

## GAS PARAMETERS OF A HYDROGEN PEROXIDE GAS GENERATOR

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### Abstract

Several factors — economic, ecological, safety, reliability, etc. — have driven the renewed interest in aerospace applications of hydrogen peroxide ( $\text{H}_2\text{O}_2$ ). Although considerable information has been published on the properties and applications of hydrogen peroxide, there is a dearth of public information on design calculations of  $\text{H}_2\text{O}_2$  decomposition. In this paper a technique is discussed for calculation of composition and thermodynamic parameters of decomposition products of hydrogen peroxide aqueous solutions at high concentrations. The resulting equations are potentially of great value to the rocket field, and are in a form that can be used readily for gas generators and rocket performance calculations. Some results of calculation are shown in order to illustrate the applicability of the given method. Finally, a useful and simple two-parameter formula for the adiabatic decomposition temperature is obtained by fitting the data resulting from calculations.

**Keywords:** Hydrogen peroxide, High test peroxide, Monopropellant gas generator, Monopropellant decomposition, Tank pressurization.

### 1. INTRODUCTION

Concentrated hydrogen peroxide was one of the leading rocket propellants up to early 60-decade (Bloom et al., 1950; Andrews, 1990; Oliveira, 2000-a). Then, progressively, it became to be substituted, in several of its functions, by liquid oxygen, nitrogen tetroxide, nitric acid, and hydrazine and its derivatives. The factors which influenced this abandon of hydrogen peroxide were, sometimes, not so reasonable, as pointed out in (Oliveira, 2000-a).

The restored and increasing interest in use hydrogen peroxide in aerospace applications as alternative to the widely employed cryogenic and hypergolic propellant combinations is due to a variety of factors. These factors include environmental concerns, personnel hazards associated with toxic propellants, and heightened sensitivity to cost to develop and operate systems for toxic or cryogenic propellants (Oliveira, 2000-a).

Hydrogen peroxide aqueous solutions with high concentrations, now commonly referred to as *high test peroxide* or HTP, meet almost all desirable characteristics for aerospace purposes. It is specially attractive for use as monopropellant or oxidizer in a bipropellant systems developed in accordance with design-to-cost methodologies (Oliveira, 2000-a).

Major current end uses of hydrogen peroxide include pulp/paper and textiles bleaching, chemical synthesis, environmental treatment and metals processing (Jeff 1999). It is commonly used in low concentrations (3%) as an antiseptic, and in slightly higher concentrations as a hair bleach. In 30% concentrations, it is commonly used as a laboratory oxidant and by semiconductor industry (in this case, with high levels of purity). In concentrations of 70 through 99% by mass it is being used in many applications today. It was first used in rockets in 1936 in 80% concentrations, both as a monopropellant and as an oxidizer. Currently, 90% solutions are commonly used, and nominal 98% solutions are commercially available in some countries (Oliveira, 2000-a).

In Brazil, solutions with concentrations up to 70% are commercially available. The main local manufacturers are *Peróxidos do Brasil* (associated to the Solvay Interlox), with production capacity of 80,000 tons (expressed as 100%  $\text{H}_2\text{O}_2$ ) in plants at Santo André-SP and Curitiba-PR, and *Degussa-Huels*, with installed capacity of 40,000 tons per year in the production plant located in Aracruz-ES (Oliveira, 2000-a). The total availability in Brazil must be investigated. However, up to now it's known that the mentioned producers could sell HTP manufactured in another countries, without any restriction. Moreover, in case of demand enough to justify the investments, the local production plants can be adequate to produce rocket grade solutions (above 70%).

Traditionally, HTP has the following applications in the aerospace field:

1. An oxidant in a rocket engine or reaction control system with various fuels,
2. A hypergolic oxidant with fuels such as hydrazine or other similar type of fuels, or
3. A source of high-temperature gas after decomposition in a catalyst chamber for:
  - (a) Monopropellant rocket engines.
  - (b) Liquid bipropellant or hybrid rocket engines with auto-ignition of the fuel charge assured.
  - (c) Turbine drives.
  - (d) Servo-mechanism usage plus other hot gas drives.
  - (e) Self-pressurization of  $\text{H}_2\text{O}_2$  tanks, or pressurization of other oxidizer tanks.
  - (f) Production of heat.
  - (g) Oxygen gas for breathing and potable water for drinking as required for space travel applications.
  - (h) Source of clean hot gases for test uses or application purposes.

