THESIS

Mortada Safar

Hungarian University of Agriculture and Life Sciences Szent István Campus, Gödöllő Institute of Technology Bachelor’s degree

Car Safety: Automatic Fire Extinguisher System

Insider consultant: Prof. **Dr. Róbert Zsolt Keresztes**

University Professor

Created by: Mortada Safar

Hungarian University of Agriculture and Life Sciences

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Introduction and objectives

Improvements to automotive safety over the years have clearly had some impact, but vehicle fires are still a serious problem. Every year, safety organizations publish findings about thousands of car fires causing injuries or deaths as well as property damage. Some fires are caused by gasoline leaks, electrical issues and impact-related damage (National Fire Protection Association [NFPA], 2021). Modern vehicles have numerous safety systems, but adding an automatic fire suppression system to these other features could improve passenger protection and also reduce the hazard of potential automotive fires (Smith et al.

Automobile fires resulting in nearly 540 fatalities and over 1,300 injuries (NFPA, 2020) were also observed by NFPA in the United States alone during year of study Ammar et al. The fire ignition sources are predominantly sourced from: mechanical issues (29%), electrical failures (24%) and fuel leaks (20%.) with the flames frequently occurring within or originating to engine compartment and/or associated with electronic systems, Johnson et al. [7]. These fires can grow quickly and put a lot of people at risk.

At present, traditional fire extinguishers will require physical intervention from either the driver or passengers, which in some cases can be very difficult. Although these are essential safety ones, their proper function can be confounded in high stress situations with relatively longer time to access and deploy (Lee et al. 2021). Traditional extinguishers might also be hard to reach in larger vehicles and rapid-fire spread situations.

This use of human intervention becomes a risk, given car fires spread quickly. Many deaths in fires on vehicles are caused by the inability of individuals to escape (Brown *et al.,* 2020). Accordingly, some automatic fire suppression systems that can detect fires and then automatically extinguish them would be put into use without the need for human involvement. It would decrease the response time to extinguish a fire, which could be used as an opportunity to improve safety (Davis *et al.,* 2022).

The research has two primary goals to make automotive fire suppression systems more efficient and reliable: First, develop a chemical agent injector that adequately deploys an effective firefighting compound in a moving car during emergency braking. This is done with a full design process to make sure that the injector can suppress intentionally targeted fires in automotive environments, targeting exactly where the fire comes from and also providing an effective spreading of suppressing agent (Garcia *et al.,* 2021). Secondary, to assess the flow properties of the chemical agent fluid during injection and make sure it can be sufficiently distributed for optimum fire suppression. The effect of important parameters such as flow rates, pressure changes and nozzle design on the dispersion pattern of the extinguishing agent will be analysed using computational fluid dynamics (CFD) simulations in this study (Kumar *et al.,* 2019).

The objectives of this study are:

- Selecting the best material to make the nozzles impact-, heat-, and manufacturing-friendly.
- 3D designs several nozzles that are appropriate for every location that can be a fire source .
- Simulate the thermal behavior to ensure the strength of the design.

Literature Review

1. Why Exterior Fire Suppression is Vital

The explosive spread of fire from the outside to the inside of a vehicle can lead to destruction and risk for both occupants and cars. In instances where you cannot afford time-critical situations traditional means like portable fire extinguishers will not be effective In general, the advancement of mechanical and vehicle fire 33 suppression frameworks part for precision has been long overdue..sec (Deng *et al.,* 2020).

1.1 Exterior fire suppression challenge

Deng *et al.* (2020) recognized a number of obstacles to creating successful outside fire suppression systems such as:

- Unpredictable: The outdoor area is unpredictable, making it difficult to detect and control fires. The present fire detectors show low sensitivity in emitting an alarm that may pave way for a delay in the detection of early fires.
- Agent Losses: Fire extinguishing agents can dissipate rapidly in open areas, leaving little or no fire suppressant on hand to fight the fires.
- Nozzle blockage: Extinguisher agent nozzles can be blocked by dust and debris that hamper their operation.

1.2 Selection of fire extinguishing agents

The report examines different types of fire extinguishing agents, including inert gases, water mist with very fine droplets or even using so-called ultrafine particles in the solution. Key findings include:

- Inert gases - effective but requiring high concentrations and otherwise inappropriate for use in a vehicle, given the size of equipment and sealing requirements.
- Water in Fine Mist: This is cooling and can be extinguished, but it does not work well on fires out of doors due to the limitations on droplet size and pressure.
- Halogenated Alkanes: They are very efficient but highly environmentally damaging and toxic
- Aerosol: Extinguishing efficiency is high, but 2) secondary fire occurs and has a disadvantage in application.
- Ultra Fine Particles: Ideal firefighting agents with multiple fires classes (A, B, C, E) and for harsh conditions due to their high level of suppression. Therefore, they are considered as one of the most attractive choices for vehicle exterior fire suppression because of their excellent effectiveness and environmentally friendly nature (Deng *et al.,* 2020).

1.3 Control Unit for Automatic Fire Detection

Consequently, the study underlines demand for high-end automatic fire detection systems tested on state monitoring and fault diagnosis techniques. Existing detectors — heat-sensitive wires or optical sensors, for example — often cause false alarms due to interference. Such improvements are aimed at improving sensitivity and reliability through robust design and monitoring systems (Deng *et al.,* 2020).

1.4 Protective Nozzle Design

Deng et al. HASUNUMA et al. (2020) have shown an example this can be done with a disk-shaped protective nozzle that prevents environmental debris from clogging the hole while enabling effective discharge of extinguishing agent at the same time. This style also improves the reliability and performance of the fire suppressant system by allowing free flow without blockades or lack thereof as well as proper direction.

1.5 Testing and System Layout

In order to maximize coverage and response time, the exterior fire extinguishing system for vehicles is designed with detectors, extinguishers, pipelines, and nozzles strategically placed. The study highlights the benefits of virtual testing in lowering costs and hazards while accelerating development, and it recommends a combination of virtual and real car tests to confirm system effectiveness (Deng *et al.,* 2020).

2. How do automatic fire extinguishers work.

The Automatic Fire Extinguisher System with Safety Features for Vehicles is well-suited to detect and extinguish vehicle fires automatically, further protecting passengers against fire ignition risks while avoiding catastrophic events. Here, we clear the idea how this system works in detail.

Components of the System

2.1 Components of the System

Sensors: sensors are gadgets that measure and identify environmental factors like light, pressure, temperature, and humidity. They then transmit the output signals to a microcontroller or other controllers for processing. Because they offer real-time data that may be utilized for monitoring and control, they are essential in a variety of applications. There are many different kinds of sensors, each designed to perform a particular task. For instance, motion sensors may identify movement in a certain region, while temperature sensors assess the surrounding temperature. As shown in Fig.1, three different kinds of sensors are used in this study. These might contain a smoke sensor to measure the amount of small particles in the air, if some of the ions are going to attach to any smoke particles that get inside the sensor, making them incapable of carrying the current, that recognizes the development of a current differential between the sealed and open chambers(Li & Chen, 2021). A temperature sensor to track heat levels by either melting a fusible substance, detecting a pace at which the ambient temperature is rising, or detecting changes in electrical current brought on by heat loads on bimetallic metals can activate a heat detector(Xiao et al., 2020), and a light sensor for measuring illumination by translating variations in incident light into variations in resistance, which decreases in proportion to the light intensity. They are composed of a variety of substances, including indium antimonide, lead sulfide, and cadmium sulfide (Jones et al., 2019). Each of these sensors contribute valuable information to the overall system. The sensors are designed to be mounted at strategic locations such as the engine compartment.

	**Temperature sensor**
	**Flame sensor**
	**Smoke sensor**

Figure 1. Different types of sensors used in the cars industry.

[file:///C:/Users/Asus/Downloads/Automatic_Fire_Extinguisher_System_with_Safety_Fea.pdf]

Microcontroller (Arduino): it serves as the CPU of the system. It collects signals from sensors and analyzes them to determine whether it is fired (Wang & Zhang 2022). An open-source hardware platform built around a microcontroller; Arduino is easy to use for a range of tasks. The Arduino Integrated Development Environment (IDE), which allows users to create and upload code with ease, and the actual Arduino board, which has input/output pins for connecting sensors and actuators, make up this system. Based on C/C++, the programming language has been simplified to make it more approachable for novices. Because it is open-source, users can learn and create by participating in a lively community that exchanges projects, libraries, and tutorials. Arduino is a sophisticated yet approachable tool for creating interactive electronic projects, and it is extensively utilized in industries including robotics and home automation as illustrated in Figure 2.

*Figure 2.*Microcontroller "Arduino".

[file:///C:/Users/Asus/Downloads/Automatic_Fire_Extinguisher_System_with_Safety_Fea.pdf]

Fire Extinguisher: essential safety tools, fire extinguishers are made to contain or put out small flames. They are suitable for particular fire classes (e.g., solids, flammable liquids, gasses, electrical equipment) and available in a variety of forms, including water, foam, dry powder, carbon dioxide (CO_2), and wet chemical. Car fire extinguishers that operate automatically use a temperature-sensitive trigger or an integrated sensor to detect heat. The system provides quick and efficient protection in emergency situations by releasing the extinguishing agent—usually dry powder or gas—when a fire is detected. This process eliminates the need for manual activation. as illustrated in fig. 9. Although CO_2 fire extinguishers are primarily designed to put out electrical fires, they can also be used to put out Class B liquid flames like benzene as presented in Figure 3 (Smith *et al.,* 2018).

Figure 3. CO_2 fire extinguisher.

