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Design and Analysis of Lightweight Fire Extinguishers using Alternately Available Metals

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ABSTRACT: This research aims to optimize the weight of already existing fire extinguishers containing Carbon Dioxide as per BIS standards IS 2190: 2010 and IS 7285-1: 2004. In the paper, an optimized and new design is proposed to minimise the weight of the pressure vessel making it easier to store in smaller compartments and also allowing faster hand-held use during emergency. The weight has been reduced substantially by using proposed materials and FEA simulations were performed on the model to check for failures under the set test conditions with the aim to minimise volume of metal used that is able to withstand the hydrostatic load of pressure gas. ANSYS Mechanical 18.2 was used for performing 3d pressure analysis while the model was designed on Solidworks 2016. A Multi Frontal Direct Solver was preferred to reach the solutions in every case. The analysis results of all the materials were compared and finally, a material was selected that was tough enough to clear the safety standards and extremely light so that even old people could use it without any issues. A simple shell of Titanium Grade-5 Alloy was found to be the proper and optimal choice to obtain good mechanical properties and lightweight.

Keywords: fire extinguisher, weight reduction, ANSYS, alloys.

I. INTRODUCTON

Fire Extinguishers are the most commonly used safety precautionary device used in the industry and households these days. In industrial environments, regulation dictates a very strict fire prevention policy. In residential areas, however, a lot less precautions are in place. The only safety measures are the conceptual and structural design of the buildings. Although a large percentage of the fires people are confronted with occur at home, most people do not have any fire extinguishing equipment at home. A lot of fires that result in destroying one's belongings and cause a lot of casualties, can be easily controlled, even without training, if a proper extinguisher or fire blanket is present and the fire is noticed in an early stage. 95 percent of all direct property damage occurs once the fire has progressed beyond the early stages. [1] This can be easily prevented using Portable Fire Extinguishers. Most of the Fire Extinguishers used in the household are heavy and cannot be used by old people in case of emergency. Hence a lightweight design is essential to solve this problem. Besides this, the design can also be used in industrial applications like in lightweight vehicles and aircraft systems which cannot carry a lot of load. This will encourage people to install fire extinguishers even at sites where there is lack of space or facilities resulting in increase of safety standards. [11], [13]

Most of the household fire extinguishers these days contain water as extinguishing agent. But water has the least set of applications out of all the other available extinguishing agents, hence Carbon Dioxide fire extinguishers are preferred more since they work on almost every type of fire and is also relatively cheaper and lighter. In carbon dioxide extinguishers, the CO2 is retained in liquid form under 800 to 900 psi and is "self-expelling," meaning that no other element is needed to force the CO2 out of the extinguisher. Carbon dioxide (CO2) extinguishers are effective against many flammable liquid and electrical fires (Class B and C). The liquified carbon dioxide, at a pressure that may exceed 800 psi depending on size and use, is expelled through a flared horn. Activating the squeeze-grip handle releases the CO2 into the air, where it immediately forms a white, fluffy "snow." The snow, along with the gas, substantially reduces the amount of oxygen in a small area around the fire. This suffocates the fire, while the snow clings to the fuel, cooling it below the combustion point. The greatest advantage to the CO2 extinguisher is the lack of permanent residue. Unlike CO2 "snow,"; water, foam, and dry chemicals can ruin otherwise undamaged components. [12] Hence, we have considered Carbon Dioxide gas as the fire extinguishing agent. This will affect the lifetime of the vessel since CO2 in its pure gaseous form is not corrosive in nature and has lower toxicity values than more effective dry chemicals and halons. Studies have shown a wide variability of CO2 tolerance. Blood concentrations ranged between at least 0.055 and 0.085 atm. (41.8–64.6 mmHg) among subjects with symptoms, suggesting that a safe CO¬2 exposure level cannot be characterized by a single value. Concentrations of fatal cases of carbon dioxide vary between 14.1 and 26% CO2 and an accompanying O2 level between 4.2 and 25%. It was also determined that CO2 tolerance decreases with age ($p < 0.0001$) and suggested that smokers might have more tolerance due to habituation of higher CO2 levels in cigarette smoke. [14] Indian legislation dictates that portable fire extinguishers have to comply with BIS standards- IS 15683:2006 “Portable Fire Extinguishers- Performance and Construction