The use of liquid monopropellants simplifies engineering problems by reducing the number of tanks and feed lines required, but a large penalty is paid in the reduction of the specific impulse obtained. Similarly, with true solid monopropellants, there is greater simplicity and no problem of compatibility, but the specific impulse is again low. There are many applications, however, where small rocket motors are needed for attitude control, vernier modifications of trajectory, or gas generator applications, where high specific impulse is not important. The low chamber temperature of these systems is usually desirable in these applications, and system simplicity is usually an absolute requirement. Moreover, there are many other systems where the specific impulse is not the main figure of merit, and the performance is better evaluated in terms of density-impulse (the product of mass density by specific impulse) (Oliveira, 2000-a).

Any compound which can be made to decompose exothermically is theoretically able to be used as a monopropellant. However, there are often difficulties in obtaining smooth decomposition. In addition, some compounds such as unsymmetrical dimethyl hydrazine (UDMH), hydrazine ( $\text{N}_2\text{H}_4$ ), isopropyl nitrate, ethylene oxide, and other substances are too toxic and/or hazardous to be used without analyse another alternatives.

HTP has been used as monopropellant gas generant in many applications. It permits a simple generator system and does not require mixture-ratio adjustments. This system is relatively easy to control and the gases are generated at predictable temperatures. Unless the monopropellant is also employed as one of the engine's main propellants, however, the generator system introduces a third propellant, often requiring special handling and tankage.

In modern aerospace vehicles the single-component gas generators working on hydrogen peroxide  $\text{H}_2\text{O}_2$  are particularly attractive due to its nontoxic characteristic and also to the ecologically clean decomposition products (water and oxygen). Usually it is used on aqueous solution containing at least 80–85% by mass of hydrogen peroxide. Solutions with lower concentration yield a gas with a lower temperature (and efficiency).

The main goal of this paper is describe the method used for determine the adiabatic temperature of decomposition of hydrogen peroxide solutions at high concentrations. Additionally are determined other parameters of initial solution and decomposition products. It's assumed concentration enough high in such way that the decomposition products be in superheated zone. This paper is extracted from (Oliveira, 2000-b), where a computer program and a detailed discussion are presented.

## 2. HYDROGEN PEROXIDE GAS GENERATOR

High test hydrogen peroxide (HTP) can be decomposed reliably into superheated oxygen gas and water vapor at a predetermined temperature depending upon the HTP concentration and the initial temperature of the solution.

Liquid hydrogen peroxide can be decomposed by exposure to heat, as in a rocket thrust chamber, by exposure to a liquid catalyst such as a potassium permanganate-water solution, or by exposure to a solid catalyst. The decomposition catalyst used to the greatest extent is the solid samarium oxide coated silver screen. However, decomposition via a liquid catalyst is feasible and it has been employed in systems where short firing durations are used. When using a liquid catalyst the major problem is the necessary provision to ensure uniform mixing of the two liquids.

Traditionally, macroscopic metallic screens and coated ceramic pellets have been used as catalysts for the decomposition of hydrogen peroxide as applied to monopropellant thrusters, liquid rocket engines, and hybrid rocket systems. Catalyst activity depends on available catalytic surface area; elemental catalysts can be severely degraded by oxidation under use conditions. New approaches to forming robust, highly active and stable decomposition catalyst systems for flightweight applications were discussed by Rusek (1996). More recently, Rusek and Anderson (1999) discussed the synthesis, characterization, and evaluation of high surface area catalyst beds, and made comparisons with traditional propulsion catalysts.

Figure (1) shows a schematic of a typical monopropellant gas generator using hydrogen peroxide. The catalytic bed consists of alternate layers of stainless steel mesh and silver-plated-brass-wire screens secured by perforated end-plates or grids, which are applied with proper preload.

The treated silver screen catalyst normally is arranged in a tightly compressed pack. When the hydrogen peroxide passes over and around the wires of the pack screens, silver ions pass into the  $\text{H}_2\text{O}_2$  solution. These silver ions react with the  $\text{H}_2\text{O}_2$  molecule decomposing it into oxygen gas and water vapor with heat being liberated. This heat increases the reaction rate by raising the temperature of the screens and the  $\text{H}_2\text{O}_2$ . In a matter of milliseconds the  $\text{H}_2\text{O}_2$  reaction rate has increased to a point where the adiabatic decomposition temperature of the  $\text{H}_2\text{O}_2$  is reached. This reaction rate continues indefinitely if required unless foreign matter poisons the silver. However, the operational life of the catalyst pack is limited by gas pressure drop, which in turn depends upon several parameters (Davis and McCormick, 1960).