[https://www.checkfire.co.uk/fire-safety/commander-fire-extinguishers/commander-renovate-5kg-co2/]

Electronic Valve: in an automobile automatic fire extinguisher, an electronic valve is essential for regulating the extinguishing agent's release. This valve is linked to a detection system, which usually makes use of sensors that keep an eye on the vehicle's temperature or fire situation. Technology electronically triggers the valve to open, releasing the extinguishing agent to put out the fire when it detects a fire or excessive heat. Rapid response times and efficient fire suppression in a vehicle's cramped areas are made possible by the electronic valve's precise, automated operation that eliminates the need for personal intervention as indicated in Figure 4 (Garcia & Lee, 2021).

Figure 4. Electric Brass Solenoid Valve

[https://www.electricsolenoidvalves.com/3-4-24-vac-electric-brass-solenoid-valve/]

Wi-Fi Module: An autonomous car fire extinguisher system with a Wi-Fi module may communicate with other devices in real time, improving safety and response effectiveness. In the event that a fire is detected, the Wi-Fi module allows the system to notify passengers via their smartphones or vehicle displays. Furthermore, the module has the ability to automatically communicate with other services, like emergency response teams or fire stations, giving them real-time fire updates. Vehicle fire safety is increased overall because to this connectivity, which

Figure 5. Wi-Fi Module

guarantees prompt response and enables passengers to take the necessary measures as displayed in Figure 5. (Zhou *et al.,* 2019).

[file:///C:/Users/Asus/Downloads/Automatic_Fire_Extinguisher_System_with_Safety_Fea.pdf]

Central Lock System: The purpose of the Central Lock System Module in an automobile automatic fire extinguisher is to improve passenger safety in the event of a fire. Passengers can swiftly and safely evacuate the car when the module automatically unlocks and opens the doors when the system senses a fire. By preventing passengers from getting stuck inside the car because of locked doors in the case of a fire, this automated feature speeds up evacuation and lowers the possibility of injuries. Combining effective escape routes with fire suppression creates an additional layer of security as demonstrated in Figure 6. (Li & Chen, 2021).

*Figure 6.*Central Lock System.

[https://carradio.ie/product/universal-car-key-less-entry-system-car-central-locking-system/]

Buzzer/Alarm: an automatic fire extinguisher system for vehicles uses a buzzer as an auditory warning system to notify anyone in the vicinity of a fire within the car. To assist prevent injuries, the device emits a loud alarm when it senses a fire, alerting potential passengers or bystanders not to enter the car. This quick, unambiguous indication guarantees that anyone coming up to the car will know it is dangerous as demonstrated in Figure 7. (Xiao *et al.,* 2020).

Figure 7. Buzzer.

[https://www.audiowellzq.com/en/product-list.aspx?pid=3&category=15]

Nozzle: the sensors constantly scan the atmosphere, while at the same time.tick(＋). The arduino sensors respond to the first detection of a fire, and via temperature flame or smoke detectors they generate signal when there is fire, then it sends disturbing messages from one station to another as immediately perceived by over 6km.

Signal Processing: Arduino processes the signals from sensors. When the fire is confirmed, then it activates to further take actions (Garcia & Lee 2021).

Activation of Fire Extinguishing System: The Arduino sends a signal to the electronic valve connected to the fire extinguisher. This valve opens, allowing the extinguishing agent to be sprayed directly onto the fire (Smith *et al.,* 2018).

2.2 Safety Measures

Simultaneously, the Arduino disconnects the vehicle's battery to prevent further electrical issues that could exacerbate the fire (Zhou *et al.,* 2019).

The central lock system is activated to unlock the doors, allowing passengers to exit the vehicle safely (Li & Chen, 2021).

- Alerting Authorities

The Wi-Fi module sends an alert message to the nearest fire station, notifying them of the incident. It can also send notifications to the vehicle occupants (Wang & Zhang, 2022).

- Continuous Monitoring

After the initial response, the system continues to monitor fire. If the fire persists, the extinguishing process can be repeated until the fire is fully extinguished (Xiao *et al.,* 2020).

- Fire Extinguishing Agents

The system can utilize various types of extinguishing agents, including:

Dry Chemicals: Such as sodium bicarbonate, which releases carbon dioxide to smother the fire (Smith *et al.,* 2018).

Foams: Like AFFF (Aqueous Film Forming Foam), which forms a barrier to prevent oxygen from fueling the fire (Jones *et al.,* 2019).

Clean Agents: Inert gases or CO2 that reduce the oxygen concentration around the fire (Zhou *et al*., 2019).

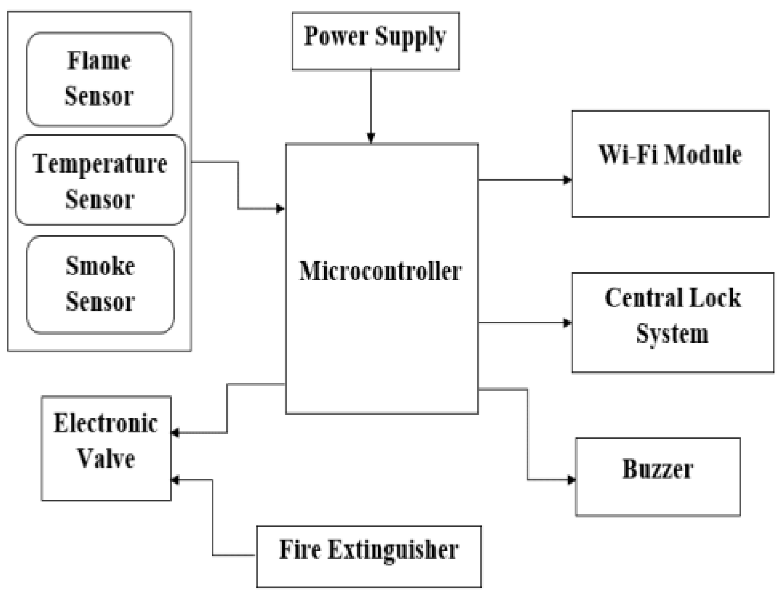


Figure 8. Block diagram of Fire Extinguishing System.

[file:///C:/Users/Asus/Downloads/Automatic_Fire_Extinguisher_System_with_Safety_Fea.pdf]

2.3 Position of system components

Sensors: The temperature sensors (e.g., LM35) should be strategically placed in areas prone to overheating, such as near the engine, battery compartment, passenger cabin, trunk, next to weels and areas where electrical components are located. This ensures early detection of temperature anomalies.

Microcontroller (Arduino): The Arduino microcontroller should be mounted in a secure, dry location within the vehicle, such as under the dashboard or in the central console. It should be easily accessible for maintenance but protected from heat and moisture.

Fire Extinguisher Electronic Valves: The electronic valves should be installed in-line with the fire extinguisher system, connected to the nozzle. They should be located between the main pipe and the areas being monitored (e.g., engine compartment) as the system should work with parallel configuration, not close to possible fire-starting point to be protected from heat.

Wi-Fi Module: The Wi-Fi module can be placed near the microcontroller to ensure a strong signal for communication. It should be housed in a location that minimizes interference from other electronic components.

Central Lock System: The central lock system components should be integrated into the vehicle’s existing locking mechanism, typically located within the doors and controlled by the vehicle’s main electrical system.

Buzzer/Alarm: The buzzer or alarm should be mounted in a location where it can be easily heard by the driver and passengers, such as on the dashboard or near the ceiling of the vehicle.

Pipelines: The pipelines connecting the surprising agent container to the nozzle should be routed through the vehicle’s structure, avoiding sharp bends and potential pinch points. They should be insulated to prevent heat loss and damage.

Nozzles: In locations that are most likely to experience a fire, such as close to the engine, battery compartment, passenger cabin, trunk, wheels, and areas with vital electrical components, the nozzles should be placed. The system guarantees thorough coverage and prompt fire suppression where fires are most likely to start by positioning the nozzles in these high-risk areas. This strategic positioning improves the system's overall efficacy by allowing it to react to possible fire outbreaks quickly and effectively, reducing damage and guaranteeing passenger safety.

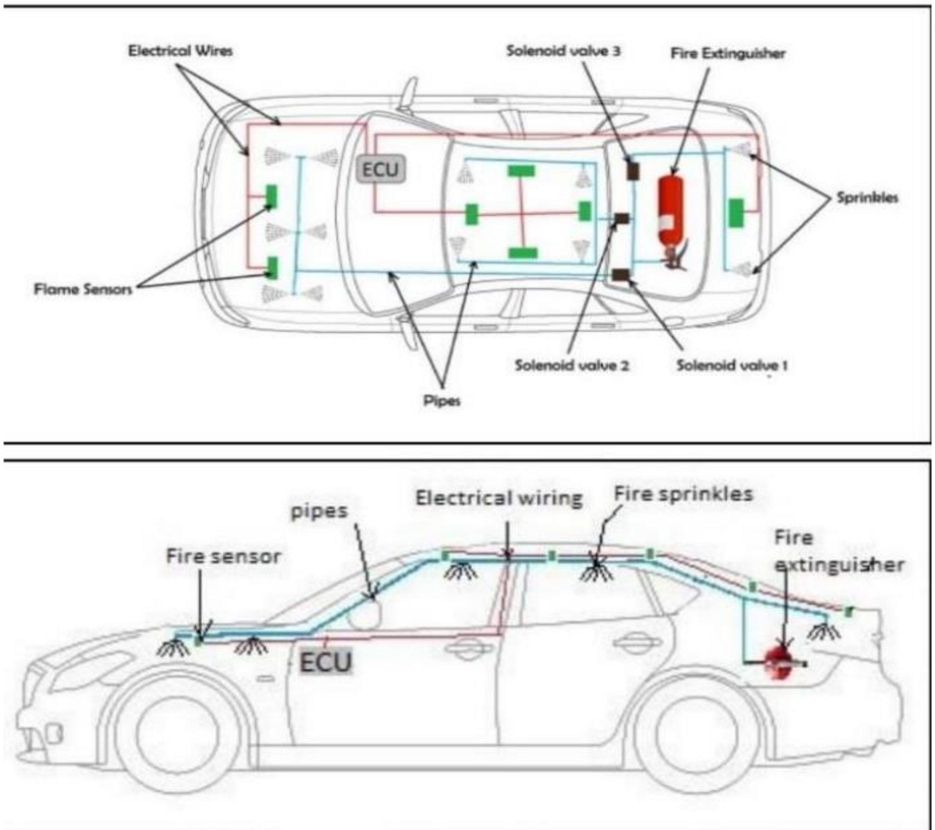


Figure 9: Layout of the system's internal component.

