A Study on Isometric Heating Process to Forecast Explosion and Find Safety Solutions for Pressure Vessels

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ABSTRACT: The article studies isometric heating process in pressure vessels, thereby calculating the risks of explosion in closed heating pressure vessels. Through the function of temperature and pressure distribution, using quantitative calculations, it analyzes potential problems when changing the parameters of equipment structure, heat sources, environment... As a result, it offers solutions in designing, manufacturing, testing and operating of pressure vessels to prevent the problem.

KEYWORDS: isometric heating, pressure vessel, allowable stresses, safety, safety factor

ABBREVIATION: CPs: Combustion Products

I. INTRODUCTION

Most of the explosions of pressure vessels are because medium pressure rises too high when heated in closed vessels. This article will use analytical methods to calculate and find the increased temperature and pressure functions of mediums over time τ and other physical parameters when the medium is heated in a closed vessel. Then it will examine functions t(τ), p(τ) to predict the explosion of pressure vessels and recommended safety solutions for pressure vessels.

II. RELATED WORK

Isometric heating process by combustion products or resistors in pressure vessels may cause explosion incidents. By using heat transfer formulas, we determine the function between temperature and pressure over time of heating in pressure vessels. We also calculate to warn pressure vessel explosion incident and energy created during the process. Through that, we give safety recommendation for operating pressure vessels.

III. MODEL OF THE SURVEYED PRESSURE VESSEL

Consider a metal closed vessel V, arbitrary shape, thickness δ, physical parameters ρ, c, λ, δ, δ(cp), n, contains the liquid medium with physical parameters m, c, t, r, which is heated by resistor P placed in medium or by the combustion products through surface F1 with physical parameters t1, d1, ε1. Tank shell with surface F, calorific into the air with temperature t and convection heat transfer coefficient α.

Looking for temperature increase function t(τ) and pressure function p(τ) of medium over time τ and the given parameters.

\[ t(\tau) = f(\tau, \text{ and all given parameters } c) \]
To be able to find analytic solutions of the problem, we need to make the following assumptions:

1) At every time $\tau$, consider the temperature $t(\tau)$ of medium is evenly distributed in closed vessel $V$ and equals the temperature of shell $V$. This hypothesis eliminates the coordinates in the function temperature $t$. This is reasonable because the heat transfer coefficient $\alpha$ in liquid medium is very big.

2) The given physical parameters is unchanged in the surveyed period $\Delta \tau$. In particular the mass of medium $m$ will not change when the vessel is closed ($V = \text{const.}$). When open valve $K$ through the air pressure $P_k = 1\text{atm} = \text{const.}$, vessel is open, water will boil at $t_s = 100 \degree C$ and evaporate and make $m$ decrease.

V. FIND THE FUNCTION OF TEMPERATURE $t(\tau)$, PRESSURE $P(\tau)$ OF MEDIUM

V.1 When the medium is heated by resistor with power $P$

1) Energy balance equation of the system (medium and shell) at time $\tau$ after infinitesimal time $d\tau$ is:

Electrical power fed into the system $dE = dU_v + dH_m + \delta Q_a$

or: $P d\tau = \rho F c_v dt + mc_p dt + \alpha F (t - t_f) d\tau$,

with $F$ is the area around the vessel, which calorific into the air change it into canonical form $\frac{dt}{dt} + at = b$:

$$\frac{dt}{d\tau} + \frac{\alpha F}{(mc_v + mc_p)} = \frac{p + \alpha Ft_f}{(mc_v + mc_p)}$$

set: $a \triangleq \frac{\alpha F}{\sum mc_i} \left( \frac{1}{\tau} \right); b \triangleq \frac{p + \alpha Ft_f}{\sum mc_i} \left( \frac{1}{\tau} \right)$

$$t_m = t_{mp} \triangleq \frac{b}{a} = t_f + \frac{P}{\alpha F}$$

deduce: $dt = -a \left( t - \frac{b}{a} \right) d\tau \triangleq -a(t - t_m) d\tau$

