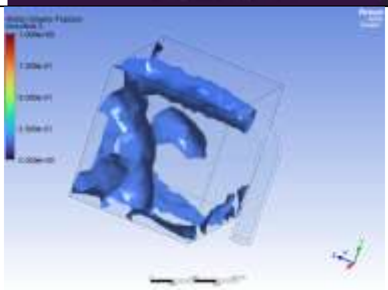
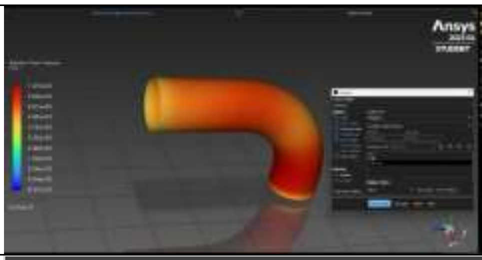
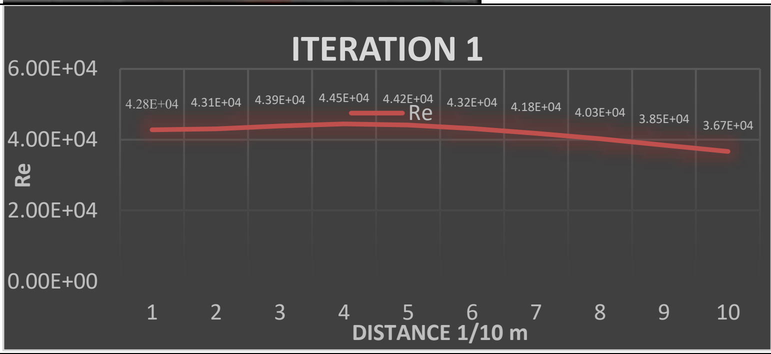
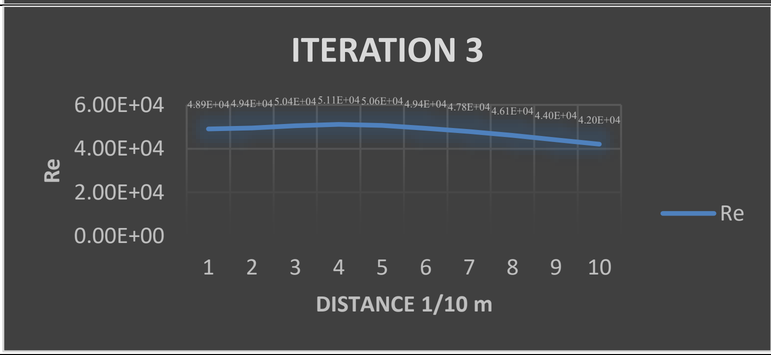
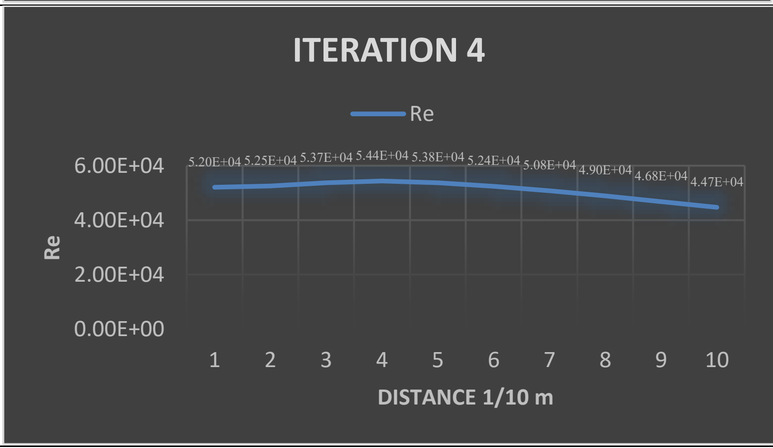
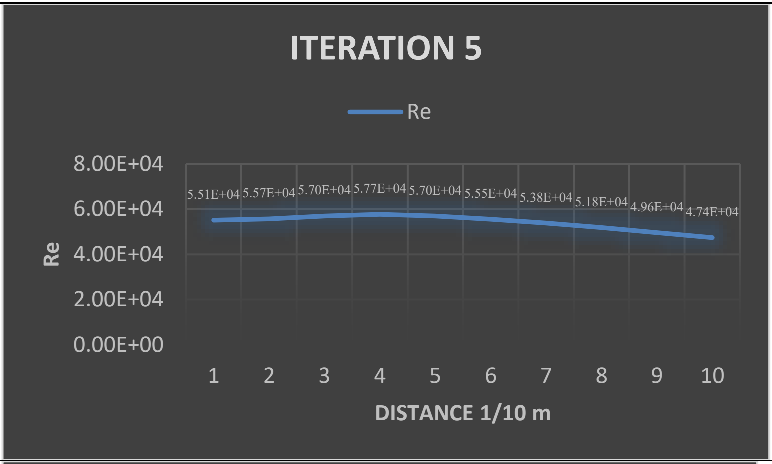
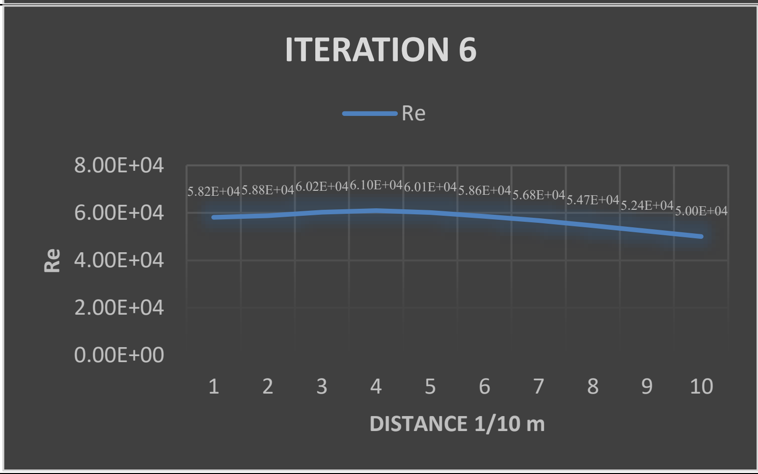
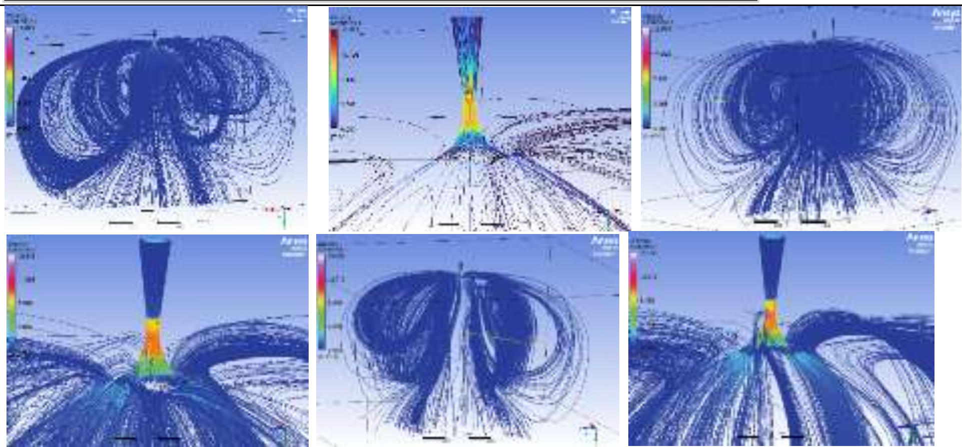
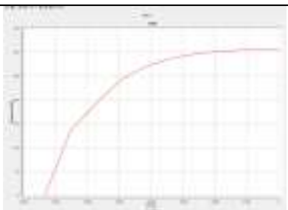
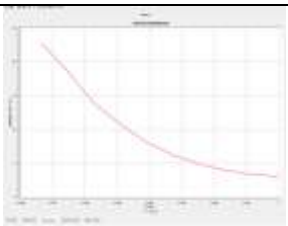
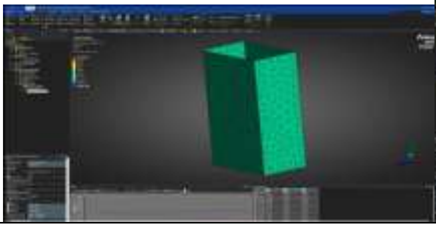
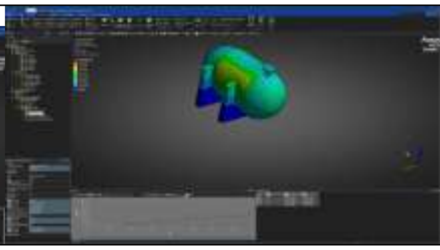
Design of foam tank using SolidWorks	
Nozzle used for design and calculations taken from FIRETECH	
Design of Elbow & Tees using SolidWorks	
Basic block diagram of working of foam-based fire-fighting system using AutoCAD	
Design of flange & stopper using SolidWorks	
CFD Analysis of High-Pressure Pipeline using ANSYS	