Specifications” as well as IS 2190: 2010 “Selection, Installation and Maintenance of First-Aid Fire Extinguishers” and IS 7285. These include an entity of empiric design rules and a series of tests the extinguisher has to pass. Furthermore, they limit the types of materials that are allowed for the construction of the portable fire extinguisher. [15] These prescriptions will be limiting factors at several levels of the design. Improvement of current designs is possible on several aspects. In this study, the most prominent aspect will be using carefully selected materials in an optimized configuration. This might allow the construction of a (super-)lightweight extinguisher, with superior performance, as discussed below. Optimal materials selection and usage might as well make more daring designs possible. [16]

II. MATERIAL SELECTION

Steel Alloys (mostly Si-Mn Steel) are used for construction of fire extinguisher pressure vessels. A typical modern “lightweight” fire extinguisher, consists of a steel (ST12- European Standards) cylindrical hull, with a typical thickness of about 1.5 to 2 mm. [9] On the inside of the hull, usually a coating, (epoxy, polyester) is fitted to protect it from corrosion. On the outside, the hull is protected by a layer of paint. Aluminium alloys (especially 6-series) are also used in the construction of lightweight fire extinguishers. [10] A better and more lightweight system is required to make it much more portable and useable in lightweight vehicles and aircrafts along with household use. [20] Hence a thorough study of multiple materials is required in order to come up with a material that is optimum in terms of strength, processability, cost and most importantly weight. Applied to the case of a portable fire extinguisher, the following materials are unsuitable for manufacturing: Ceramics or glasses: since they are very brittle and sometimes porous. Magnetic materials: magnetic behaviour is an undesirable property in this case. [17] Materials that are not watertight (fibres, particulates, foams,): the contents of the vessel may not be lost.

Apart from the demands due to BIS safety standards, several material characteristics will be desirable from the viewpoint of the producer and his customers. First of all, the designer or user will favour low weight, low cost, good formability and ductility, … On the other hand, society in general will be concerned with sustainability and the impact on the environment. In this respect, the recyclability of the materials, the energy cost related to the production of the device, greenhouse gas-exhaust caused by construction and the availability of the selected materials (rare resources) will be important factors. [18] Even the amount of water needed for the production can be used as a criterion. These "environmental costs" should be reduced as much as reasonably possible. Several degrees of sustainability can be considered. For some materials recycling simply is not an option (e.g. some composites can only be broken down by combustion). For other materials, a distinction will be made between cradle to grave recyclability, where the material is degraded every time it is recycled, and cradle to cradle recyclability where materials can be recycled without degrading. Steel alloys often allow cradle to cradle recycling, which gives them an inherent advantage compared to other materials. [6] . The challenge is to design the device as such, that it complies with both regulations and satisfies as much of the previously mentioned desirable characteristics as possible. Keeping in mind all the design philosophies mentioned above, the following materials shown in TABLE I, were chosen for the study

Table I: Materials selected for study and their data [2-4]

Material	**Density**	**Ultimate Tensile Strength**	**Tensile Yield Strength**	**Modulus of Elasticity**	**Shear Modulus**	**Melting Point**	**Poisson's Ratio**	**BHN**
Aluminium 7075-T6 alloy	2.81 g/cc	572 MPa	503 MPa	71.7 GPa	26.9 GPa	477 - 635 °C	0.33	150
Titanium 6246 Alloy	4.65 g/cc	1200 MPa	1050 MPa	114 GPa	42.9 GPa	1595 - 1675 °C	0.33	360
Titanium Grade 5 alloy 6Al-4V	4.43g/cc	1170 MPa	1100 MPa	114 GPa	44 GPa	1604 - 1660 °C	0.33	379

TABLE II: DATA OF CURRENTLY MOST-USED MATERIAL[5]

Material	Density	Ultimate Tensile Strength	Tensile Yield Strength	Modulus of Elasticity	Shear Modulus	Melting Point	Poisson's Ratio	BHN
Si-Mn steel 32G2SF1	7.45 g/cc	940 MPa	870 MPa	200 GPa	79.3 GPa	-	0.26	-

III THEORY

Generally, cylinder pressure vessels are divided into two groups-thin and thick cylinders. A cylinder is considered thin when the ratio of its inner diameter to wall thickness is more than 15. There are two principal stresses in thin cylinder-the circumferential or tangential stresses (σ_t) and longitudinal stress (σ_l). It is assumed that the stresses are uniformly distributed over the wall thickness. [19] Considering equilibrium of forces acting on the half portion of cylinder of unit length.