Separating variables and integrating, we have:

$$\int_{\tau_0}^{\tau - t_m} dt = - \int_0^{\tau - t_m} a dt \Rightarrow \ln \frac{\tau - t_m}{\tau_0 - t_m} = - a \tau$$

$$\Rightarrow \text{Function } t(\tau) \text{ is formed:}$$

$$t(\tau) = t_m - (t_m - t_0) \exp(-a \tau)$$

2) The increased pressure function $p(\tau)$ of medium is: $p(\tau) = g(t(\tau))$
With the function \( g(t) \) can be determined by \( p(\tau) = \rho RT(\tau) \) when the medium is ideal gas, and other media can be determined by tables, graphs or empirical formula of each medium: For example, when medium is water, \( p(\tau) \) can be calculated by Antoine empirical formula:

\[
t(\tau) = \frac{4020}{12 - \ln p[\text{bar}]} - 235 \Rightarrow p(\tau) = 162755 \exp\left[-\frac{4020}{t(\tau) + 235}\right], \text{[bar]}
\]

V.2 When the medium is heated by combustion products

1) Energy balance equation of the system is:

\[
\delta \frac{\alpha}{\alpha} = dU + dI + \delta Q \quad \Rightarrow \quad \alpha F_1(t_1 - t) \, dt = m \, c_p \, dt + \alpha F_2(t - t f) \, dt
\]

With \( F_1 \) and \( F_2 \) are the parts of the shell which contact with combustion products and with air (Fig. 1.)

The canonical form of this equation is:

\[
\frac{dt}{d\tau} \quad + \quad t \left( \frac{\alpha F_1 + \alpha F_2}{\sum m_i c_i} \right) \quad = \quad \alpha F_1 t_f \quad + \quad \alpha F_2 t_f \quad \sum m_i c_i
\]

set: \( a = \frac{\sum m_i c_i}{\sum m_i c_i} \); \( b = \frac{\sum \alpha F_1}{\sum \alpha F_1} \); \( t_m = \frac{\alpha F_1}{\sum \alpha F_1} \)

\[
\Rightarrow \int_{t_0}^{t} dt = \int_{t_0}^{t} a \, dt \quad \Rightarrow \quad \ln \frac{t(\tau) - t_m}{t_0 - t_m} \quad = \quad -a \tau
\]

\[
\Rightarrow \quad t(\tau) = t_m - (t_m - t_0) \exp(-a \tau)
\]

2) The type of the function \( t(\tau) \) and \( p(\tau) \) of the medium when heated by combustion products is the same as when heated by electric heaters, only the values of coefficients \( a, b, t_m \) are different. Especially, when heated by combustion products, then \( t_m \) is blocked by:

\[
t_m = \left( a_1 F_1 t_f + a_2 F_2 t_f \right) / (\sum \alpha F_i) \times t_m
\]

When heated by resistor: \( t_m = t_f + \frac{P}{aP} \) can raise unlimitedly when \( a \rightarrow 0 \)

V.3 Preliminary investigate the rules of increase \( t(\tau) \) and \( p(\tau) \) of medium in Fig. 2

![Fig. 2. The rules of increase \( t(\tau) \) and \( p(\tau) \) of the medium, which heated isobarically or isochorically.](image)

VI. CALCULATE FOR EXPLOSIVE WARNING OF PRESSURE VESSELS

VI.1 Determine the explosive pressure on the surfaces of vessels

1) Determine allowed pressure \( P_\alpha \).

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From the formula for calculating the thickness of vessel \( \delta = f(p, \delta_{cp}, c, \text{other coefficients } c_i) \), we can determine the allowed pressure \( p_n \) (when checking calculation) as the solution of \( p = f^{-1}(\delta_{cp}, \delta, c, c_i) = p_{cp} \) with the reserve coefficient of thickness \( c[\text{mm}]= 0 \) and other factors, which taken the minimum value as stipulated.