Hydrogen peroxide decomposition is a significantly exothermic process (96.3 MJ/kg-mole of  $\text{H}_2\text{O}_2$  at 25° C). Large volumes of oxygen are evolved as it decomposes. If the peroxide strength is high enough, the material will boil and large volumes of steam will also be generated.

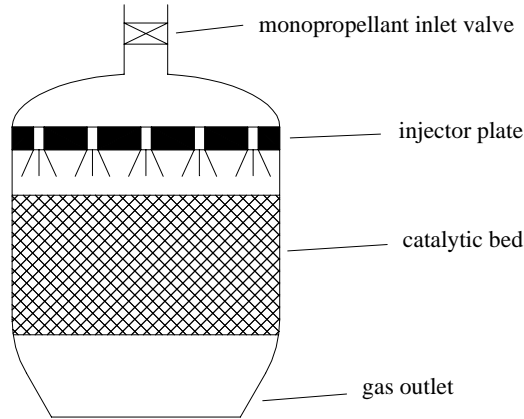


Figure 1: Scheme of a monopropellant gas generator.

For concentrations up to 64.7%  $\text{H}_2\text{O}_2$ , the maximum adiabatic decomposition temperature that may be experienced is  $100^\circ\text{C}$ ; i.e., there is sufficient water present to absorb the total heat of decomposition by generation of steam. For concentrations above 64.7%, the final adiabatic temperature that may be attained increases with increase in initial  $\text{H}_2\text{O}_2$  concentration. For 70%  $\text{H}_2\text{O}_2$ , the heat of decomposition is 1984.2 kJ/kg solution and the adiabatic decomposition temperature is  $240^\circ\text{C}$ , with a volume expansion of 2,580 times the starting volume. For 85%  $\text{H}_2\text{O}_2$ , the heat of decomposition is 2453 kJ/kg with a potential adiabatic temperature of  $620^\circ\text{C}$  and a volume expansion ratio of 4,600.

### 3. DECOMPOSITION PROCESS

The decomposition of hydrogen peroxide always involves the over-all reaction



Here,  $\Delta H_{\text{dec}}$  denotes the enthalpy of the decomposition reaction. For anhydrous  $\text{H}_2\text{O}_2$  at  $0^\circ\text{C}$  the enthalpy of the decomposition is  $\Delta H_{\text{dec}} = -12648$  kcal/kg-mole. The water in this case is considered to be in the gaseous state.

The mechanisms and rates of decomposition may differ, however, depending on the type of decomposition. The liquid-phase decomposition has been studied by Whittaker and Drew (1957), who derived the rate equation

$$k = 104 \exp(-14400/\mathcal{R}T) \quad \text{mole/liter-s}, \quad (2)$$

and suggested that the decomposition is not entirely heterogeneous. Numerous materials substantially catalyze the decomposition. As the catalysts can be used permanganates of alkaline metals ( $\text{NaMnO}_4$ ,  $\text{KMnO}_4$ ) or grids of silver wire. A review of the effects of various materials is given by Schumb, Satterfield and Wentworth (1955).

The working process of the HTP gas generator consists in the catalytic decomposition of  $\text{H}_2\text{O}_2$  in accordance with the thermochemical equation (1). The heat released during the decomposition of the  $\text{H}_2\text{O}_2$  solution is used to vaporize the ballast water, and heat the mixture of water vapor and molecular oxygen.

## 4. COMPOSITION AND THERMODYNAMIC PARAMETERS

The calculation of composition and thermodynamic parameters of the steam and gas is done as follows. Note that it is assumed concentration high enough to vaporization of all liquid water in the decomposition products. Thus, the products are in the superheated region.