[https://www.jetir.org/papers/JETIR2004466.pdf]

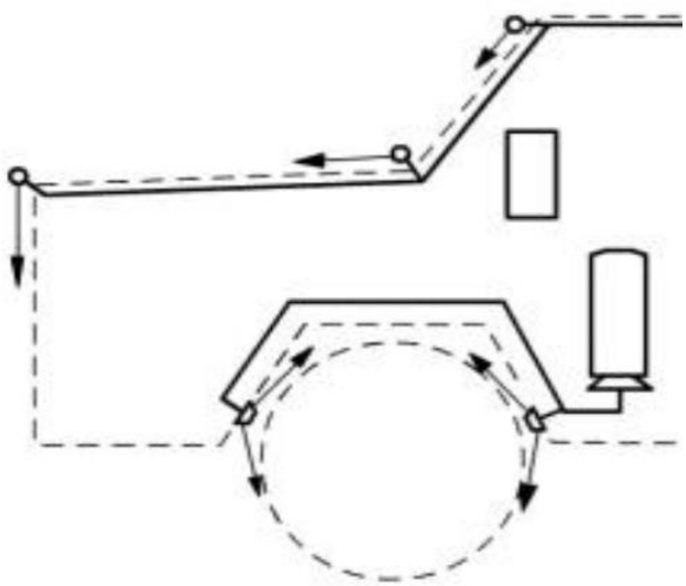


Figure 10: Layout of wheels fire extinguishing system.

3.Materials and methodology

3.1 pipelines and nozzles

Materials for pipelines and nozzles of automatic fire extinguisher used in vehicle have high importance, as they must withstand extreme temperatures; pressure variation due to use or weather changes are other variables affecting the system performance along with possible chemical reactions between pipe materials from substantially different manufacturers (due likely differences on its manufacturing tube sheet processes) whose internal surfaces contact each other after a fire suppression condition is triggered.

Table 1. Physical and chemical properties of different materials used for pipeline and nozzles.

Material	Melting Point (°C)	Thermal Conductivity (W/m·K)	Tensile Strength (MPa)	Flexibility	Corrosion Resistance	Pressure Resistance
Stainless Steel	~1,400-1,530	16-25	500-900	Low (Rigid)	High	High
PTFE (Teflon)	~327	0.25	~20	High (Flexible)	Very High	Moderate (up to 225 psi)
Brass	~900-940	100-120	~250-550	Moderate (Semi-Rigid)	Moderate to High	High
Aluminum	~660	205	90-200	Low to Moderate	Moderate	Moderate
Braided Rubber	Varies by composition	Low (~0.15-0.35)	Varies	Very High (Flexible)	Varies; often reinforced	Moderate to High (with wire)

Tubing: Automotive fire suppression systems rely upon the use of durable, flexible tubing that is both resistant to heat and corrosion; Stainless steel and PTFE (polytetrafluoroethylene) are often used because they can stand up to high pressure much better than other materials. Stainless steel tubing has superior high temperature and pressure resistance, so it is the perfect choice where great heat levels have with respect to being close to engine and exhaust components. In short, PTFE tubing is flexible and gives you optimum chemical flow, but its maximum operating pressure limits it to 225 psi in that size. Using different material such as solid metal would impede consistent fuel delivery due to the swell of male AN measurement (and barb) so another option for these high-flow lines is hose ends specifically designed around usage: simply a braided rubber covered with wire reinforcement. Neither exchanging material was reactive, while multiple replacing substances are non-combustible with proved very low risk of system failure as a result of chemical fire suppression agent reactions (Smith 2020).

Sprinkler heads and nozzles in a vehicle fire suppression system are made from heat- ad corrosion-resistant metals such as brass, stainless steel or aluminum with each material selected for the particular needs of that portion of the system. Brass is a common choice for its durability and resistance to corrosion, while stainless steel offers added strength for high-pressure needs. Aluminum Not as strong, but also lighter and, with a lower melting point than iron it can be used for less stress-bearing parts. The type of sprinkler design is a key to appropriately spreading material suppressants across different areas in order that the fire can quickly and completely be covered. The nozzle with structure and material engineering applied at extreme automotive tolerances provides the sprinkler to become a solid fire suppression system when needed (Jones, 2021) it operates in any cold or hot harsh environment.

The selection of materials is critical not only for performance but also for ensuring long-term reliability and the prevention of blockages from contaminants like dust or debris, helping maintain the system's readiness over time (Harris et al., 2020).

In summary, the automatic car fire extinguisher system is a critical development in automotive safety that meets the pressing requirement to shield occupants and automobiles from the destructive power of fire. The system reduces the chance of harm and damage by ensuring prompt fire detection and efficient suppression through the use of sensors, microcontrollers, and well-positioned nozzles. By facilitating automatic evacuation and prompt notification of emergency services, the integration of elements like the central lock system and Wi-Fi communication module further improves safety.

However, the design of the nozzles and the choice of materials need to be improved in order to maximize the system's performance. Further developments in heat resistance and flexibility could improve the system's dependability, particularly in high-temperature regions, even though the current materials are durable and corrosion-resistant. To guarantee more effective dispersion of extinguishing materials and enable quicker and more efficient fire suppression, the nozzle designs should also be improved. With these improvements, the automatic fire extinguisher system will be able to satisfy the strictest safety regulations and offer complete protection in a variety of fire situations.

3.2 Tubing and nozzles design

3.2.1 Boundary Conditions

Condition of the Inlet Boundary (Source Pressure): Assign the inlet pressure to the extinguisher's storage pressure, which for a fully charged extinguisher is approximately 55 bars. As the CO_2 is released, this pressure will gradually drop.

3.2. 2Condition of the Outlet Boundary (Ambient Pressure)

The CO2 flow and expansion via the orifice are driven by the ambient pressure (1 bar) at the outlet (nozzle exit).

3.2.3 The state of the thermal boundary

When CO_2 is released, the temperature at the nozzle and tubing system will drop considerably. To take thermal contraction into consideration, set boundary conditions to replicate these temperatures (such as -79°C) along the tube and nozzle.

3.2.4 Condition of the Wall Boundary (Material Limitations)

Both low temperatures and high pressure must be tolerated by the nozzle walls and tubing. Model mechanical strains brought on by high pressure and thermal stresses brought on by low temperature using boundary conditions.

3.2.5 Condition of Flow Boundaries

Make sure that every orifice contributes equally to the overall flow rate by setting the desired flow rate as a boundary condition at the nozzle orifice. To satisfy the overall requirement, for instance, each of the six orifices must maintain a flow rate of roughly 0.055 kg/sec.

4. Key parameters

4.1 Discharge Pressure

To maintain a sufficient flow rate and guarantee that CO_2 is released at a velocity high enough to effectively suppress fires, CO_2 extinguishers typically work at discharge pressures of 55–60 bars. Effective fire suppression requires a quick discharge that quickly lowers the oxygen content surrounding the fire and cools the flames, which is made possible by the high pressure (NFPA 10, 2021). Since the nozzle and tubing must be able to endure these high pressures without leaking or deforming, the increased discharge pressure also affects the materials chosen for these components. Durable materials, such as stainless steel or specialty thermoplastics, are usually chosen to meet these requirements because of their high-pressure resistance, capacity to withstand the extreme cold and quick expansion of CO_2 discharge without compromising structural integrity (UL 154, 2020).

4.2 Flow rate

The flow rate controls how fast CO_2 may reach the fire and is usually adjusted to allow the extinguisher to fully discharge in a predetermined amount of time, usually 10 to 15 seconds for standard-sized units. A 5 kg extinguisher, for example, could need a flow rate of 0.33 kg/s to discharge completely in roughly 15 seconds. In order to ensure reliable and efficient discharge performance, this flow rate is essential in calculating the proper tubing diameter and nozzle orifice size (ISO 7165, 2019). Mass flow rate=Discharge time Total /mass = 15s/5kg≈0.33kg/s

4.3 Tubing and nozzle material

Because CO_2 can drop as low as -79°C during discharge, tubing material needs to be able to tolerate both high pressure and extremely low temperatures. Because of their resilience to cold and resilience to rapid expansion, materials such as stainless steel are frequently selected (EN 3, 2014). In order for users to wield handheld extinguishers comfortably and avoid cold burns, the tubing material should also be lightweight and ergonomic.