2) Determine explosion pressure \( p_n \):

Since \( p_{cp} \) is proportional to \( \delta_p \) and breaking stress of the material \( \sigma_n \triangleq n \delta_{cp} \), so we can calculate the explosion pressure of vessel by the formula:

\[
p_n = f^{-1}(n \delta_{cp}, \delta, c=0, c_i) = np_{cp},
\]

The formulas for calculating the explosion pressure to the surfaces that are frequently under pressure such as cylindrical shells, spherical shell, elliptical shell, cone shell are presented in the following table:

<table>
<thead>
<tr>
<th>Surfaces</th>
<th>Structure</th>
<th>Designed calculation; ( \delta )</th>
<th>Checked calculation ( p_n )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cylinder</td>
<td>( D \times P )</td>
<td>( \delta = \frac{pD}{(2kp\delta^2 + p)} + C )</td>
<td>( p_c = \frac{2kp\delta^2 b}{(D+b\delta)} )</td>
</tr>
<tr>
<td>Ellipse</td>
<td>( B \times P )</td>
<td>( \delta = \frac{p0.05D}{(4kp\delta^2 + p)} + C )</td>
<td>( p_c = \frac{2kp\delta^2 b\delta_n}{D^3 + 2b\delta} )</td>
</tr>
<tr>
<td>Cone</td>
<td>( B \times P )</td>
<td>( \delta = \frac{pD}{2k\delta^2 p \cos \gamma} + C )</td>
<td>( p_c = \frac{2kp\delta^2 b \cos \gamma}{D^3 + 2b\delta} )</td>
</tr>
</tbody>
</table>

Note:
- \( k \): inner/outer pressure coefficient
- \( \delta_{cp} \triangleq \phi \eta \delta^* \): allowable stress
- \( \phi \): coefficient of resistance of manufacturing
- \( \eta \): coefficient of effect of medium (erosion, explosion...)
- \( \delta^* \): Allowable quantum stress = f(material, structural, method of manufacturing) \( \triangleq \min(\delta_{pull}, \delta_{compress}, \delta_{tires})/n \) (\( n \): safety coefficient)

VI.2 Determine the temperature of explosion of medium \( t_n \) and the time of explosion \( t_n \)

When know \( p_n \) we can determine the temperature of explosion of medium \( t_n \) according to tables or empirical formula takes the following form:

\( p_n = g(t_n) \), hence, we can calculate:

\[
t_n = g^{-1}(p_n) = t_m - (t_m - t_0) \exp(-a \tau_n)
\]

Therefore we can predict the time of the explosion \( \tau_n \) using formula:

\[
\tau_n = \frac{1}{a} \ln \frac{t_m - t_0}{t_m - t_n},\ [s]
\]

In this formula, \( a, t_m \) are calculated using the method of heated medium in Section 4, i.e.:

The time of explosion of vessel when heated by electricity: \( \tau_n = \frac{\sum m_i \gamma}{aF} \ln \frac{t_m - t_0}{t_m - t_n},\ [s] \)

The time of explosion of vessel when heated by combustion products: \( \tau_n = \frac{\sum m_i \gamma}{a \eta F} \ln \frac{t_m - t_0}{t_m - t_n},\ [s] \)

VI.3 Warning of the power of the explosion

Explosion is a process in which medium expands very fast, making the pressure of medium \( p = p_n - p_k = 1\ atm \) falls rapidly, spreading material and its enthalpy \( \Delta H \) energy into the environment. The time of explosion is overall stipulated under TNT is \( \Delta t \approx 0.1s \).
Vessel containing medium with mass $m$, temperature $t_n$, when exploding it releases energy: 
$$Q = mc_p(t_n - t_{sk}) \text{[MJ]}$$

with $t_{sk}$ is the medium boiling temperature at atmospheric pressure $p_k = 1\text{ atm}$.

The maximum energy can be reached:
$$Q_m = mc_p(t_m - t_{sk}) \text{[MJ]}$$

The power of the explosion is: 
$$P = \frac{Q}{\Delta t} \text{[MW]}$$

The maximum power can be achieved:
$$P_m = \frac{Q_m}{\Delta t} \text{[MW]}$$

Usually we compare the power of explosion with 1 kg of TNT’s energy:
$$q_{TNT} = 4,187 \text{ MJ/kg}; \quad P_{TNT} = 41.87 \text{ MW/kg}. \quad (1\text{kt} = 10^3\text{kgTNT})$$

