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Stress Analysis of Pulse Detonation Engine Tube

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ABSTRACT: *The pulse detonation engine (PDE) has recently emerged as an aerospace propulsion system of the future. In the PDE system, self-sustaining detonation waves propagate in tubes and gases burning behind the detonation front are exhausted backward repeatedly. The PDE system momentum is equal in absolute value to the exhausted gas momentum, but in the opposite direction. The PDE system has high thermal efficiency because of its constant-volume combustion, and it has a simple structure composed of tubes. In this paper we analyze the pulse tube for the pressure build-up during detonation. Axial circumferential and hoop stress are calculated for a selected pipe with respect to temperature for single shot experiments.*

Keywords: *Pulse detonation, deflagration, detonation, thrust stand, hoop stress.*

I. PULSE DETONATION ENGINE

All regular jet engines and most rocket engines operate on the deflagration of fuel, that is, the rapid but subsonic combustion of fuel. The pulse detonation engine is a concept currently in active development to create a jet engine that operates on the supersonic detonation of fuel.

The main difference between a PDE and a traditional pulse jet engine is that the mixture does not undergo subsonic combustion but instead, supersonic detonation. In the PDE, the oxygen and fuel combination process is supersonic, effectively an explosion instead of burning. PDE is considerably more efficient. In the pulse jet engine the combustion pushes a considerable amount of the fuel/air mix (the *charge*) out the rear of the engine before it has had a chance to burn (thus the trail of flame seen on the V-1 flying bomb).

Even while inside the engine the mixture's volume is continually changing, which is an inefficient way to burn fuel. In contrast, the PDE deliberately uses a high-speed combustion process that burns all of the charge while it is still inside the engine at a constant volume to increase the amount of heat produced per unit of fuel above any other engines, although conversion of that energy into thrust would remain inefficient.

The major difficulty with a pulse-detonation engine is starting the detonation. While it is possible to start a detonation directly with a large spark, the amount of energy input is very large and is not practical for an engine. The typical solution is to use a deflagration-to-detonation transition (DDT) that is, start a high-energy deflagration, and have it accelerate down a tube to the point where it becomes fast enough to become a detonation.

The most widely used is the "Shchelkin spiral", which is designed to create the most useful eddies with the least resistance to the moving fuel/air/exhaust mixture. The eddies lead to the flame separating into multiple fronts, some of which go backwards and collide with other fronts, and then accelerate into fronts ahead of them.

NASA maintains a research program on the PDE, which is aimed at high-speed, about Mach 5, civilian transport systems. However most PDE research is military in nature, as the engine could be used to develop a new generation of high-speed, long-range reconnaissance aircraft that would fly high enough to be out of range of any current anti-aircraft defences, while offering range considerably greater than the SR-71, which required a massive tanker support fleet to use in operation.

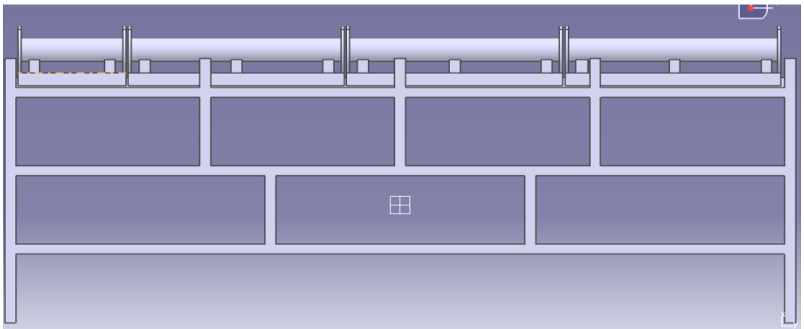
II. THE TEST RIG DESIGN

As the research is active at world level to develop a pulse detonation engine, we at PEC University of technology recently entered in the field of research with a sponsored project from DRDO. Initially the test rig was designed for carrying out the single detonation with acetylene and oxygen. The test rig as shown in the figure has a thrust stand on which the experimental pulse detonation system has been installed so that it can slide freely with minimum friction.

The pulse tube was selected from the stainless steel seamless pipes available in the market which were analysed for the strength so that it can sustain the pressure build up during detonation. The pressure developed during C_2H_2 design value was kept as 100 bar. The tube length was kept variable in the form of pieces of the tube joined with the help of flanges. Any number of different lengths can be connected to get the desired length of the pipe. The figure-1 shows the front top and side view of the rig.