	 
CFD Analysis of Nozzle using ANSYS	      
CFD analysis of water tank using ANSYS	

CFD analysis of elbow	
Iteration of simulation pipeline-Iteration 1	
Iteration of simulation pipeline-Iteration 2	
Iteration of simulation pipeline-Iteration 3	
Iteration of simulation pipeline-Iteration 4	

Iteration of simulation pipeline- Iteration 5	
Iteration of simulation pipeline- Iteration 6	
Nozzle iterations- iteration 1 to 6	
Dimensions of water tank	 Water tank size: water tank design l 704mm B 384mm H 869 mm outlet pipe settings 12.5mm filling radius 10cm capacity 220L
Fuselage Design and component view of Cessna 208 Caravan	
Graph of Pressure with respect to distance for nozzle	

Graph of Velocity distribution for nozzle	
FEA of water tank and foam tank using ANSYS Workbench	 

Calculations-

For Fuselage and Nozzle-

Floor Area = 6.74 m^2 (From solidworks 3D)

6.5 L per minute per sq. meter (L/min/m^2) must be covered according to NFPA (National Fire Protection Association) guidelines, according to their standard value for low-expansion foam-based fire-fighting systems on hydrocarbon fuel spills according to standards NFPA 11 and 403 for faster flow of foam, and minimum time of discharge is 5 minutes, which is a safety factor, to prevent restarting the fire and fight the fire for long enough for the crew to take quick action

Total water area required is = $Time\ \times \dot{Q}\ \times Area$ = Time × Application Rate × Area

Which comes out to be = 5 × 6.5 × 6.74 = 219.05L of water

Including 3% of foam and the remaining 97 % is water, so we are using 3% [15] [17] AR-AFFF concentrate [14], which amounts to = 219.05 L of water × 0.03 (30% so 30/100) = 6.5712L of foam

To calculate total discharge, we need to multiply discharge and Area which is 43.81L (6.5 L/min/m^2 × 6.74 m^2) of water and foam mixture per minute

Ideal flow rate of nozzle is set standard by NFPA 11 standards i.e. 10 Liters per minute

We get the number of nozzles by having the ratio of total discharge by discharge per nozzle (flow rate per nozzle) (43.81 L/min/ 10 L/min = 4.38 nozzles required, but we cannot make 4.38 nozzles logically so it rounds off to 5 nozzles) which is 5 nozzles

Therefore, the new tank size becomes 250L (219.05L + 6.57 L = 225.62 L is the total tank size, we are using 250L for safety as a margin) the operation pressure is set to be 7-10 bar, with having the foam compatibility of AR-AFFF (3X3) [16] [18] [20]

A Sprinkler nozzle is sourced which has the operating pressure of 7-10 bar i.e. PN 7-10 rated

The nozzle which will be used in the real model will not be pressure rated but will serve the same function

The Area to be covered by each nozzle is = A / No. nozzles = 1.314m^2 per nozzle

i.e. it should cover a radius of 0.65m

For High-Pressure Pipeline (HPP Selection)-

Pipe selected is an SS316 pipe which has high strength, corrosion-resistant, which is most suitable for aviation foam systems.