PFA's remarkable blend of mechanical robustness, thermal stability, and chemical resistance makes it an extremely beneficial material for fire extinguishing system design. PFA is appropriate for applications involving the transportation of pressurized, chemically reactive chemicals like CO_2 due to its remarkable ability to preserve mechanical integrity at high temperatures (up to 260°C) and its resistance to chemical degradation (Martins & Lee, 2022). Additionally, PFA's low coefficient of friction guarantees smooth flow within tubes and components, eliminating pressure drops, and its low permeability lowers the possibility of gas loss during conveyance within fire suppression systems (Johnson & Kim, 2021). Furthermore, PFA has exceptional UV and weather resistance and is non-flammable. PFA tubing and nozzles are a great option for managing high-pressure CO_2 discharge while maintaining safety and reliability.

Table 2. Physical and Chemical Properties of PFA for Fire Suppression.

Property	Value
Density	2.12 - 2.17 g/cm³
Melting Point	302 - 310°C
Maximum Service Temperature	260°C
Thermal Conductivity	0.20 W/m·K
Tensile Strength	25 - 35 MPa
Elongation at Break	300 - 400%
Flexural Modulus	500 - 700 MPa
Coefficient of Friction	0.05 - 0.10
Chemical Resistance	Resistant to acids, bases, solvents
Water Absorption	< 0.03%
UV and Weather Resistance	Excellent
Flammability	Non-flammable

[https://www.matweb.com/search/DataSheet.aspx?MatGUID=77f6d9271049465b9ec8a2d138f3a93c&ckck=1]

To determine the wall thickness, we use **Barlow's formula** for cylindrical pressure vessels:

$$t = \frac{P.D}{2.S}$$

where:

- t = wall thickness
- P = internal pressure (assumed around 60 bars or 6.0 MPa)
- D = internal diameter (assumed 20 mm)
- S = allowable stress for the tubing material (20 MPa)

$$t = \frac{6,0.20}{2.20}$$

$$t = 3 \text{ mm}$$

Table 3. dimension and material properties of PFA3.4 Nozzle Orifice Size and Spray Pattern.

Material	Working Temperature (°C)	Working Pressure (bar)	Inner Diameter (mm)	Outer Diameter (mm)	Bursting Pressure (bar)	Allowable Stress (MPa)	Weight (kg/m)	Wall Thickness (mm)
PFA (Perfluoroalkoxy)	-200 to +260	55-60	20	26	90	20	0.67	3

A CO_2 extinguisher's nozzle orifice design is crucial to producing an efficient spray pattern that optimizes fire suppression capabilities. With an angle usually between 30 and 60 degrees, the nozzle design should ideally produce a cone-shaped or directed jet spray pattern. In order to smother flames and displace oxygen across the fire zone, the CO_2 must be able to cover a larger region, which is made possible by this spread (Martins et al., 2020). In order to ensure that CO_2 reaches the target region while reducing turbulence or rebound, a cone form offers the perfect balance of reach and coverage. As an alternative, directed jet sprays are useful in targeted applications where a narrow, high-velocity stream might work better, especially in small areas (Mehdizadeh *et al.,* 2018).

Maintaining the proper pressure and flow rate is essential for CO2 discharge; a smaller aperture boosts discharge velocity and produces a powerful jet with greater cooling efficiency. In contrast, when a bigger area needs to be covered, a larger orifice expands the CO_2 in a broader pattern but at a lower velocity, which is helpful (Kim *et al.,* 2019). According to research, CO2 gas's cooling effect—which results from its quick expansion and low boiling point—can greatly aid in putting out flames by bringing down the ambient temperature (Huang et al., 2021). By simulating flow characteristics and spray behavior, computational fluid dynamics (CFD) simulations are frequently used to optimize nozzle design, guaranteeing that the selected orifice size and spray angle are optimal for both reach and spread (Song & Lim, 2022).

To determine the internal diameter the orifice to achieve a total flow rate of **0.33 kg/sec** of CO_2, we can follow these steps:

Determine Flow Rate per Orifice: Since we are considering a single orifice in this case, the flow rate Q is already **0.33 kg/sec**.

Using the Flow Equation: The flow rate for a gas through an orifice can be expressed as:

$$Q = Cd.A.\sqrt{\frac{2.P}{\rho}}$$

Rearranging for area A:

$$A = \frac{Q}{Cd.\sqrt{\frac{2.P}{\rho}}}$$

Plug in Values: For CO_2, assume:

- **Discharge Coefficient (Cd)** = 0.7
- **Flow Rate (Q) =** 0,33 kg/s
- **Pressure (P)** = 55 bars = 5,500,000 Pa
- **Density (ρ)** of CO_2 at 55 bars is approximately **68 kg/m³**.

Calculate the Orifice Area: Now we can calculate the area using these values:

$$A = \frac{0,33}{0,7.\sqrt{\frac{2.5500000}{68}}}$$

$A = 1,172125.10^{-3}\text{m}^2$

Convert Area to Diameter: Finally, convert the area to diameter:

$$d = 2.\sqrt{\frac{A}{\pi}}$$

$$d = 2.\sqrt{\frac{1{,}172125.10^{-3}}{\pi}}$$

$$d = 0{,}38631544m$$

$$d = 38{,}63mm$$

In our case we will have 2 different designs with 6 and 4 orifices

To determine the internal diameter of the tubing and the orifice size of each nozzle when using **6 orifices** to achieve a total flow rate of **0.33 kg/sec** of CO_2, we can follow these steps:

Calculate the Flow Rate Per Orifice

Given that we have **6 orifices**, the flow rate for each orifice is calculated as follows:

$$\text{Flow Rate per Orifice } = \frac{Total\ Flow\ Rate}{number\ of\ orifices}$$

$$\text{Flow Rate per Orifice } = \frac{0{,}33}{6} = 0{,}055kg/s$$

Using the Flow Equation: The flow rate for a gas through an orifice can be expressed as:

$$Q = Cd.A.\sqrt{\frac{2.P}{\rho}}$$

Rearranging for area A:

$$A = \frac{Q}{Cd.\sqrt{\frac{2.P}{\rho}}}$$

$$A = \frac{0{,}055}{0{,}7.\sqrt{\frac{2.5500000}{68}}}$$

$A = 1{,}953542.10^{-4}\text{m}^2$

Convert Area to Diameter: Finally, convert the area to diameter:

$$d = 2.\sqrt{\frac{A}{\pi}}$$

$$d = 2.\sqrt{\frac{1{,}953542.10^{-4}}{\pi}}$$

$$d = 0{,}015771m$$

$$d = 15{,}771mm$$

For 4 orifices, the flow rate for each orifice is calculated as follows:

$$\text{Flow Rate per Orifice } = \frac{Total\ Flow\ Rate}{number\ of\ orifices}$$

$$\text{Flow Rate per Orifice } = \frac{0{,}33}{4} = 0{,}0825kg/s$$

Using the Flow Equation: The flow rate for a gas through an orifice can be expressed as:

$$Q = Cd.A.\sqrt{\frac{2.P}{\rho}}$$

Rearranging for area A:

$$A = \frac{Q}{Cd.\sqrt{\frac{2.P}{\rho}}}$$

$$A = \frac{0{,}0825}{0{,}7.\sqrt{\frac{2.5500000}{68}}}$$

$A = 2{,}930313.10^{-4}\text{m}^2$

Convert Area to Diameter: Finally, convert the area to diameter:

$$d = 2.\sqrt{\frac{A}{\pi}}$$

$$d = 2.\sqrt{\frac{2{,}930313.10^{-4}}{\pi}}$$

$$d = 0{,}019315m$$

$$d = 19{,}315mm$$

5. Results and discussion

5.1 Designs:

5.1.1 Assembly illustrations

Gas tank/ hood interieur nozzle assembly

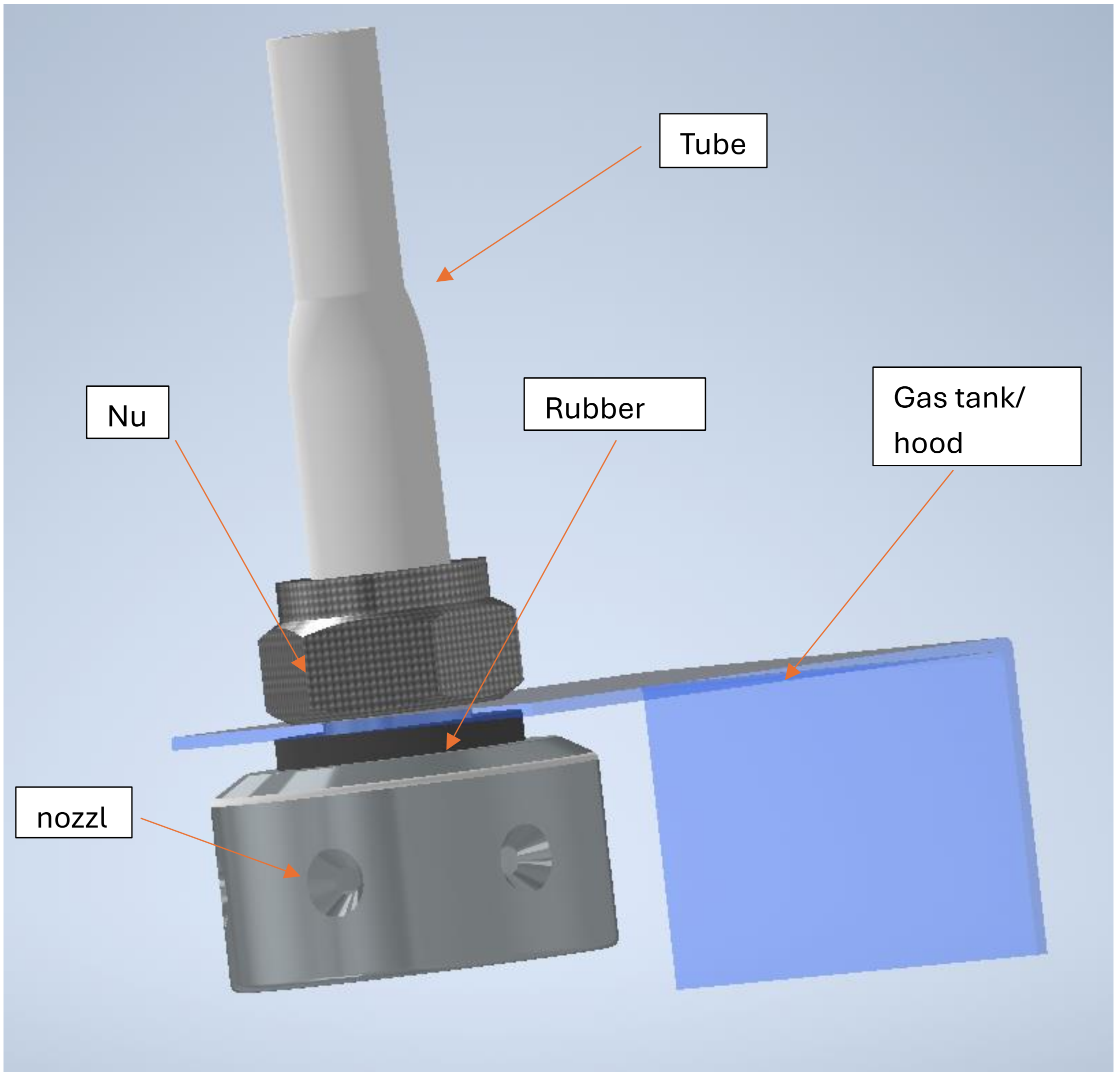


Figure 11. Assembly of the nozzle in the gas tank and engine compartment.

5.1.2 Flanged fitting

When durability and sealing are crucial, a flanged fitting is a dependable and efficient choice for joining parts like nozzles or tubing to car fuel tanks. This kind of fitting has a flat surface, or "flange," that is welded or bolted to the tank wall to form a tight, leak-proof seal. The flange design is a popular option for gasoline systems that need to be serviced on a regular basis since it makes disassembly simple, which is beneficial for maintenance and inspection. Flanged fittings offer a reliable option for a leak-proof connection, which is essential for safety in fuel tanks that hold volatile liquids like gasoline or diesel (Bauccio, 1994).

To further stop leaks and withstand chemical corrosion, flanged fittings are frequently built with gaskets or O-rings made of fuel-resistant materials, such as Viton or fluoropolymers. Additionally, they can handle a variety of materials, such as aluminum, stainless steel and PFA , which are frequently utilized in automotive applications because of their strength and resistance to corrosion (Smith et al., 2002). Flanged fittings are a robust and versatile choice for fuel tank applications because they lower the chance of connection failure from vibration and temperature cycling, which are common in automotive conditions.

5.1.3 Wheel nozzle assembly

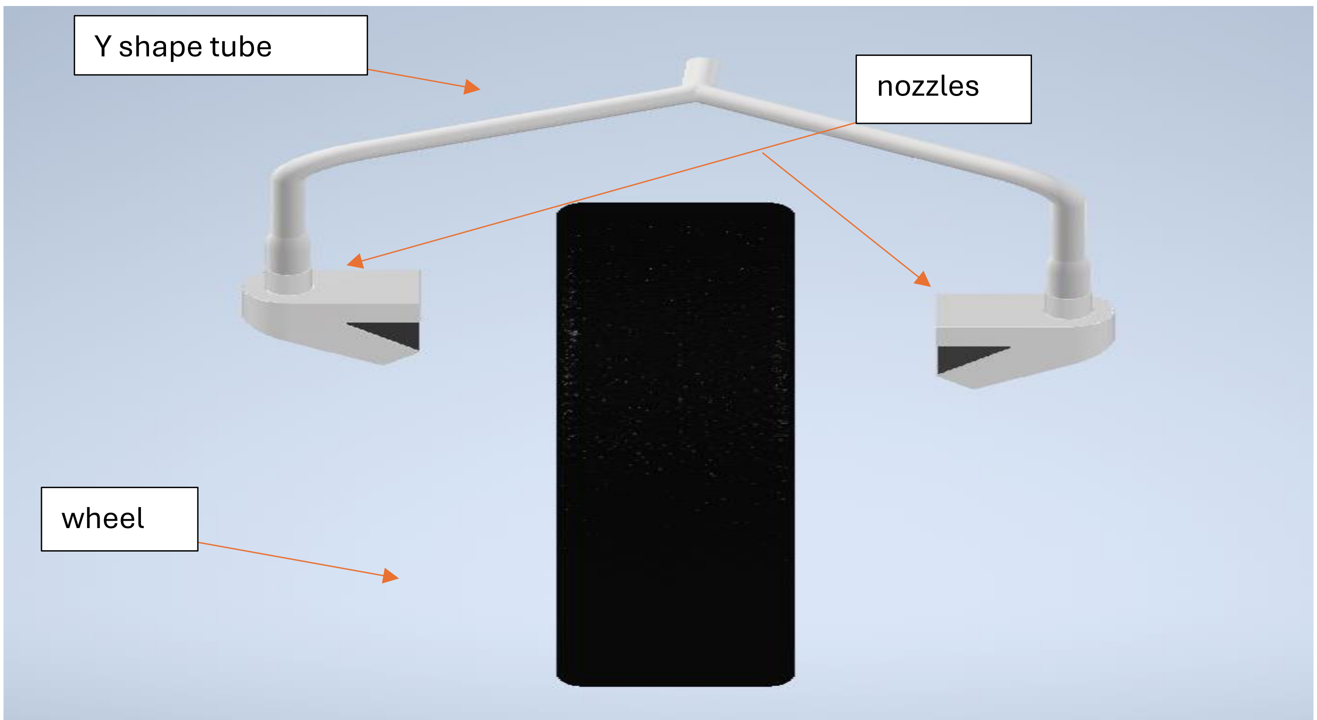


Figure 12.Assembly of the nozzles at the wheels.

5.1.4 Barbed fitting:

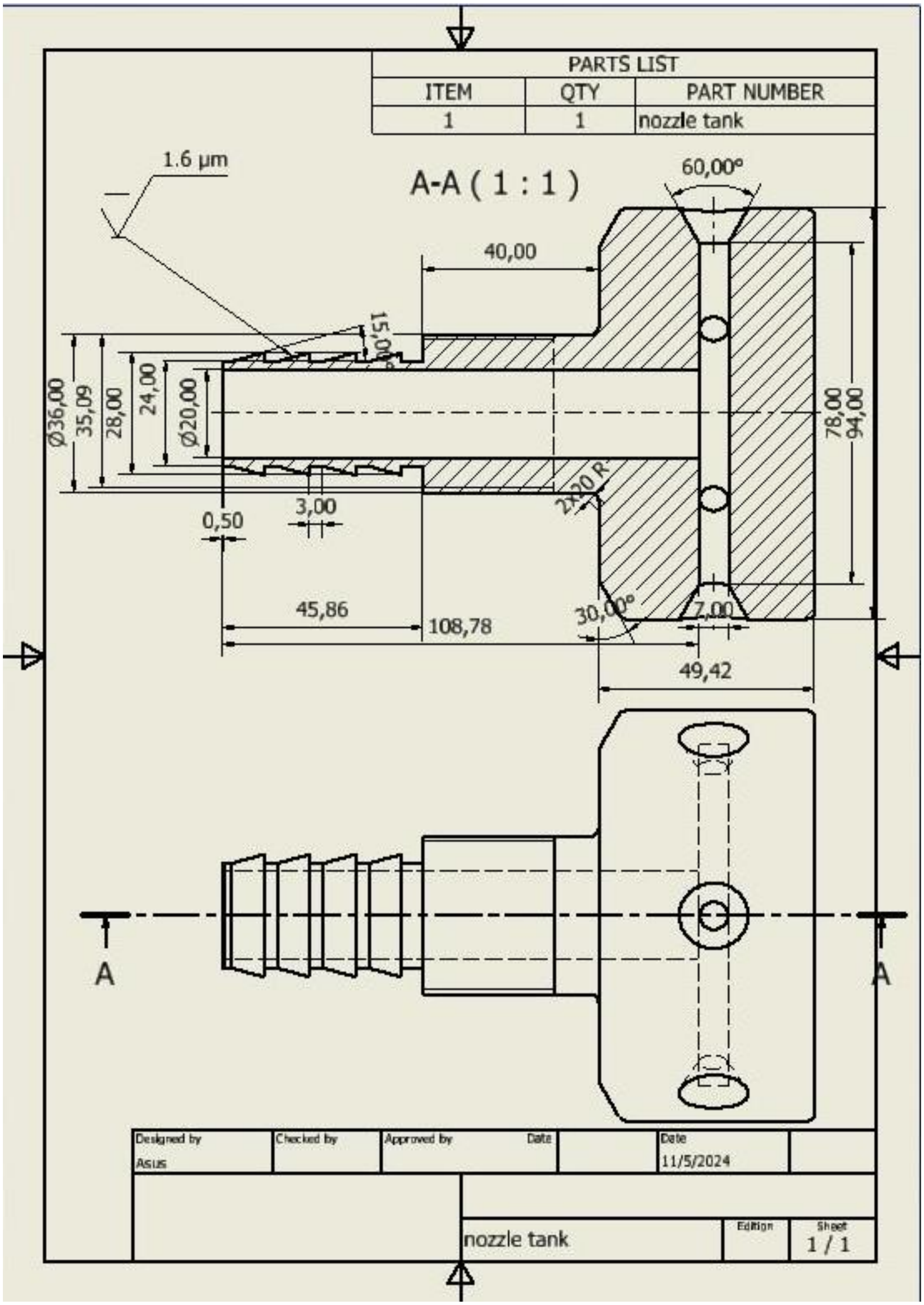
Achieving a secure connection requires careful dimensioning and material considerations when designing a barbed fitting for a PFA (Perfluoroalkoxy) tube with an inner diameter (ID) of 20 mm and a wall thickness of 3 mm. PFA is perfect for demanding applications because of its great chemical resistance and flexibility (Kroschwitz & Seidel, 2004). To achieve an interference fit that guarantees a tight seal, the barb's outer diameter (OD) should be somewhat more than the tube's ID, around 21.5–23 mm. A barb angle of 15 to 30 degrees facilitates simple insertion and secure retention, while a barb height of roughly 10 to 15% of the tube's ID (or 2 to 3 mm) improves grip without overstressing the tube.