III. ANALYSIS OF THE PULSE TUBE STRENGTH

Stainless Steel Grade 304 is the used for the pulse tube. It is austenitic, corrosion resistant steel with excellent *strength*. The selection of the pulse tube was on the basis of the strength and the stresses developed due the pressure build-up due to detonation of the gases. The tube for which the results have been shown has an internal diameter of 48mm and thickness of the pipe is 6mm. The figures below show the arrangement of the pipe and the thrust stand.



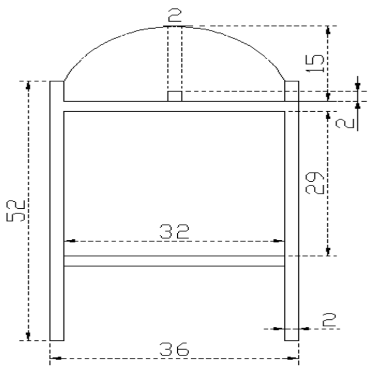


Figure 1 2 View drawing of Test stand (Dimensions in Inches)

3.1 Stress Calculations

While most of the literature is seen on the phenomenon of Pulse detonation the literature on the tube design is hardly available. In the present case the stress has been calculated using the standard expression from the strength of material text books. Longitudinal, circumferential and radial stresses have been calculated for the different pipes which are available in the market. The stress calculations for the selected tube dimensions are being shown here. The analysis can also be done using software like ANSYS etc. The author is of the view in this case simple analysis can serve the purpose, however later on the detailed analysis will be done as the research further progresses.

Longitudinal Stresses in the Detonation Tube.

$$\sigma_l = \frac{P_{in} R_{in}^2}{R_{out}^2 - R_{in}^2} \quad (1)$$

Where

P_{in} The pressure build up in the tube

P_{out} Outside pressure

R_{in} Inner diameter of the pipe

R_{out} Outer diameter of the tube.

σ is the stress developed due pressure build up.

Circumferential Stresses in the Detonation Tube

$$\sigma = \frac{R_{in}^2 P_{in} - R_{out}^2 P_{out} + (P_{in} - P_{out}) R_{in}^2 R_{out}^2 / R^2}{R_{out}^2 - R_{in}^2} \quad (2)$$

Radial Stresses in the Detonation Tube

$$\sigma = \frac{R_{in}^2 P_{in} - R_{out}^2 P_{out} - (P_{in} - P_{out}) R_{in}^2 R_{out}^2 / R^2}{R_{out}^2 - R_{in}^2} \quad (3)$$

The mechanical properties of selected SS304 are as shown in the table 1.

Table-1

Property	Value
Tensile Strength, ltimate	505 MPa
Tensile Strength, Yield	215 MPa
Modulus of Elasticity	193 - 200 GPa
Poisson's Ratio	0.29
Charpy Impact	325 J
Shear Modulus	86 GPa

IV. RESULTS

The figures 2 below shows the axial/longitudinal stress w.r.t the pressure in the pulse tube. The stress developed varies linearly. The curve shows the stress developed upto 100 bar of pressure. The maximum stress developed at 100 bar is 177X106 N/m2. Which is fairly within the limit of 215 MPa?

The yield stress of SS304. Figure 2, 3, and 5 show the variation of stree developed in the tube at different conditions as shown.