$D_iP_i = 2\sigma_t t$

$$\sigma_t = P_iD_i/2t \qquad (1)$$

P_i = internal pressure (N/mm^2) D_i = internal diameter of cylinder (mm) t = cylinder wall thickness (mm)

Considering equilibrium of forces in the longitudinal direction. $\pi P_iD_i^2/4 = \pi\sigma_l D_i t$

$$\sigma_l = P_iD_i/4t \qquad (2)$$

Taking equations (1) & (2) into considerations it is seen that the circumferential stress is twice the longitudinal stress. Therefore, we have these criteria:

i. When the circumferential stress exceeds the yield strength, failure will occur lengthwise. Also, when the longitudinal stress exceeds the yield strength, failure will occur in the transverse section. It can be concluded that in case of thin cylinders subjected to the internal pressure, the tendency to burst lengthwise is twice as great as at transverse section.
ii. In case of thin cylinders subjected to internal pressure, the circumferential stress is the criterion for determining the cylinder wall thickness. $t = P_iD_i/2\sigma_t$

where (σ_t) is the permissible tensile strength for cylinder

material. [7]

- In this analytical analysis it is assumed that there are no longitudinal circumferential joints in the cylinder, ie. A seamless cylinder. Also, we have assumed the cylinders to be thin cylinders since in each case the ratio of diameter to wall thickness is adhering to the criteria. Hence using slight modification, the following formula was derived for wall thickness of thin cylinders,

$$t = \frac{Pi\ Di}{2\sigma_t\eta - P_i} + CA$$

- The neck of the extinguisher is also designed keeping the minimum thickness criteria. The opening size may vary in different models as per the required jet velocity but the minimum thickness required for the neck is given by,

$$t = \frac{Pi\ Di}{2\sigma_t\eta - P_i} + CA$$

Formed heads are used as end closures for the cylindrical pressure vessels. There are two types of end closures-domed heads and conical heads. The domed heads are further classified into three groupshemispherical, semi-ellipsoidal and

- torispherical. Hemispherical heads have minimum plate thickness, minimum weight and consequently lowest material cost. However, the amount of forming required to produce the hemispherical shape is more. The thickness of the hemispherical head is given by,

$$t = \frac{Pi\ Ri}{2\sigma t\eta - 0.2P_i} + CA \quad [7]$$

t = minimum thickness of the shell plate (mm) P_i = design pressure (MPa or N/mm^2) D_i = allowable stress for the plate material (N/mm^2) η = weld joint efficiency CA = Corrosion allowance (mm)

Since the calculations are done on a seamless single piece cylinder, hence weld joint efficiency is considered as 1 and corrosion allowance is taken as 0.

IV CALCULATION

Let us consider Clean Carbon Dioxide Gas Based Fire Extinguishers manufactured by PROTEC Model PRO 5-CD [8] for dimensions and reference weight. This size is ideal for usage at home and for putting out small household fires.

The dimensions are-

- Capacity- 5Kg.
- Height - 700 mm.
- Diameter - 152 mm.
- Fire Rating - 89B

Besides these, the pressure specifications are -

- Working Pressure - 70 bar
- Test Pressure - 250 bar

Taking Factor of Safety as - 3

Si-Mn steel 32G2SF1 (existing shell material)
Density= 7450 Kg/m^3
Tensile Yield Strength = 870 N/mm^2
Therefore Max. Allowable Stress = 870/3 = 290 N/mm^2
Cylinder Shell Thickness : Using $t_c = pD_s / (2fJ - p)$ t_c = 6.84 mm.
End Shell Thickness : Using $t_h = pR_s / (2fJ - 0.2p)$ T_h = 3.30 mm.
Volume of metal used: $V= \pi/4(600-D_i)(D_o^2 - D_i^2) + \pi/6(D_o^3 - D_i^3)$ = 1.938×10^{-3} m^3
Therefore, Mass of metal used = V x Density = 14.44 Kg.

Now, consider the alternative materials proposed -

a. *Aluminium 7075-T6 Alloy* Density= 2810 Kg/m^3
Tensile Yield Strength = 503 N/mm^2

Therefore Max. Allowable Stress = 503/3 = 167.66 N/mm^2 Cylinder Shell Thickness : Using $t_c = pD_s / (2fJ - p)$ t_c = 12.24 mm.
End Shell Thickness :Using $t_h = pR_s / (2fJ - 0.2p)$ T_h = 5.75 mm.
Volume of metal used: $V= \pi/4(600-D_i)(D_o^2 - D_i^2) + \pi/6(D_o^3 - D_i^3)$ = 3.331×10^{-3} m^3

Therefore, Mass of metal used = V x Density = 9.36 Kg. Percentage reduction in weight = 35.18%

b. *Titanium 6246 Alloy*
Density= 4650 Kg/m^3

Tensile Yield Strength = 1050 N/mm^2 Therefore Max. Allowable Stress = 1050/3 = 350 N/mm^2 Cylinder Shell Thickness : Using $t_c = pD_s / (2fJ - p)$ t_c = 5.63 mm.
End Shell Thickness :Using $t_h = pR_s / (2fJ - 0.2p)$ T_h = 2.73 mm.