The PFA tube can compress between barbs with a barb spacing of 3 to 5 mm, and employing 2 to 4 barbs is usually ideal for striking a balance between grip and fitting ease. For damage-free insertion, the barb's leading tip should be tapered between 5 and 10 degrees. Material compatibility is crucial. For chemical endurance, stainless steel or a resistant plastic such as PVDF are good options, and a smooth surface finish (around 1.6 µm Ra) lowers the possibility of tube abrasion during fitting (Bauccio, 1994).

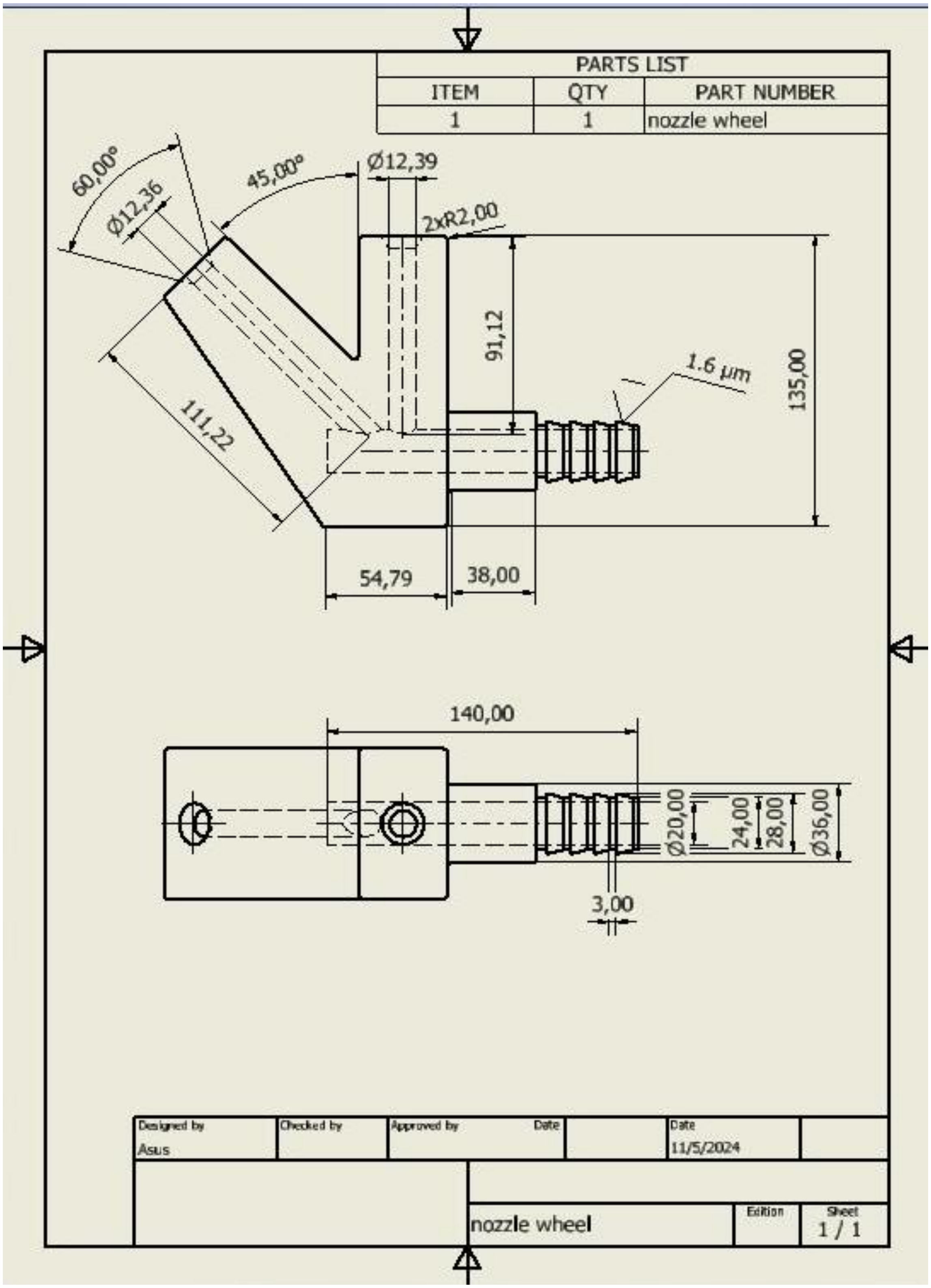
Prototyping and testing in a CAD environment are essential for confirming fit and examining the tube for leaks or stress when the design is finalized. Barb OD 21.5–23 mm, barb height 2–3 mm, barb angle 15–30 degrees, spacing 3–5 mm, and insertion taper 5–10 degrees are important factors (Smith et al., 2002). A secure connection appropriate for high-purity and chemical-resistant applications is guaranteed when these rules are followed.The technical drawings below show the practical dimensions for the barbed fitting.

5.2. Technical drawing

5.2.1 Gas tank / engine compartment nozzle



5.2.2 Wheel nozzle



5.3 Simulation

I imported my design geometry and set up the material characteristics for PFA, taking note of its particular thermal qualities such as density, specific heat, and thermal conductivity, in order to simulate a part in ANSYS Transient Thermal that experiences a brief fire exposure followed by quick cooling. Twenty degrees Celsius is the initial criterion that I established. I applied a heat flux to the exposed surface to simulate fire intensity during the three-second fire exposure phase. I estimated this to be about 100,000 W/m² to represent moderate fire conditions. I configured this heat flux to activate from 0.01 seconds, peaking instantly, and holding it for 3 seconds before lowering the heat input back to ambient using ANSYS's tabular data input. After that, I set the bulk temperature at -73°C and used a convection boundary condition with a high heat transfer coefficient (around 200 W/m²·K) to mimic a sudden cooling phase at -73°C for 15 seconds.

Using an initial time step of 0.1 seconds and enabling automatic modifications to capture the quick temperature changes, I modified the time-stepping controls in the Analysis Settings to guarantee good accuracy. I evaluated the stress and strain that the part would experience as a result of thermal expansion and contraction by combining the thermal simulation with a static structural analysis. This made it possible for me to assess whether the PFA material could tolerate the heat stresses without breaking or deforming too much. I could ascertain whether the design was strong enough to withstand these drastic temperature swings without failing by looking at the stress and strain distributions.

In order to incorporate perfluoroalkoxy (PFA) as a custom material in ANSYS Workbench, we will need to develop a new material description that possesses features that are suitable for static structural and transient thermal. The data used in this simulation is on the image below.

Properties of Outline Row 3: PFA

	A	B	C	D	E
1	Property	Value	Unit		
2	Material Field Variables	Table			
3	Density	2150	kg m^-3		
4	Isotropic Elasticity				
5	Derive from	Young's Modulus an...			
6	Young's Modulus	700	Pa		
7	Poisson's Ratio	0.46			
8	Bulk Modulus	2916.7	Pa		
9	Shear Modulus	239.73	Pa		
10	Tensile Yield Strength	15	MPa		
11	Compressive Yield Strength	20	MPa		
12	Tensile Ultimate Strength	35	MPa		
13	Compressive Ultimate Strength	30	MPa		
14	Isotropic Thermal Conductivity	0.25	W m^-1 K^-1		
15	Specific Heat Constant Pressure, C_p	1200	J kg^-1 K^-1		

Figure 13.Properties of PFA.

