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Hydrostatic Pressure in Liquids

Understanding the Hydrostatic Pressure in Liquids and Physical Significance

Utpal Anand

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Free/Libre and Open Source Software for Education
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Declaration

I, the undersigned, hereby declare that this handbook, entitled "Hydrostatic Pressure in Liquids", has been compiled to serve as a resource for the study of physics. This work brings together knowledge from various scientific contributions to provide a comprehensive guide for students and learners.

This handbook is intended solely as an educational resource and does not claim originality in its entirety, as it is a compilation of existing scientific knowledge curated for academic purposes.

Pune, December 2024

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Abstract

In this module, we will study the pressure exerted by the fluid/liquid on the material submerged in it, that is the building concept for fluid dynamics and helps in multiple field across different industries. Hydrostatic pressure is due to the weight of the fluid above and increases with depth, fluid density, and gravitational acceleration.

Hydrostatic pressure increases with depth. This is because the deeper the material displaces the fluid, the greater the weight of the fluid above, which increases the pressure. The denser the fluid, the greater the pressure it applies on the material. This pressure is also proportional to the acceleration due to gravity, g. The formula for hydrostatic pressure is:

$$P = \rho g h$$

Keywords: Hydrostatic pressure, fluid dynamics, Buoyant Force, Underwater Science, Aquatic Science

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Introduction

Introduction

Hydrostatic force and pressure concepts have evolved over centuries, beginning with practical observations and culminating in modern scientific principles. This document outlines the historical development and key contributions to our understanding of these concepts.

Historical Development

Ancient Observations

- Early civilizations (e.g., Mesopotamians, Egyptians, Greeks) noted the behavior of water in practical contexts such as irrigation, aqueduct construction, and shipbuilding.
- Archimedes (287–212 BCE) formulated the principle of buoyancy:

$$\text{Buoyant Force} = \text{Weight of the Displaced Fluid}.$$

Medieval to Early Modern Science

- **Hydrostatics**: The study of fluids at rest gained traction during this period.
- Blaise Pascal (1623–1662): Formalized the concept of pressure (P) as force per unit area:

$$P = \frac{F}{A},$$

  and introduced Pascal's Law: *A change in pressure in an enclosed fluid is transmitted undiminished to every part of the fluid and the walls of its container.*

Development of Hydrostatic Force

- The pressure at a depth h in a fluid is given by:

$$P = \rho g h,$$

  where:

  - ρ: Density of the fluid.
  - g: Acceleration due to gravity.

- h: Depth of the fluid.

- Daniel Bernoulli and Leonard Euler (18th Century) advanced fluid dynamics and reinforced hydrostatic principles for fluids at rest.

Modern Developments

- **Thermodynamics and Continuum Mechanics**: Expanded hydrostatic principles to include compressibility and temperature effects.
- **Computational Fluid Dynamics (CFD)**: Enabled simulations of hydrostatic and hydrodynamic forces in complex systems.
- **Planetary Sciences**: Hydrostatic equilibrium explains the shapes of planets and stars as a balance between gravitational forces and fluid pressures.

Summary Table

Period	**Key Developments**
Ancient Observations	Practical experience; Archimedes' principle of buoyancy.
Medieval to Early Modern	Pascal's Law; formalization of pressure ($P = F/A$).
18th Century	Bernoulli and Euler advanced fluid dynamics.
Modern Era	Thermodynamics, CFD, and planetary applications.

Table 1.1: *Summary of the development of hydrostatic force and pressure concepts.*

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Hydrostatic Pressure in Liquids

Hydrostatic pressure is the pressure exerted by a fluid at rest due to the force of gravity. It increases linearly with depth and can be calculated using the formula:

$$P = \rho g h, \tag{2.1}$$

where:

- P is the hydrostatic pressure (in Pascals, Pa),
- ρ is the density of the liquid (in $\mathrm{kg/m^3}$),
- g is the acceleration due to gravity ($9.8\,\mathrm{m/s^2}$),
- h is the depth of the liquid column (in meters, m).

Key Points

- Hydrostatic pressure increases linearly with depth.
- The formula assumes that the density ρ is constant throughout the liquid.
- Pressure is commonly measured in Pascals (Pa) or hectopascals (hPa), where $1\,\mathrm{hPa} = 100\,\mathrm{Pa}$.