**VII. RECOMMENDED SAFETY SOLUTIONS FOR PRESSURE VESSELS**

Conditions that medium heating vessel will not explode:

$$p(\tau) > p_{sk} \text{ at } t(\tau) < t_n \text{ with all values of } \tau \text{ during operation time, or } t_m < t_n$$

**VII.1** The vessels with medium heated by electricity will be safe when

$$t_m = t_f + \frac{P}{\alpha F} < t_n$$

To ensure those conditions, we can do the following solutions:

1. Select or adjust the electric power to

$$P < \alpha F(t_n - t_f) \text{[W]}$$

2. Increase $t_n$ by increasing $\delta$ of the shell of the vessel, or make the shell with heat resistant material, which high $\beta cp$.

3. Increase $\alpha F$ by increasing the cooling condition and cooling area $F$.

4. Not to rise temperature $t_m$ in premises to prevent fire.

5. Adjust power $P$ to summer mode, winter mode according to the average value $t_f$.

**VII.2** The vessels with medium heated by combustion products will be safe when

$$t_m = (\alpha_1 F_1 t_{f1} + \alpha_2 F_2 t_{f2}) / (\alpha_1 F_1 + \alpha_2 F_2) < t_n$$

To achieve this inequality we can take the following solutions:

1. Control the combustion process so that the temperature of combustion products is:

$$t_{f1} < \frac{1}{\alpha_1 F_1} |t_n \sum \alpha F_i - \alpha_2 F_2 t_{f2}| \text{[°C]}$$

This is important because the maximum temperature:

$$t_{mc} = t_{f1}$$

2. When installing, adjust the area of contact with the combustion products $F_i$, so that it is not too big

$$F_1 < \frac{1}{\alpha_1 F_1} |t_n \sum \alpha F_i - \alpha_2 F_2 t_{f2}| \text{[m²]}$$

3. Increase $\alpha_2 F_2$ reasonably.

4. Adjust $t_{f1}$ and $F_1$ to summer or winter mode, whichever suits seasonal average temperatures $t_f$.

5. Increase $t_n$ by choosing proper materials and thickness $\delta$ when designing and manufacturing vessels.

Other solutions can be inferred when analyse variables of two inequalities 6.1 and 6.2 more detailedly.

**VIII. THE STEPS OF CALCULATION CHECK TO PREDICT THE SAFETY OF AN ACTUAL PRESSURE VESSEL**

**VIII.1** Describing problem

Need to make a check of calculation of the heating process (isometric, isobaric) and explosion safety of a vessel, in which water is heated by resistor or by combustion products with specific structure and parameters as in Figure 3, and preset values given in Table 2.
Table 2: The given parameters of the problem

<table>
<thead>
<tr>
<th>Details</th>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shell</td>
<td>Inner diameter</td>
<td>D</td>
<td>0.25 m</td>
<td></td>
</tr>
<tr>
<td></td>
<td>height of surface contacting fire</td>
<td>h₁</td>
<td>0.05 m</td>
<td>Height of hot cylinder</td>
</tr>
<tr>
<td></td>
<td>height of other surfaces</td>
<td>h₂ = h₃ = h₄</td>
<td>0.1 m</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Thickness</td>
<td>δ</td>
<td>0.003 m</td>
<td></td>
</tr>
<tr>
<td>Steel shell</td>
<td>specific weight</td>
<td>ρ₁</td>
<td>7850 kg/m³</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Specific heat</td>
<td>c₁</td>
<td>460 J/kgK</td>
<td></td>
</tr>
<tr>
<td></td>
<td>allowable stress</td>
<td>σₚ</td>
<td>120 MPa</td>
<td></td>
</tr>
<tr>
<td>Medium H₂O</td>
<td>mass</td>
<td>m₂</td>
<td>10 kg</td>
<td></td>
</tr>
<tr>
<td></td>
<td>isobaric specific heat</td>
<td>c₂</td>
<td>4180 J/kgK</td>
<td></td>
</tr>
<tr>
<td></td>
<td>initial temperature = air temperature</td>
<td>t₀</td>
<td>27 °C</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Boiling temperature of water at 1 atm</td>
<td>t₁</td>
<td>100 °C</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Latent heat of vaporization</td>
<td>R</td>
<td>2050 kJ/kg</td>
<td></td>
</tr>
<tr>
<td>Heating</td>
<td>power of resistor</td>
<td>P</td>
<td>2000 W</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Temperature of combustion products</td>
<td>t₁₁</td>
<td>600 °C</td>
<td></td>
</tr>
</tbody>
</table>