### 4.1 Mass Density of the Hydrogen Peroxide Solution

Assuming that there is no volume contraction after the dissolution, then the total volume of the liquid solution is the sum of the individual volumes of water and peroxide, i.e.,  $V_s = V_{\text{H}_2\text{O}} + V_{\text{H}_2\text{O}_2}$ . Taking into account that the total mass of the liquid solution is the sum of component masses ( $m_s = m_{\text{H}_2\text{O}} + m_{\text{H}_2\text{O}_2}$ ), and considering that  $V_s = m_s/\rho_s$ , then the mass density of the solution is given by

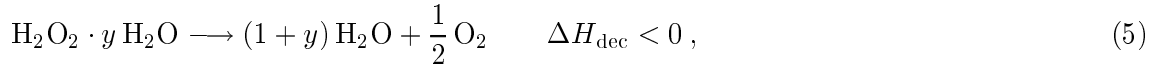
$$\frac{1}{\rho_s} = \frac{1-c}{\rho_{\text{H}_2\text{O}}} + \frac{c}{\rho_{\text{H}_2\text{O}_2}}, \quad (3)$$

where  $c$  accounts for the peroxide mass concentration in the aqueous solution, i.e.,

$$\frac{m_{\text{H}_2\text{O}_2}}{m_s} = c, \quad \frac{m_{\text{H}_2\text{O}}}{m_s} = 1 - c. \quad (4)$$

### 4.2 Mol Fraction of Water in the Solution

Considering the fact that all the gaseous oxygen came from the  $\text{H}_2\text{O}_2$  decomposition, since the  $\text{H}_2\text{O}$  dissociation is negligible at the involved temperatures, the decomposition of the *aqueous solution* can be expressed as follows:



where  $y$  denotes the number of moles of  $\text{H}_2\text{O}$  per 1 mol of  $\text{H}_2\text{O}_2$  present in the solution.

The mass concentration of  $\text{H}_2\text{O}_2$  in the solution,  $c$ , can be expressed as function of  $y$ :

$$c = \frac{34.016}{34.016 + 18.016 y}. \quad (6)$$

Therefore,

$$y = \frac{34.016}{18.016} \left( \frac{1}{c} - 1 \right). \quad (7)$$

### 4.3 Mass Fractions in Decomposition Products

In accordance with equation of reaction, Eq. (1), the mass fractions of water  $w_{\text{H}_2\text{O}}$  and oxygen  $w_{\text{O}_2}$  in the decomposition products of **anhydrous**  $\text{H}_2\text{O}_2$  are

$$w_{\text{H}_2\text{O}} = \frac{\mathcal{M}_{\text{H}_2\text{O}}}{\mathcal{M}_{\text{H}_2\text{O}_2}} = \frac{18.016}{34.016}, \quad (8)$$

$$w_{\text{O}_2} = \frac{1}{2} \frac{\mathcal{M}_{\text{O}_2}}{\mathcal{M}_{\text{H}_2\text{O}_2}} = \frac{1}{2} \frac{32.000}{34.016} = \frac{16.000}{34.016}, \quad (9)$$

where  $\mathcal{M}_{\text{H}_2\text{O}}$ ,  $\mathcal{M}_{\text{O}_2}$ , and  $\mathcal{M}_{\text{H}_2\text{O}_2}$  are the molecular masses of water, oxygen, and hydrogen peroxide, respectively. Obviously,  $w_{\text{H}_2\text{O}} + w_{\text{O}_2} = 1$ .

If the mass concentration of  $\text{H}_2\text{O}_2$  in the solution is  $c$ , 1 kg of solution contains  $c$  kg of pure  $\text{H}_2\text{O}_2$ . Since the oxygen forms only from  $\text{H}_2\text{O}_2$  in the quantity  $16.000/34.016$  kg per 1 kg of

$\text{H}_2\text{O}_2$ , the mass fraction of oxygen in 1 kg of hydrogen peroxide solution with concentration  $c$  will be

$$w_{\text{O}_2} = \frac{16.000}{34.016} c, \quad (10)$$

while the mass fraction of water is

$$w_{\text{H}_2\text{O}} = 1 - w_{\text{O}_2} = 1 - \frac{16.000}{34.016} c. \quad (11)$$

The temperature of the forming steam and gas does not exceed 1400 K, and at this temperature the degree of dissociation of  $\text{H}_2\text{O}$  and  $\text{O}_2$  is negligible. Thus, due to these facts, the composition of the steam-gas mixture does not depend on the pressure and is determined only by the concentration of the  $\text{H}_2\text{O}_2$  solution and, of course, by the initial temperature of solution. Certainly, if the concentration is below a given value, the released heat could not be enough to vaporize all the water, and results a heterogeneous system with two phases.