5.4 Comparison

5.4.1 Gas tank / engine compartment nozzle

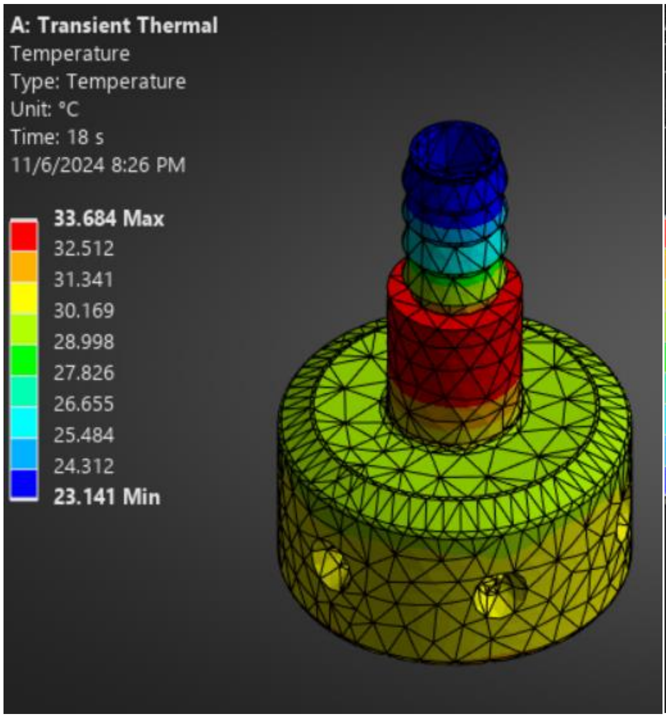


Figure 15: temperature PFA

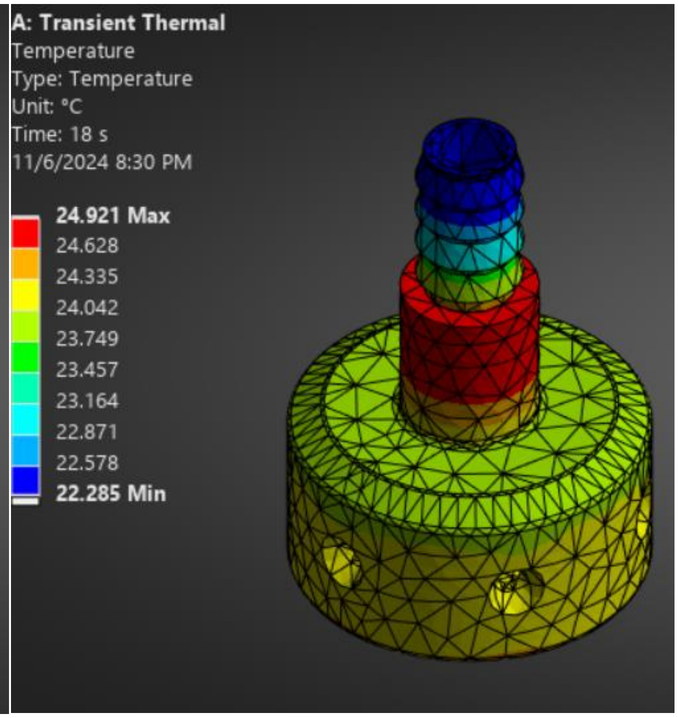


Figure 14: temperature steel

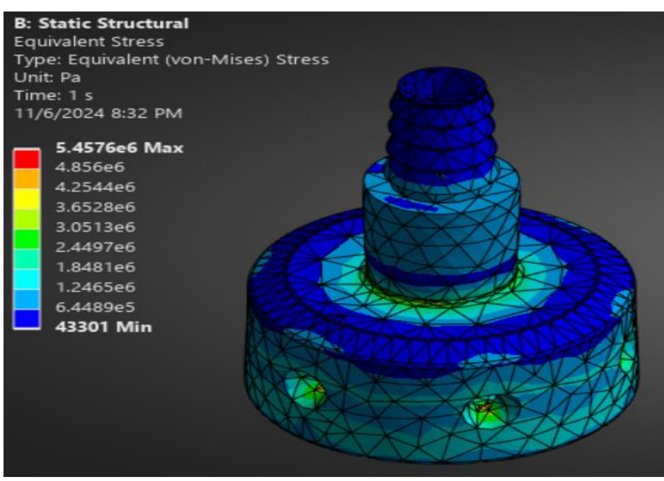


Figure 17: equivalent elastic strain steel

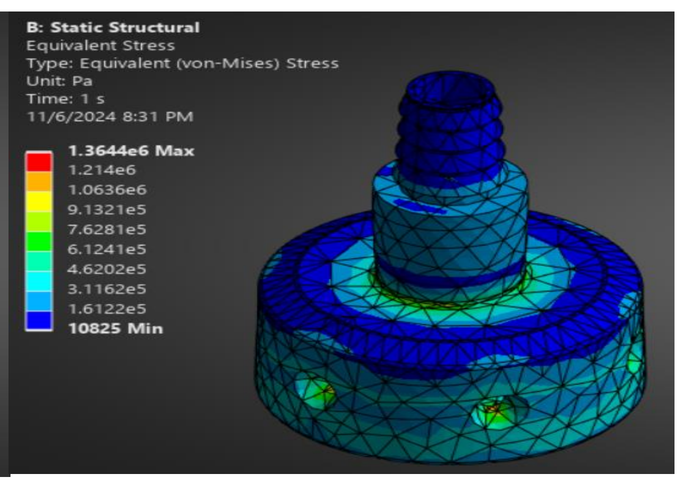


Figure 16: equivalent elastic strain PFA

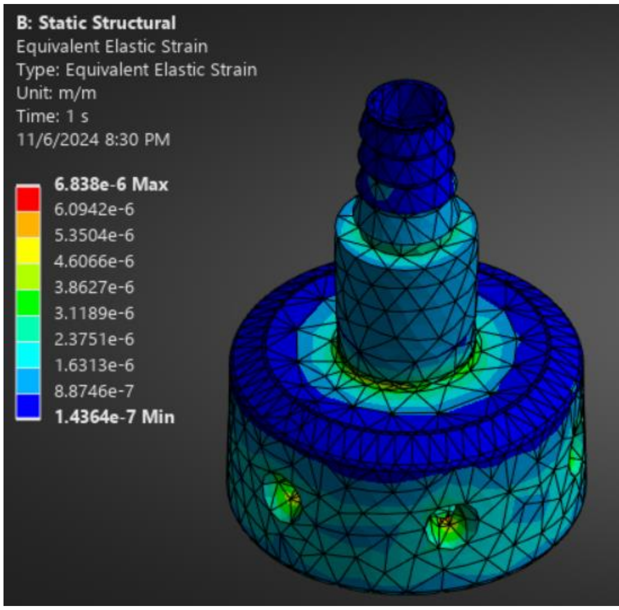


Figure 19: equivalent stress steel

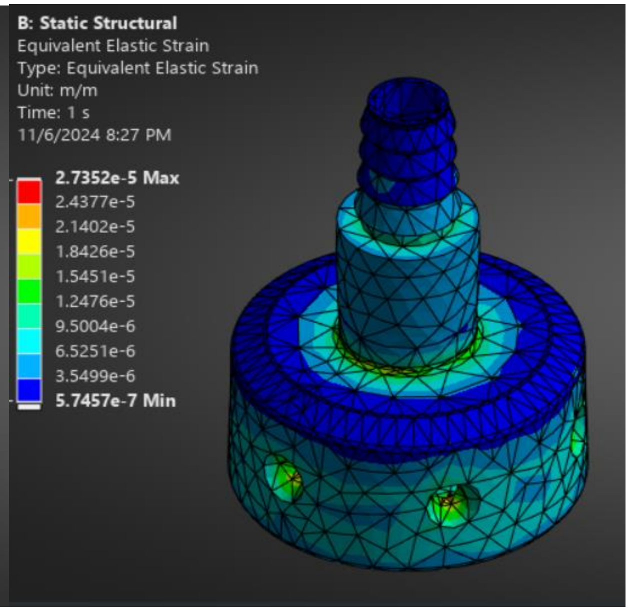


Figure 18: equivalent stress PFA

5.4.2 Wheel nozzle

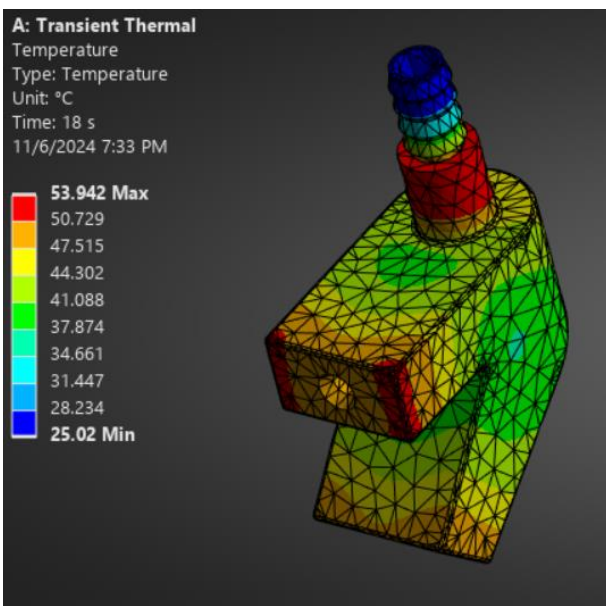


Figure 21. equivalent stress steel

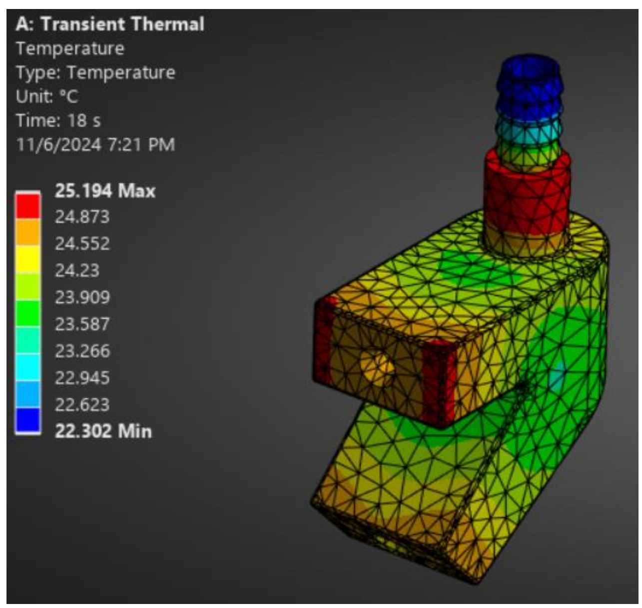


Figure 20. equivalent stress PFA

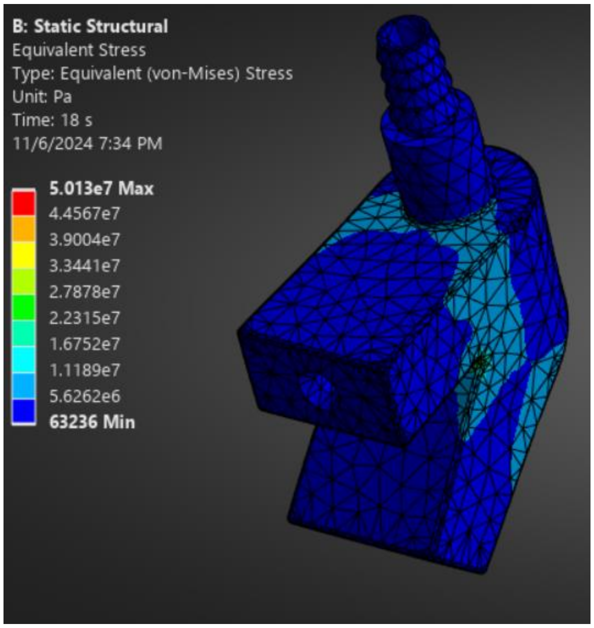


Figure 25: temperature PFA

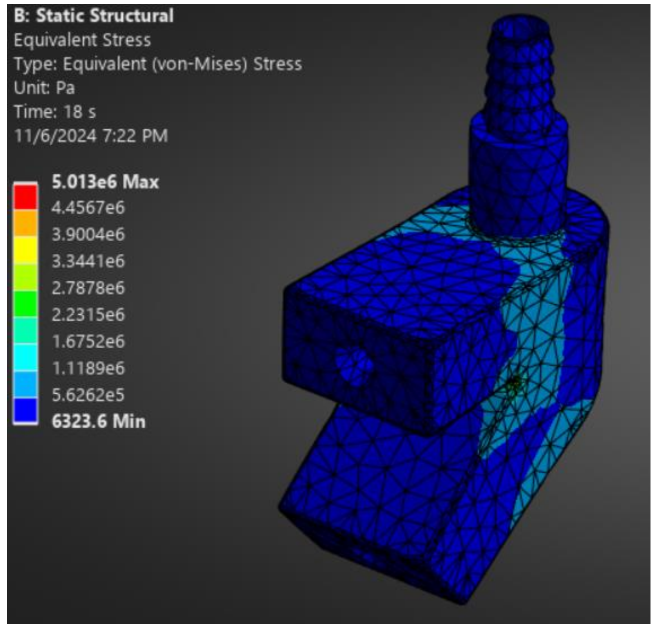


Figure 24: temperature steel

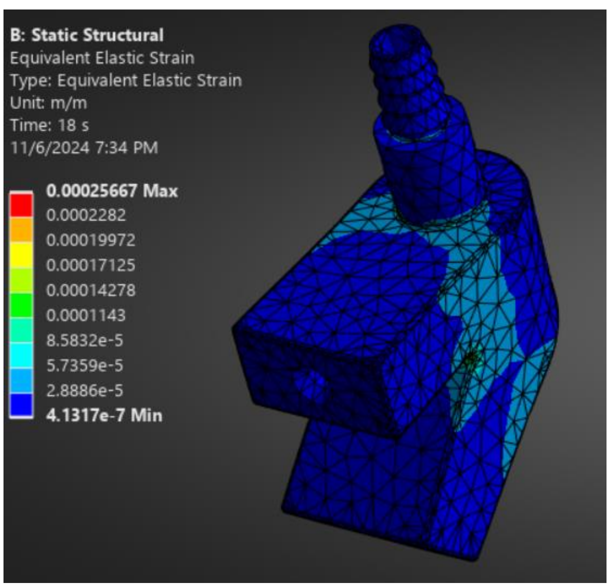


Figure 22:equivalent elastic strain PFA

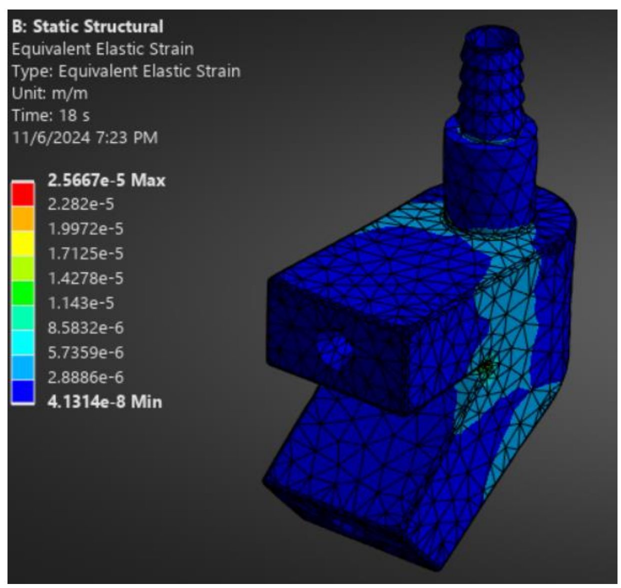


Figure 23:equivalent elastic strain steel

According to the results of this thermal simulation, PFA and steel performed similarly in terms of durability under these particular fire and cooling conditions. The temperatures attained during the fire exposure stayed below the 305°C melting point of PFA, preventing any thermal degradation of the material even though it has a lower melting point. Regarding stress, the PFA component's maximum recorded stress values fell within its permissible stress limit of roughly 10–15 MPa. This is comparable to how steel performed, which likewise remained within its permitted stress range because of its far greater temperature resistance. Furthermore, the simulation did not surpass the permissible strain for PFA, which is typically approximately 0.03 (or 3%), guaranteeing that the material maintained its structural integrity without experiencing undue deformation. Naturally, steel, which is renowned for having a higher yield strength and rigidity, stayed well within its bounds. PFA is therefore a good substitute for steel in situations involving short, controlled fire exposure and quick cooling conditions because it not only withstood the thermal stress without melting but also remained within safe bounds for both stress and strain.

6. Conclusion

Based on the findings of this thesis, PFA (Perfluoroalkoxy) emerges as a superior choice over steel for automotive fire suppression applications due to its unique combination of beneficial properties, particularly in high-performance and safety-critical environments. Although steel is widely recognized for its mechanical strength and heat resistance, PFA offers significant advantages that make it more suitable in this context, especially under conditions involving fire exposure and rapid cooling.

PFA's remarkable thermal stability—its melting point of 305°C was never surpassed throughout the fire simulations—is one of its most noteworthy advantages. PFA remained much below this melting temperature throughout the fire and cooling processes, maintaining its structural integrity and avoiding any thermal softening or degradation. Furthermore, PFA's permissible stress range (10–15 MPa) and strain limit (about 3%), which were not surpassed throughout the testing, guaranteed that the material could withstand mechanical loads and heat stressors without deforming or failing. Steel's characteristics, in contrast, also stayed within acceptable bounds; however, PFA has an advantage in withstanding abrupt temperature fluctuations without developing residual stress or warping because of its flexibility and resistance to thermal cycling.