Pressure Increase for Water (1 cm Depth)

For water, the density is approximately:

$$\rho = 1000\,\mathrm{kg/m^3}.$$

Let the depth $h = 0.01\,\mathrm{m}$ (1 cm). Substituting into the formula:

$$P = \rho g h = (1000\,\mathrm{kg/m^3})(9.8\,\mathrm{m/s^2})(0.01\,\mathrm{m}),$$

$$P = 98\,\mathrm{Pa}.$$

Since $1\,\mathrm{hPa} = 100\,\mathrm{Pa}$, we find that:

$$P = 0.98\,\mathrm{hPa} \approx 1\,\mathrm{hPa}.$$

Thus, the hydrostatic pressure of water increases by approximately 1 hPa for every 1 cm of depth. (1 hPa = 1 hectopascal = 100 Pa = 100 N/m2)

The hydrostatic pressure increases linearly with depth and depends on the density of the liquid. For water, the pressure increases by approximately 1 hPa for every 1 cm of depth. The formula $P = \rho g h$ can be applied to any liquid, provided the density is known.

2.1 Hydrostatic Pressure in Different Liquids

In water, ethanol and benzene, the hydrostatic pressure is low so there is very low deformation. While in tetrachloromethane, we can see little deformation with little more pressure. But while in mercury and unknown (20 g/cm^3), there is large deformation due to the high pressure applied on the object.