#### 4.4 Mol Fractions in Decomposition Products

The mol fractions of the decomposition products are obtained from (5):

$$n_{\text{H}_2\text{O}} = \frac{1 + y}{1.5 + y}, \quad (12)$$

$$n_{\text{O}_2} = \frac{0.5}{1.5 + y}. \quad (13)$$

#### 4.5 Partial Pressures of Decomposition Products

Assuming Dalton's Law to hold accurately, which is the case only with perfect gases, the fractional *partial pressure* is equal to the mol fraction, and

$$p_{\text{H}_2\text{O}} = n_{\text{H}_2\text{O}} p_p, \quad (14)$$

$$p_{\text{O}_2} = n_{\text{O}_2} p_p = p_p - p_{\text{H}_2\text{O}}. \quad (15)$$

Here,  $p_p$  denotes the pressure of mixture at reaction chamber.

#### 4.6 Determination of Thermodynamic Properties

Decomposition of the  $\text{H}_2\text{O}_2$  solution in the flow at the gas generator occurs at constant pressure and under adiabatic conditions. The isobaric-adiabatic process in the flow is accomplished, as it is known, with constant enthalpy of the working fluid. Therefore, the theoretical temperature of the steam-gas  $T_p$  can be determined from the condition of conservation of total enthalpy:

$$H_s = H_p, \quad (16)$$

where  $H_s$  is the total specific enthalpy of the  $\text{H}_2\text{O}_2$  solution with concentration  $c$  at initial temperature  $T_s$  (at the temperature at the gas-generator inlet);  $H_p$  is the total specific enthalpy of steam-gas mixture at the unknown temperature  $T_p$ .

The left and right sides of Eq. (16) are calculated as follows:

$$H_s = c H_{\text{H}_2\text{O}_2} + (1 - c) H_{\text{H}_2\text{O},l} + \Delta H_{\text{dis}}, \quad (17)$$

$$H_p = w_{\text{H}_2\text{O}} H_{\text{H}_2\text{O},g} + w_{\text{O}_2} H_{\text{O}_2}, \quad (18)$$

where  $H_{\text{H}_2\text{O}_2}$  is the total specific enthalpy of anhydrous  $\text{H}_2\text{O}_2$  at temperature  $T_s$ ;  $H_{\text{H}_2\text{O},l}$  is the total specific enthalpy of water at temperature  $T_s$ ;  $\Delta H_{\text{dis}}$  is the heat of dissolution of solution of  $\text{H}_2\text{O}_2$  in water, a function of the solution concentration  $c$ ;  $H_{\text{H}_2\text{O},g}$  is the total specific enthalpy of water vapor at temperature  $T_p$  and pressure  $p_{\text{H}_2\text{O}}$ ;  $H_{\text{O}_2}$  is the total specific enthalpy of gaseous oxygen at temperature  $T_p$  and pressure  $p_{\text{O}_2}$ .

The values of the total enthalpies of  $\text{H}_2\text{O}_2$ ,  $(\text{H}_2\text{O})_l$ ,  $(\text{H}_2\text{O})_g$ ,  $(\text{O}_2)_g$ , and  $\Delta H_{\text{dis}}$  are taken from appropriate handbooks. Here,  $\Delta H_{\text{dis}}$  was estimated as explained in (Oliveira, 2000-b), and the other needed enthalpies were evaluated by using the fitting curves presented on NASA SP-273 (Gordon and McBride, 1976). Such equations hold for thermally perfect gases (and, therefore, are independent of the pressure). So, the results deviates from the real values for high pressures ( $p_p > 20$  bar).

## 5. PROCEDURE FOR CALCULATING SUPERHEATED STEAM REGION

The calculation is done according to the formulas given in the previous sections. Since the temperature of the steam-gas mixture  $T_p$  is unknown before the calculation, it is determined by the trial-and-error method. The order of operations in this case is as follows: assume  $c$ ,  $T_s$  and  $p_p$ ; calculate the value of  $H_s = H_s(c, T_s)$  from relationship (17); give several values of  $T_p$ , close to the expected value, and calculate  $H_p = H_p(T_p)$  by relationship (18). The true value of the theoretical temperature of the steam-gas  $T_p$  will be that value for which Eq. (16) is satisfied.