The fact that PFA is lightweight is still another important benefit. Because PFA is so much lighter than steel, the fire suppression system's total weight is greatly decreased. The vehicle's handling, general performance, and fuel efficiency are all improved by this weight decrease. Manufacturers can reduce weight without sacrificing durability or safety by using PFA components in place of steel.

In addition to its thermal and mechanical advantages, PFA is naturally resistant to corrosion, in contrast to steel, which over time is vulnerable to rust and chemical deterioration when exposed to corrosive substances or moisture. PFA is perfect for automotive applications where exposure to different chemicals, fuels, and environmental conditions is frequent because of its non-reactive surface and chemical resistance. This corrosion-free quality lowers maintenance needs and improves the fire suppression system's long-term dependability, both of which are critical for the longevity and safety of vehicles.

In automotive applications, PFA's superior electrical insulation qualities provide an additional degree of security when utilized in close proximity to wiring or electronic components. In fire scenarios where sparks or electrical failures could be dangerous, this insulating property offers further protection.

7. Summary

By contrasting its performance with that of conventional steel, this thesis investigates the suitability of perfluoroalkoxy (PFA) as a material for vehicle fire suppression systems. PFA exhibits notable benefits in terms of corrosion resistance, lightweight composition, thermal stability, and durability under heat stress, as demonstrated by simulation and analysis. With a melting point of 305°C that was never surpassed during simulated fire exposure, PFA is stable at high temperatures in contrast to steel, which is prone to corrosion and adds significant weight. Furthermore, PFA survived the mechanical and thermal loads in both fire and rapid cooling situations without going beyond its permissible strain limits (~3%) or stress limits (10–15 MPa).

PFA's lightweight design, which enhances fuel economy and facilitates handling in automobiles, and its corrosion-free quality, which guarantees long-term dependability with less maintenance, are two of its key advantages, according to this study. PFA improves safety around electronic components by providing superior electrical insulation. Overall, the results show that PFA offers a strong, low-maintenance, and effective substitute for steel, providing not only heat and strength resistance but also weight reduction and corrosion resistance—all of which are critical for contemporary automotive applications. According to this thesis, PFA is the best material for automotive fire suppression systems because it provides performance advantages that meet the requirements of durability, efficiency, and vehicle safety.

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