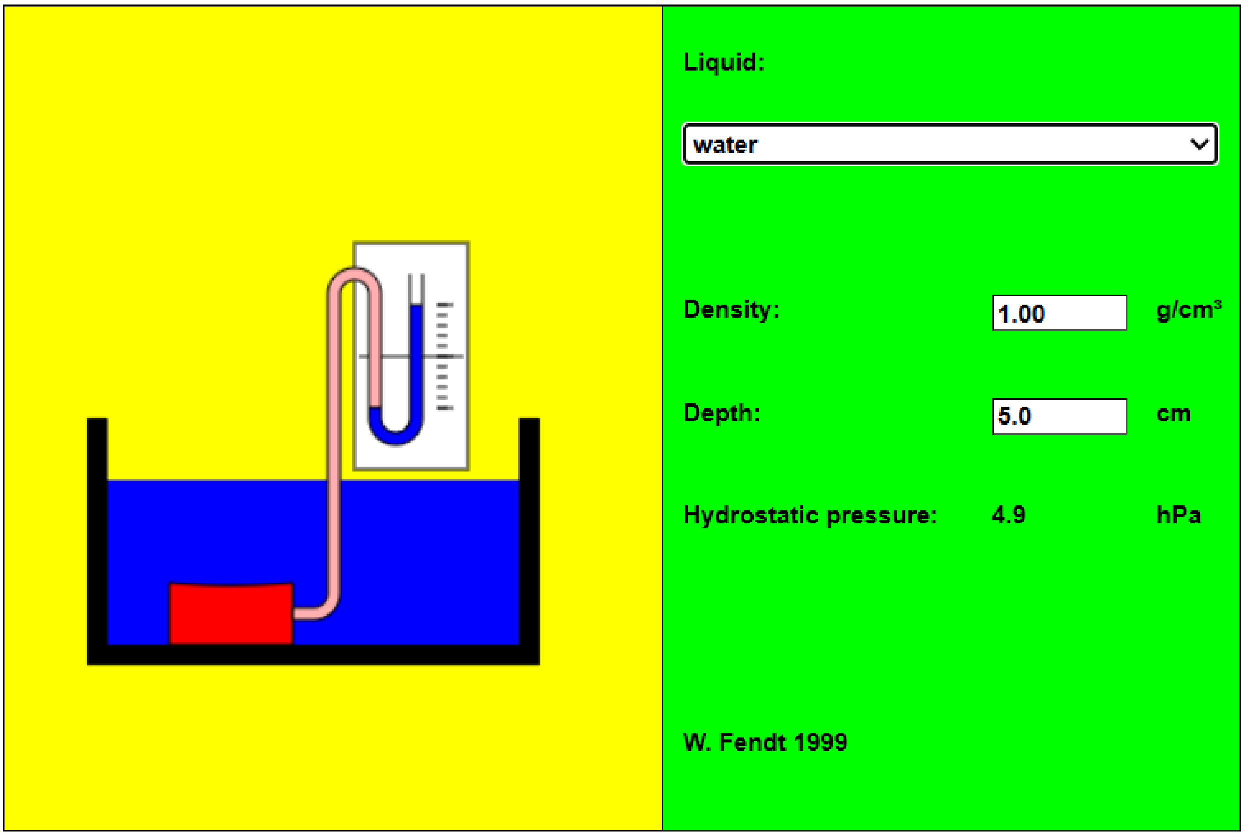

Figure 2.1: *In Water* (1.00 g/cm^3)

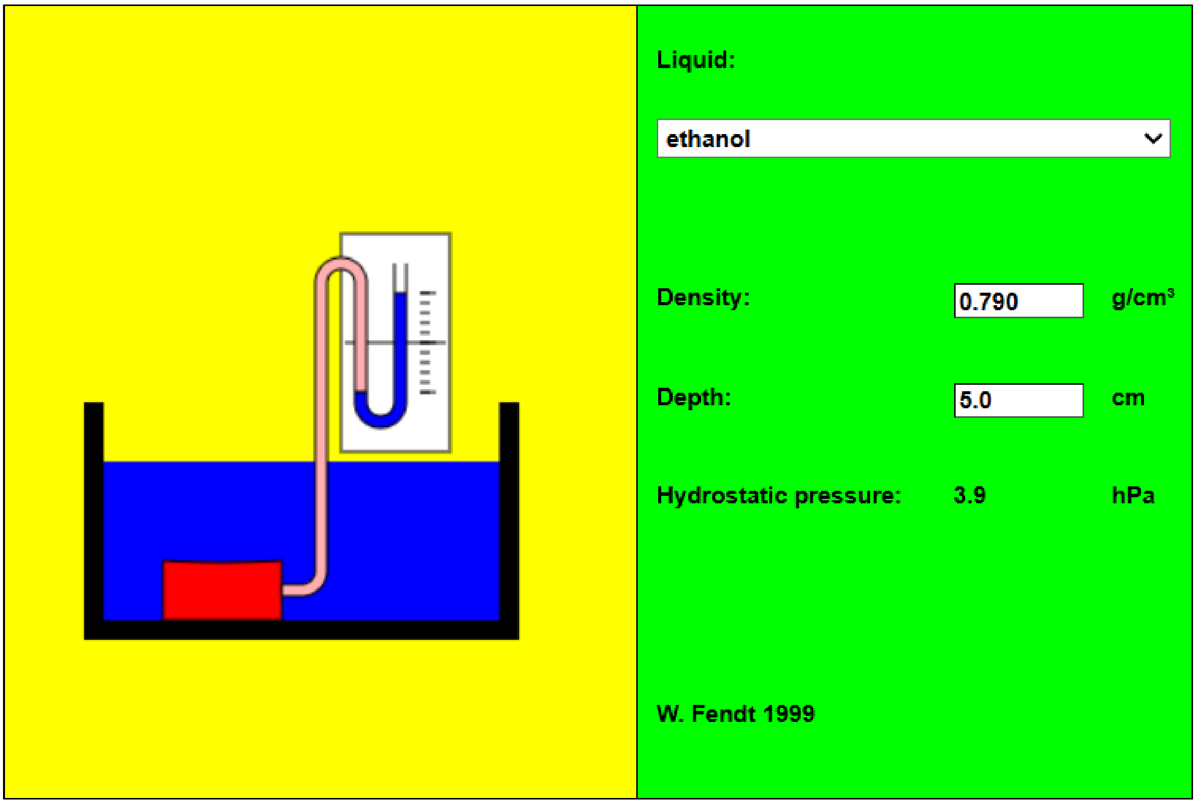

Figure 2.2: *In Ethanol* ($0.790\ g/cm^3$)