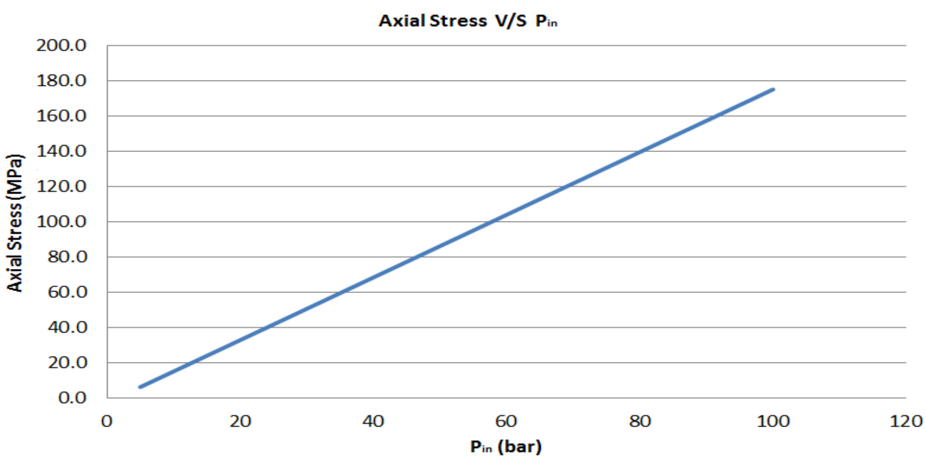


Figure 2 Axial Stress V/S P_{in}

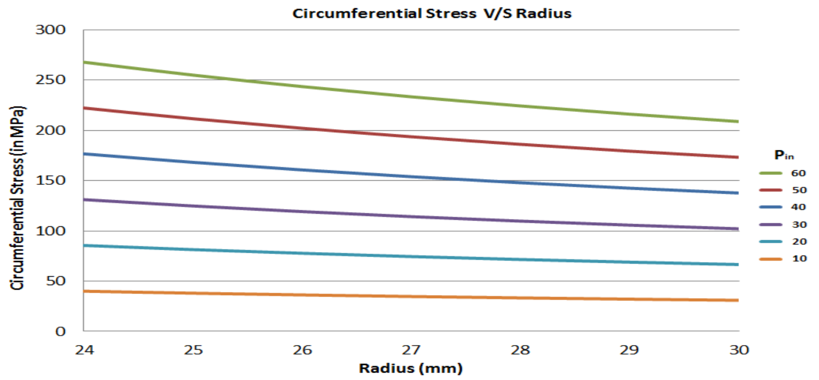


Figure 3- Circumferential stress V/S radius

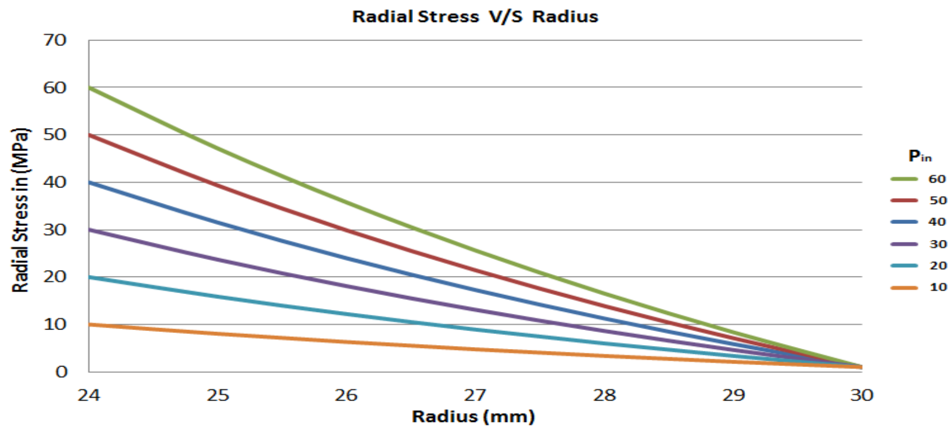


Figure 4-Radial Stress V/S Radius

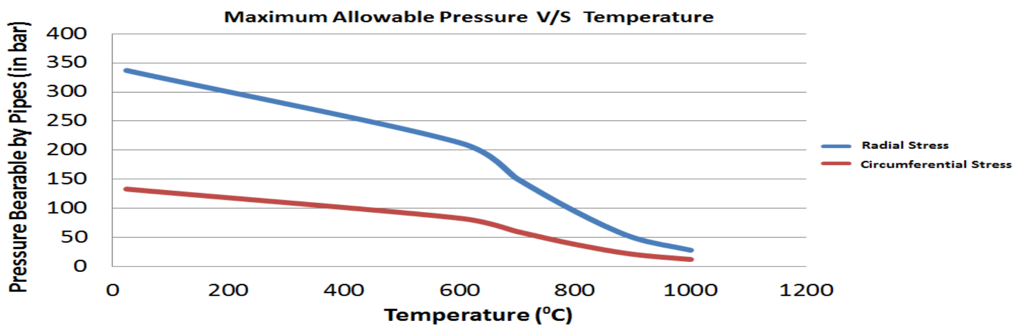


Figure 5- Maximum allowable V/S Temperature of the Detonation Tube

V. Conclusion

From the figures above shown that the pipe selected i.e SS304 with internal diameter of 48 mm and external diameter of 60mm can bear a pressure of 100 bar within the elastic parameter upto 400^{o}C of temperature and hence the testing can be done on the rig till the tube it reaches to a temperature of 400^{o}C. The temperature rise depends upon the number of shots and frequency of shots therefore the safe time and frequency of the testing can be determined w.r.t the temperature of the tube.

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