The complete algorithm for calculation of the temperature of decomposition products is given below. It is assumed mass composition high enough for vaporization of water in the products.

1. Assume the mass concentration  $c$ , the initial temperature  $T_s$  of the solution, and the reaction chamber pressure  $p_p$ .

2. Calculate the mass fractions of steam and gaseous oxygen in the products:

$$w_{\text{O}_2} = \frac{16.000}{34.016} c ,$$

$$w_{\text{H}_2\text{O}} = 1 - w_{\text{O}_2} .$$

3. Calculate the total enthalpy of the liquid solution at the initial temperature  $T_s$  (this the temperature at the inlet of the gas generator):

$$H_{\text{H}_2\text{O}_2} = H_{\text{H}_2\text{O}_2}(T_s)$$

$$H_{\text{H}_2\text{O},l} = H_{\text{H}_2\text{O},l}(T_s)$$

$$\Delta H_{\text{dis}} = \Delta H_{\text{dis}}(T_s)$$

$$H_s = c H_{\text{H}_2\text{O}_2} + (1 - c) H_{\text{H}_2\text{O},l} + \Delta H_{\text{dis}} .$$

4. Estimate the partial pressures of decomposition products using Dalton's Law:

$$p_{\text{H}_2\text{O}} = n_{\text{H}_2\text{O}} p_p$$

$$p_{\text{O}_2} = n_{\text{O}_2} p_p = p_p - p_{\text{H}_2\text{O}} .$$

5. Assume  $T_p$  and calculate the total enthalpy of the gaseous products:

$$H_{\text{H}_2\text{O},g} = H_{\text{H}_2\text{O},g}(T_p, p_{\text{H}_2\text{O}})$$

$$H_{\text{O}_2} = H_{\text{O}_2}(T_p, p_{\text{O}_2})$$

$$H_p = w_{\text{H}_2\text{O}} H_{\text{H}_2\text{O},g} + w_{\text{O}_2} H_{\text{O}_2} .$$

6. Repeat the step 5 for different  $T_p$ 's until meeting the total enthalpy conservation:

$$H_s = H_p .$$

The true temperature of the steam-gas is 3–5% lower than the theoretical adiabatic temperature due to incomplete decomposition of  $\text{H}_2\text{O}_2$ . After determining the composition and temperature of the steam-gas, its remaining parameters are calculated as the parameters of a gaseous mixture whose composition is known.

## 6. RESULTS AND FINAL REMARKS

In this paper a technique was discussed for calculation of parameters of HTP decomposition. Some results are shown next.

Figure (2-a) shows the theoretical temperature of decomposition ( $T_p$ ) versus the mass concentration of  $\text{H}_2\text{O}_2$  ( $c$ ), for different solution's temperatures ( $25^\circ\text{C}$  and  $60^\circ\text{C}$ ). As can be seen, fixed  $T_s$ , the behavior  $T_p = T_p(c)$  is linear.

The theoretical variations of temperature of decomposition ( $T_p$ ) due to changes in the solution's temperatures ( $T_s$ ) are presented on Fig. (2-b). The results are parameterized by the mass concentration of  $\text{H}_2\text{O}_2$  ( $c$ ), and  $T_s$  variates in the range from  $25^\circ\text{C}$  up to  $60^\circ\text{C}$ . These results shown that, fixing  $c$ ,  $T_p$  changes linearly with  $T_s$ .