Volume of metal used: $V= \pi/4(600-D_i)(D_o^2 - D_i^2) + \pi/6(D_o^3 - D_i^3)$ = 1.610×10^{-3} m^3

Therefore, Mass of metal used = V x Density = 7.50 Kg.

Percentage reduction in weight = 48.06%

c. *Titanium Grade 5 Alloy-6Al-4V* Density= 4430 Kg/m^3

Tensile Yield Strength = 1100 N/mm^2 Therefore Max. Allowable Stress=1100/3=366.66 N/mm^2

Cylinder Shell Thickness : Using $t_c = pD_s / (2fJ - p)$ t_c = 5.36 mm.

End Shell Thickness :Using $t_h = pR_s / (2fJ - 0.2p)$ T_h = 2.61 mm.

Volume of metal used: $V= \pi/4(600-D_i)(D_o^2 - D_i^2) + \pi/6(D_o^3 - D_i^3)$ = 1.536×10^{-3} m^3

Therefore, Mass of metal used = V x Density = 6.80 Kg.

Percentage reduction in weight = 52.90%

V= volume

D_o = Outer Diameter

D_i = Inner Diameter

V ANALYSIS

The solid model for each fire extinguisher was made on Solidworks 2016 for analysis. Each cylinder was given the minimum required thickness as derived from the calculations. The pressure analysis was performed on ANSYS Mechanical 18.2 APDL. Each model was applied with the test pressure of 250 bar and criteria like Total Deformation, Von-Mises Stress, and Factor of Safety were checked for each model. Factor of Safety> 1.3 was kept as a criterion for failure in each case.

Fig. 1: Solid Model of Fire Extinguisher created on Solidworks 2016

After the model was made and imported to ANSYS as a parasolid file, Meshing was performed on the geometry. Uniform fine mesh size was kept with edge length 0.7mm. Symmetry was inserted on 3 planes to simplify calculations. The resulting geometry consisted of 20,53,997 nodes and 4,63,809 elements with skewness of 0.74.

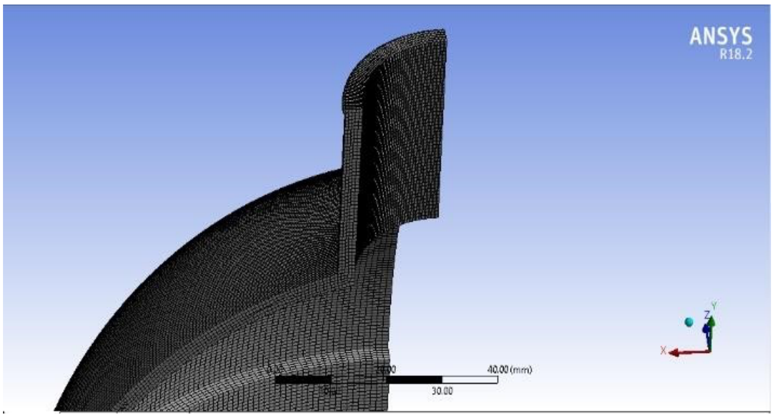

Fig. 2: Super-Fine Uniform Mesh on geometry

The analysis was then performed on all the models with Pressure loading of 250 bar. The results obtained were as follows-

TABLE III: RESULTS FOR STRESS ANALYSIS OF FIRE EXTINGUISHER

Materials	**Max. Total Deformation**	**Max. Elastic Strain**	**Max. Equivalent Stress (VonMises)**	**Min. Factor of Safety**
Si-Mn steel 32G2SF 1	0.16084 mm	2.8239 e-003	564.78 MPa	1.5404
Aluminium 7075-T6 Alloy	0.21312 mm	5.0124 e-003	357.37 MPa	1.4075
Titanium 6246 Alloy	0.29511 mm	6.1916 e-003	705.84 MPa	1.4876
Titanium Grade 5 Alloy6Al-4V	0.1808 mm	3.4449 e-003	688.97 MPa	1.5444

VI RESULTS

The following are the results for the study performed on the Fire Extinguishers of different materials on ANSYS. The stress distribution and factor of safety for each material are compared to determine whether the alternative lightweight model qualifies for usage or not. The results for the Factor of Safety is as follows:

A. Si-Mn steel 32G2SF1 (Already existing material)

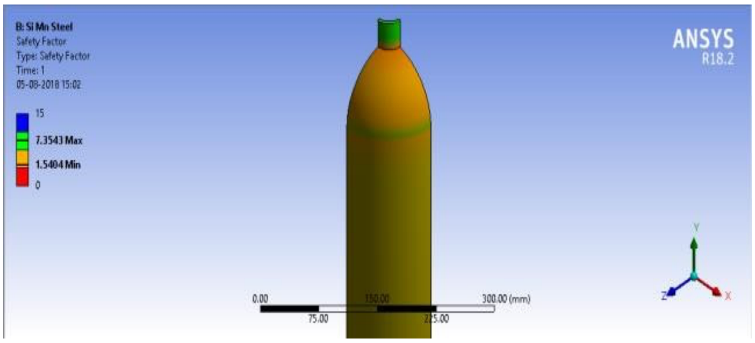

Fig. 3: Factor of Safety of Si-Mn Fire Extinguisher

B. Aluminium 7075-T6 Alloy

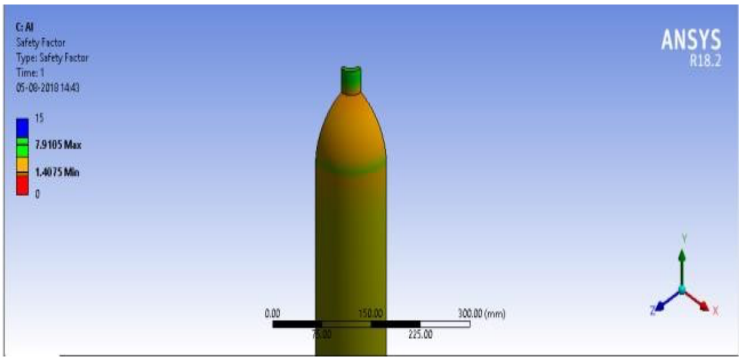

Fig. 4: Factor of Safety of Al 7075-T6 Fire Extinguisher

C. Titanium 6246 Alloy

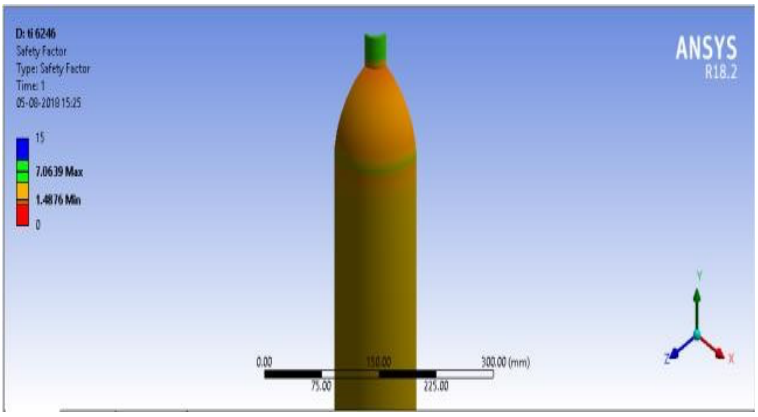

Fig. 5: Factor of Safety of Ti 6246 Fire Extinguisher

D. Titanium Grade 5 Alloy-6Al-4V

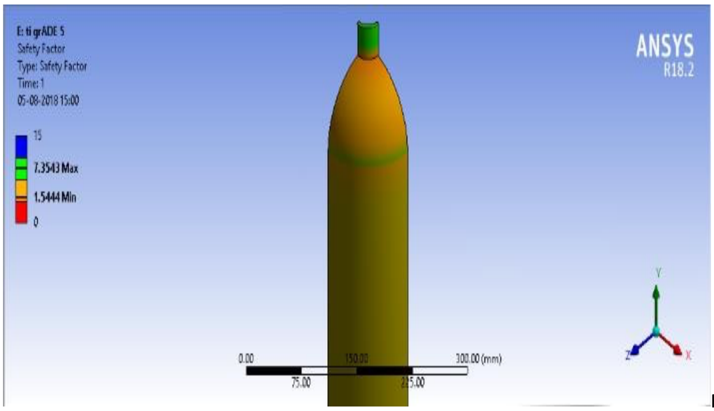

Fig. 6: Factor of Safety of Ti 6Al4V Fire Extinguisher

VII CONCLUSIONS

From the above analysis and calculations, we can clearly see that Ti 6Al 4V alloy gives the lightest fire extinguisher with a weight reduction of 53%. Considering its use in houses the lightweight would enable the older generations to use it without much effort. This can create drastic effects on the rates of fire suppression in its initial stage.

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