Sealed vessel with thickness δ and parameters δ, ρ, n, σₚ, elliptical bottom, cylindrical shell with cone lid, in the lid fitted K valves, which can close or open to perform the isochoric or isobaric heating process. Cylindrical and elliptical shell is filled with water with parameters m₂, c₂, t₀, t₁, R, which is heated by resistor with power P or by combustion products with complex convection heat transfer coefficient α₁ through hot surface F₁. Ambient air temperature is t₁₁ = t₀

![Fig. 3. Pressure water heating vessel](image)

We should make a check of calculation of the parameters of isobaric or isochoric heating process, predict the explosion of pressure vessels and recommend safety solutions for them.

Based on the above theoretical formula, we can present the detailed calculations according to the following table:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Heated by resistor P</th>
<th>Heated by combustion products</th>
<th>Explanation, Remark, Note</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Symbol, Formula</td>
<td>Answer</td>
<td>Symbol, Formula</td>
</tr>
<tr>
<td>Conical lid area</td>
<td>Pₓ = nR\sqrt{R² + h₄}</td>
<td>0.0629 m²</td>
<td></td>
</tr>
<tr>
<td>Elliptical bottom area</td>
<td>Fₑ = nR² +</td>
<td>0.0854 m²</td>
<td>ε = D/2</td>
</tr>
</tbody>
</table>
**Table 4: Steps to make a check of calculation for prediction and results**

<table>
<thead>
<tr>
<th>Surface</th>
<th>Parameter</th>
<th>Heated by resistor P</th>
<th>Heated by combustion products</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Symbol, formula</td>
<td>Answer</td>
<td>Symbol, Formula</td>
<td>Answer</td>
</tr>
<tr>
<td>Elliptical bottom</td>
<td>$P_{ex} = \frac{2kX_{0}d_{0}}{D^{2} + 2h_{0}}$</td>
<td>45.6 bar</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$P_{me} = \frac{3}{4}P_{ex}$</td>
<td>11.4 bar</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$T_{eu} = 4020 - 235$</td>
<td>320°C</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$T_{ma} = \frac{1}{12}T_{eu}$</td>
<td>28°C</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$T_{ena} = \frac{1}{12}T_{ma}$</td>
<td>198°C</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$Q_{e} = m_{e}\Delta T_{ena}$</td>
<td>92 MJ, 2.2 kg TNT</td>
<td>$\Delta T_{ena} = 0.1$</td>
<td></td>
</tr>
<tr>
<td>Cylindrical Shell</td>
<td>$P_{ex} = \frac{2kX_{0}d_{0}}{D^{2} + 2h_{0}}$</td>
<td>28.5 bar</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$P_{me} = \frac{3}{4}P_{ex}$</td>
<td>7.1 bar</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$T_{eu} = 4020 - 235$</td>
<td>289°C</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$T_{ma} = \frac{1}{12}T_{eu}$</td>
<td>22.6 bar</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$T_{ena} = \frac{1}{12}T_{ma}$</td>
<td>198°C</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$Q_{e} = m_{e}\Delta T_{ena}$</td>
<td>7.73 MJ, 0.9 kg TNT</td>
<td>$\Delta T_{ena} = 0.1$</td>
<td></td>
</tr>
<tr>
<td>Conical Lid</td>
<td>$P_{ex} = \frac{2kX_{0}d_{0}}{D^{2} + 2h_{0}}$</td>
<td>0.62</td>
<td></td>
<td>$R = \frac{D}{2}$</td>
</tr>
<tr>
<td></td>
<td>$P_{me} = \frac{3}{4}P_{ex}$</td>
<td>1.7 bar</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$T_{ena} = \frac{1}{12}T_{ma}$</td>
<td>24.8°C</td>
<td></td>
<td>$k = 1$</td>
</tr>
<tr>
<td></td>
<td>$Q_{e} = m_{e}\Delta T_{ena}$</td>
<td>44 bar, 92 min, vessel</td>
<td>$\Delta T_{ena} = 0.1$</td>
<td>$254 \text{uC}$</td>
</tr>
</tbody>
</table>