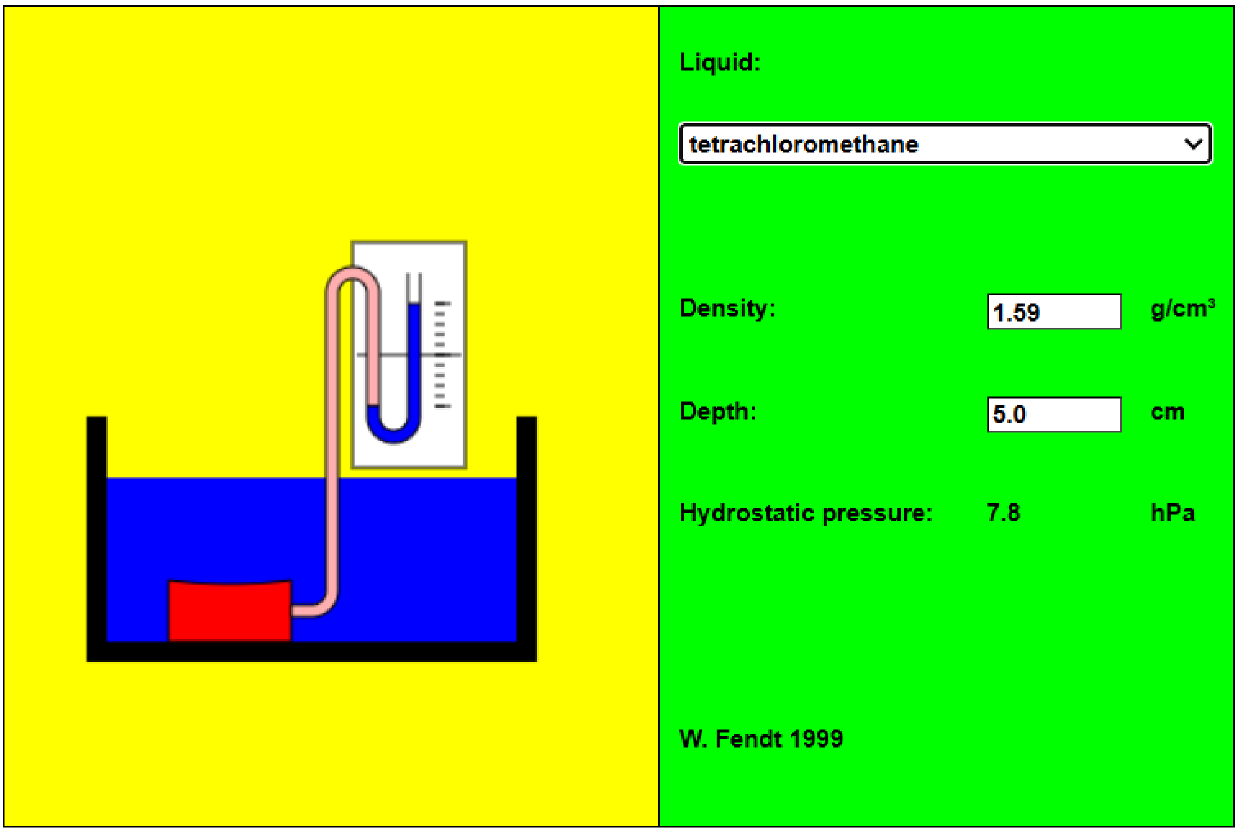

Figure 2.4: *In Tetrachloromethane* ($1.59\ g/cm^3$)