According to Hazen-William's equation or the charts of pipe size:

For a discharge of 43.68l min^-1 at 7-10 bar operating pressure a 19mm to 25mm I.D pipe is needed

The velocity should be kept below 3ms^-1 to reduce turbulent flow and the bends should be kept minimum

Should include High-pressure rate elbows and tees, and threaded or flanged joints, pressure gauge, and foam proportioner (we have not calculated for proportioning system)

For Pipe pressure drop, $\dot{Q} = \frac{6.5L}{min\, m^2}$ $\qquad P = \left(\frac{Q}{K}\right)^2 K = \left(\frac{Q}{P}\right)^2$

K = 2.6417/sqrt (10) = 0.83537 P = 2.6417/0.83537 = 10 psi Length of initial pipe = 5m

Branch pipe = 0.735m

According to Barlow's formula for minimum wall thickness: $t = \frac{P.D}{2\,.S\,.E+P}$

t = height (mm)

- *P = pressure (15 bar = 1.5 MPa), D = diameter (mm), S = allowable stress (e.g., 137 MPa for A106 Gr B), E = weld efficiency (typically 1.0 for seamless)*

*For a DN25 pipe we need a O.D of 33.4mm which gives a thickness of 4.2mm this fits with **ASME B36.10M** standards.*

For the elbows-

We chose a low radius bend i.e. LR bend = - Centre-to-End (90° elbow): ~38 mm - Back-to-Face (180° return): ~76 mm

For 90deg turn the midpoint length should be = 76mm

For the Combination Pump:

Use the velocity equation: $Q = A/\dot{v}$

The pipe diameter is 25mm Pump head is $= \frac{P}{\rho g} = 102m$

Taking 15 % extra for a failsafe design Pump head = 116m

Type: Side channel centrifugal pump is better for this setup

Operating pressure = 7-10bar Motor power = 2-3 KW Elevation (static lift) = 1.3 m

Pipe length = 10 m Pipe velocity = 3 m/s Pipe diameter = DN25 (ID ≈ 25 mm = 0.025 m)

Friction factor (f) ≈ 0.03 (for turbulent flow in smooth steel pipe)

Nozzle pressure requirement = 10 bar = 1,000,000 Pa

Gravity (g) = 9.81 m/s² Static head = 1.3m

Velocity head $= \frac{v^2}{2g} = 0.458m$ $H_f = f \cdot \frac{l}{d} \cdot \frac{v^2}{2g} = 5.09m$ ***Nozzle head*** $= \frac{p}{\rho g} = 102m$

Therefore, Total dynamic head (TDH) = Static Head + Velocity Head + Friction Head + Nozzle Head = 1.3m + 0.458m + 5.09m + 102m = 108.79m

Itemized Cost Estimation of Physical Model, including overhead

5. Future Extensions:

The system analyzed in this paper can serve as a base for smart, flexible fire-fighting systems in the future. The sensor-based activation can be improved with more advanced sensors, including small thermal imaging cameras, to offer real-time information on the exact location, size, and spread rate of a fire. Using IoT-based communication, and intelligent systems, along with software and advanced sensors, this information could be sent to the cockpit and ground stations, seriously improving situational awareness.[29] The use of machine learning can make a predictive fire management system possible. Through study of cargo manifest data, flight plan, and ambient sensor data, such a system might be able to evaluate fire threat in real-time and even allow adaptive foam release, to use the agent smartly only as much as needed and prevent collateral damage.

Improvements in materials science and foam chemistry also have large potential. The move towards Fluorine-Free Foams (F3) continues [21] [23], as research emphasizes their performance improvement to be comparable with or be more than that of traditional foams.[22] Optimizing the system for next-generation F3 agents [19] [30] [31] [32] [33] [34] is the future. Investigation into nano-enhanced composite materials may find materials that are much stronger and more fire-proof while weighing lesser, decreasing the impact of the system on aircraft payload.

Lastly, the modularity of the system allows it to be scalable to future platforms. The fast-emerging automated aircraft technologies pose a new application. Both are based on heavy lithium-ion battery packs, posing a major fire threat. A tiny, extremely lightweight version of the system may be designed for placement in their battery compartment, where it would be extremely useful at stopping thermal runaway.

6. Conclusion:

The system is a platform, a template for the future. Combination with smart sensors and AI, innovation in foam chemistry, the change to Fluorine-Free Foams (F3), and the step up to future aviation platforms guarantee the long-term importance of this work.

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