**VIII.3 Calculation check to predict pressure vessels safety**

**ISO 3297: 2007 Certified Organization**

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Explosive timed
\[ \tau_{nn} = \sum_{n=1}^{\infty} \frac{m_{ne}}{S_{n}} \Delta t_{ne} \]
6574 = 1.8h
\[ \tau_{mk} = \sum_{n=1}^{\infty} \frac{m_{ne}}{S_{n}} \Delta t_{ne} \]
4574 = 1.27h

Explosive energy
\[ Q_n = m_{ne} c_p (t_{nn} - t_s) \]
6.44 MJ
1.5 kg TNT

Explosive Power
\[ P_n = \frac{Q_n}{\Delta t_{ne}} \]
64.4 MW
\[ P_{mk} = \frac{Q_{mk}}{\Delta t_{ne}} \]
140 MW

Max Explosive Power
\[ P_{np} = \frac{Q_{np}}{\Delta t_{ne}} \]
194 MW
\[ P_{mp} = \frac{Q_{mp}}{\Delta t_{ne}} \]
140 MW

VIII.4 Safety limitations of parameters

According to the formula showed in paragraph 6, we can calculate safety limitations of parameters of vessel:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Heated by resistor $P$</th>
<th>Heated by combustion products</th>
</tr>
</thead>
<tbody>
<tr>
<td>Symbol, formula</td>
<td>Answer</td>
<td>Symbol, formula</td>
</tr>
<tr>
<td>Safety $P$ in summer</td>
<td>$P_{ah} = \alpha F (t_{nn} - t_{fa})$</td>
<td>816 W</td>
</tr>
<tr>
<td>Safety $P$ in winter</td>
<td>$P_{ah} = \alpha F (t_{nn} - t_{fa})$</td>
<td>853 W</td>
</tr>
<tr>
<td>Temp. of CPs in summer</td>
<td>$T_{n} &lt; \frac{1}{\alpha_{1}} \sum_{i=1}^{\infty} a_{1} F_{1} \alpha_{2} F_{2} (t_{nn} - t_{fa}) / (\alpha_{1} F_{1})$</td>
<td>342°C</td>
</tr>
<tr>
<td>Temp. of CPs in winter</td>
<td>$T_{n} &lt; \frac{1}{\alpha_{1}} \sum_{i=1}^{\infty} a_{1} F_{1} \alpha_{2} F_{2} (t_{nn} - t_{fa}) / (\alpha_{1} F_{1})$</td>
<td>342°C</td>
</tr>
<tr>
<td>Fire-contacting area</td>
<td>$F_{1} &lt; \frac{a_{2} F (t_{nn} - t_{fa})}{\alpha_{1} (t_{nn} - t_{fa}) + a_{2} (t_{nn} - t_{fa})}$</td>
<td>0.05 m²</td>
</tr>
</tbody>
</table>

Fig. 4. Graph $t(\tau)$ of water when isobarically or isochorically heated by resistor or combustion products
IX. CONCLUSIONS

The increasing temperature and pressure of medium functions are derived directly from the derivative heat balance equation of system (medium and shell), with reasonable assumptions so they will have enough accuracy in calculation and design if dependent parameters are determined accurately enough.

The parameters when the vessel explodes are determined by strength of materials and functions \( t(\tau) \), \( p(\tau) \) above, should be accurate enough to be able to make a reference to forecast explosion of vessel. The safety solutions derived from the quantitative expression of the safety conditions is \( t(\tau) < t_n \), after changing the variables of \( t(\tau) \) và \( t_n \); we can infer safety solutions. The main solutions are outlined in article 7. Specific solutions can be inferred when analyzing the consequence expressions of the above-mentioned safety conditions.

REFERENCES