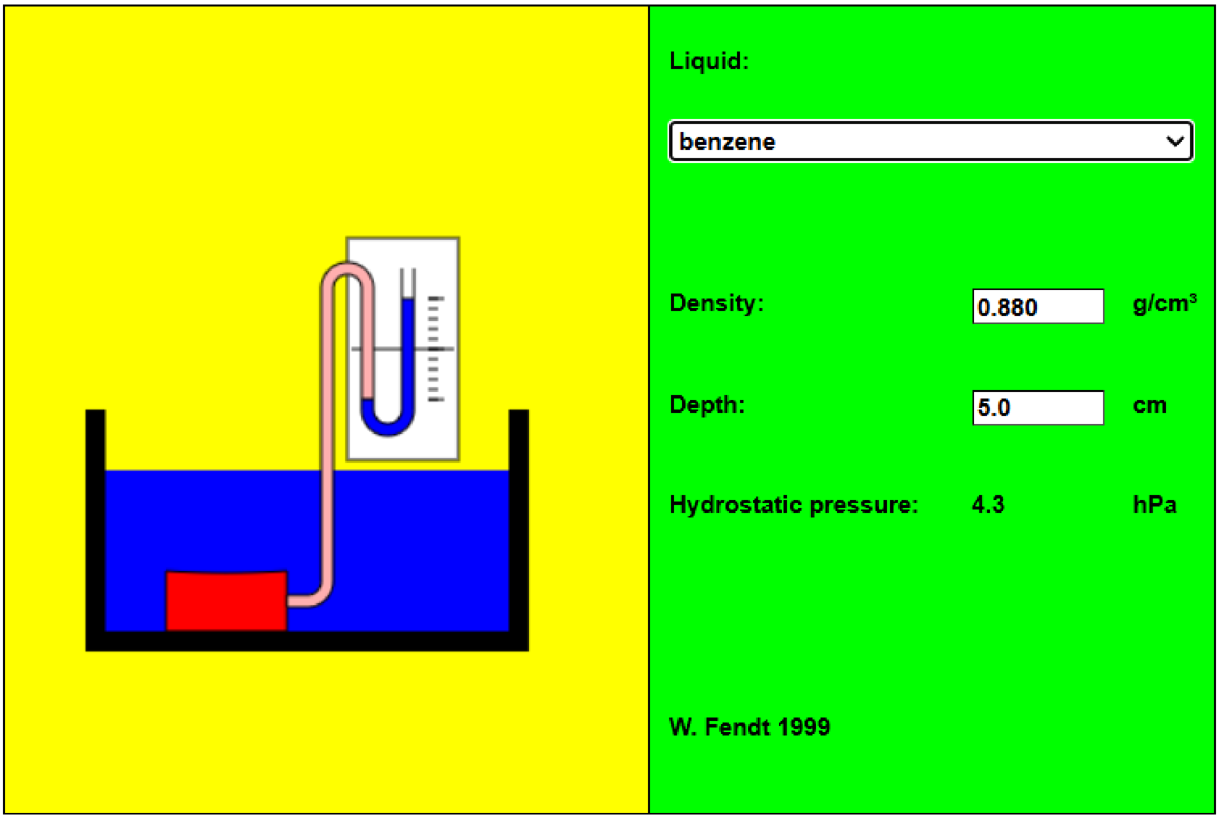

Figure 2.3: *In Benzene* $(0.880\ g/cm^3)$

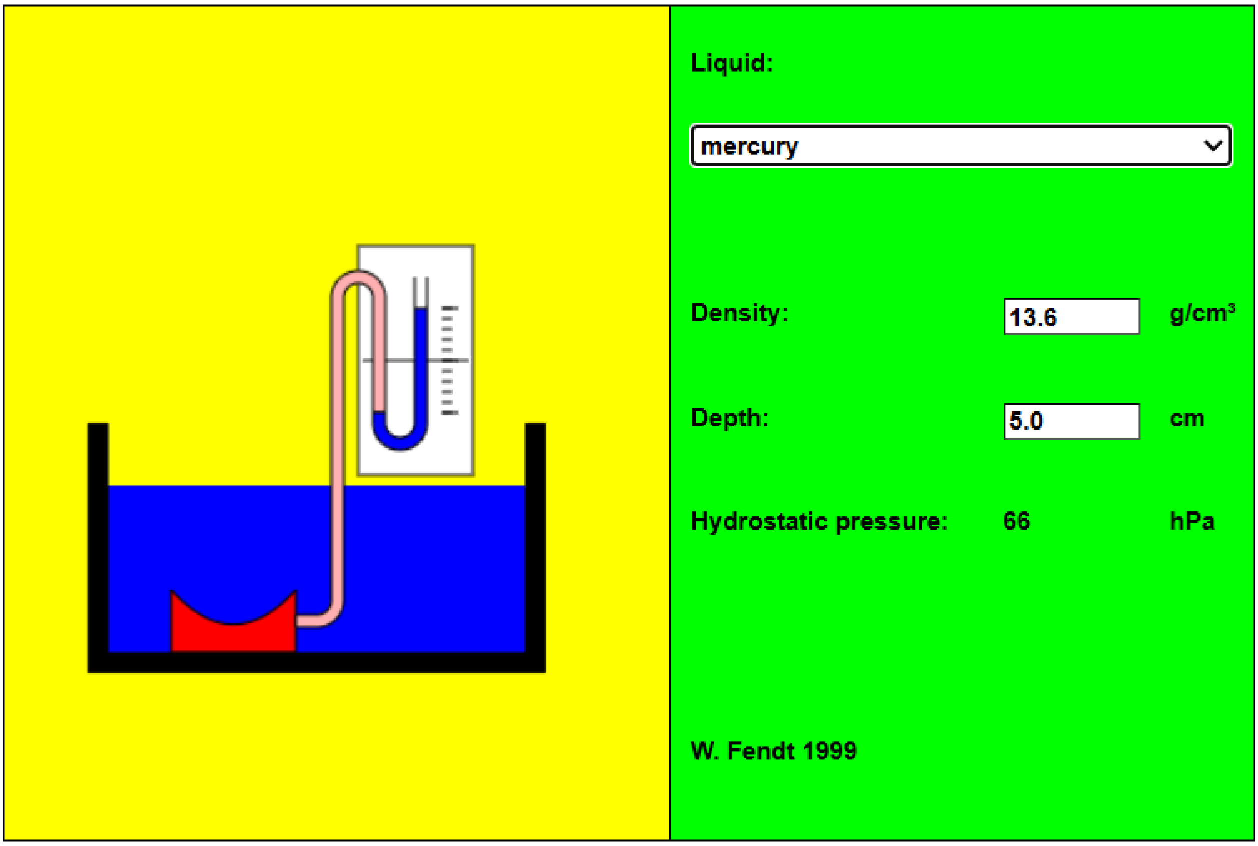

Figure 2.5: *In Mercury* $(13.6\ g/cm^3)$

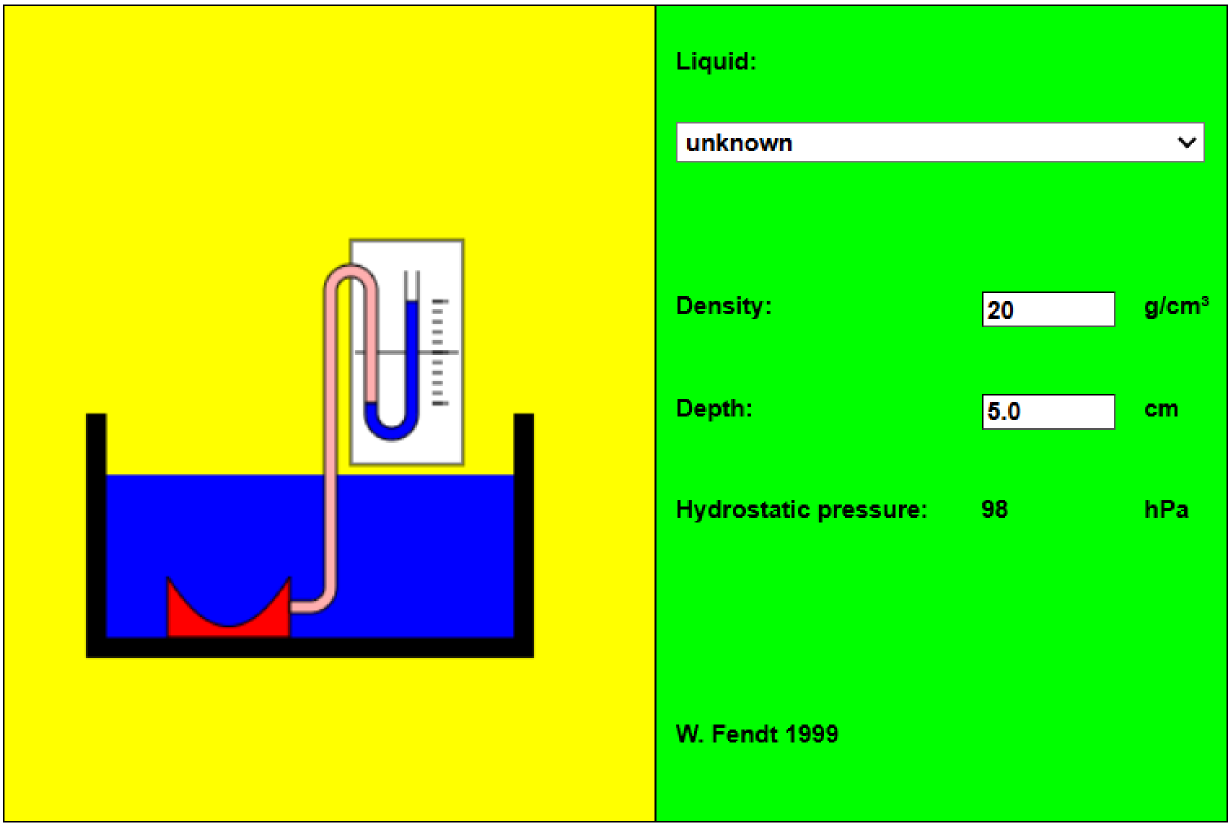

Figure 2.6: *In Unknown* (20 g/cm^3)

Liquid	Density (in g/cm^3)	Depth (in cm)	Hydrostatic Pressure (in hpa)
Water	1.00	5	4.9
Ethanol	0.790	5	3.9
Benzene	0.880	5	4.3
Tetrachloromethane	1.59	5	7.8
Mercury	13.6	5	66
Unknown	20	5	98

Table 2.1: *Hydrostatic Pressure in Different Liquids*

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Physical Significance

On 18 June 2023, Titan, a submersible operated by the American tourism and expeditions company OceanGate, **imploded** during an expedition to view the wreck of the Titanic in the North Atlantic Ocean off the coast of Newfoundland, Canada.

Understanding Submersible Implosions: A Case Study of Deep-Sea Challenges

Submersibles like the Titan, used for Titanic expeditions, operate under extreme conditions in the deep ocean. When such vessels implode, it is often due to the failure of their pressure hull under immense hydrostatic pressure. Here, we explore the factors contributing to such an event and its consequences in simple terms.

What Causes an Implosion?

1. Extreme Pressure at Depth

- As you go deeper underwater, the pressure increases by about 1 atmosphere (101,325 Pa) for every 10 meters.This is due to an increase in **hydrostatic pressure**, the force per unit area exerted by a liquid on an object.
- The deeper the object goes under the sea, the greater the pressure of the water pushing down on the object.
- At the Titanic's depth, roughly 3,800 meters, the pressure reaches around 38 MPa, which is about **380 times** the atmospheric pressure on the surface.
- This means the hull must withstand crushing forces that would collapse most surface structures instantly.

2. Material Weaknesses

Submersibles are built from strong materials like titanium, carbon fiber, or steel to resist these pressures. However, these materials can have:

- **Manufacturing defects**: Small flaws during production.
- **Material fatigue**: Weakening from repeated dives.
- **Micro-cracks**: Tiny imperfections that grow over time.
- Carbon fiber, while strong in tension, is **more prone to compressive failure** compared to metals like titanium.

3. Structural Integrity Failures

The pressure hull must be perfectly sealed and uniformly strong. Failures can happen if:

- There is a flaw in the design, like uneven thickness or weak joints.
- Damage from previous dives goes unnoticed.
- The hull is weakened by repeated pressure cycles over time.
- Once the hull breaches, water rushes in with immense force, causing instant collapse.

4. Dynamic Loads and Operational Risks

Deep-sea submersibles face additional stresses, such as:

- Uneven pressure distribution.
- Sudden underwater shocks or impacts.
- These stresses can weaken the hull further, especially if combined with material or design flaws.

What Happens During an Implosion?

- **Initial Breach**: A small crack or weak spot in the hull fails.
- **Rapid Compression**: Water rushes in faster than the speed of sound, compressing the submersible in milliseconds.

Destruction:

- The submersible is crushed into a fraction of its size.
- The immense energy released generates heat, vaporizing some materials instantly.
- For humans inside, the event is so fast they wouldn't perceive it.

Exploring the deep sea is a remarkable but risky endeavor. Submersible implosions like that of the Titan remind us of the challenges involved and the importance of rigorous engineering and safety protocols.

Sources:

Recent Implosion: Titan Submersible Implosion

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