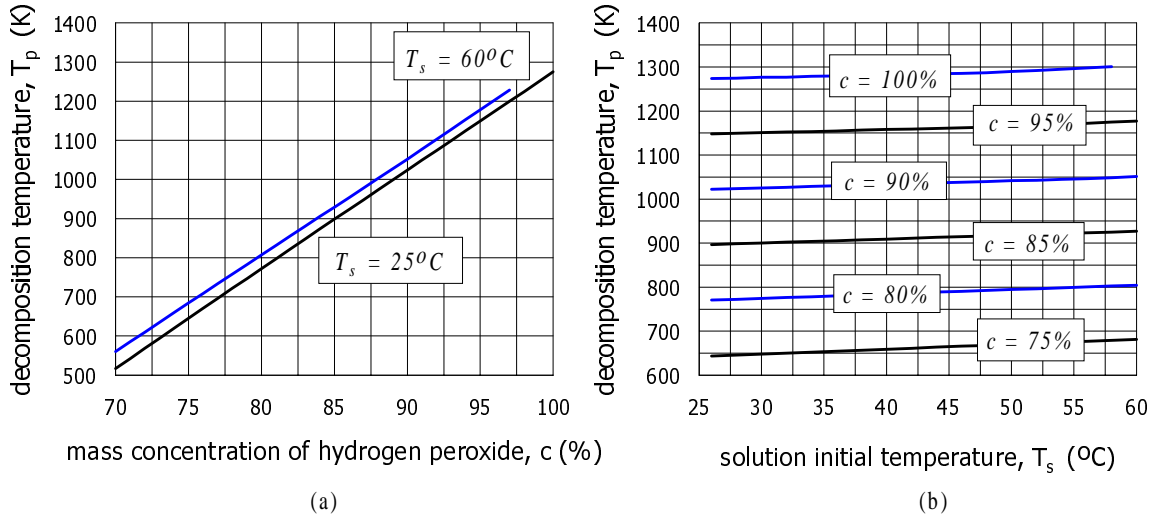


Figure 2: Decomposition temperatures for different concentrations of hydrogen peroxide and temperatures of solution.

The above decomposition temperature results can be summarized in the following expression, obtained by curve fitting process, and considering the linear variations with the solution initial temperature and concentration:

$$T_p = 1.43 T_s + (2523.18 c - 1676.4) . \quad (19)$$

This formula could be useful during the preliminary design of a space system which uses hydrogen peroxide decomposition in some of its sub-systems.

For pressures above 20 bar the water vapor departs from the thermally perfect gas behavior, and the influence of pressure become important. This fact, although considered in the given method, was not taken into account in the above results.

After calculation of composition and temperature of the decomposition products of HTP, by the given method, another parameters of the gaseous mixture can be evaluated using the formulae presented in the appendix.



The given method and resulting equations of composition and thermodynamic properties are potentially of great value to the rocket field, and are in a form that can be used readily for space vehicles performance calculations. They apply to a gas generator for: (1) monopropellant engine; (2) tank pressurization in a liquid rocket engine (LRE) or a hybrid rocket engine (HRE); and (3) gaseous oxidizer in a restartable bipropellant engine system.

Finally, must be remembered that, sometimes, HTP is used as oxidizer of the basic propellant of a LRE or HRE; therefore, by using HTP as substance for gas generation one can simplify the design of the engine, increase its reliability, and facilitate rocket operation.

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## APPENDIX

### ADDITIONAL PARAMETERS OF DECOMPOSITION PRODUCTS

After determination of  $n_{O_2}$  and  $n_{H_2O}$  and  $T_p$ , it's possible to know the other parameters of gaseous mixture resulting from the decomposition:

$$\mathcal{M}_p = n_{H_2O} \mathcal{M}_{H_2O} + n_{O_2} \mathcal{M}_{O_2}$$

$$\mathcal{R}_p = \frac{\mathcal{R}}{\mathcal{M}_p}$$

$$c_{p,p} = n_{H_2O} c_{p,H_2O} + n_{O_2} c_{p,O_2}$$

$$c_{v,p} = c_{p,p} - \mathcal{R}_p$$

$$k_p = \frac{c_{p,p}}{c_{v,p}}$$

$$c^* = \sqrt{\frac{1}{k_p} \left( \frac{k_p + 1}{2} \right)^{\frac{k_p + 1}{k_p - 1}} \mathcal{R}_p T_p}$$

It was used the notation:  $\mathcal{M}_p$  – molecular mass,  $\mathcal{R}_p$  – gas constant,  $c_{p,p}$  – specific heat at constant pressure,  $c_{v,p}$  – specific heat at constant volume,  $k_p$  – specific heat ratio, and  $c^*$  – characteristic exhaust velocity.

If  $V_s$  and  $\rho_s$  denote, respectively, the volume and mass density of the solution and, since the mass of products of decomposition  $m_p$  is equal to the mass of the solution  $m_s$ , then  $m_p = m_s = V_s \rho_s$ .

Assume, in first approximation, that the gaseous mixture formed after decomposition of HTP has a thermally perfect gas behavior. Therefore the ratio of the products to the solution volumes is

$$\frac{V_p}{V_s} = \rho_s \frac{\mathcal{R}_p T_p}{p_p},$$

where  $p_p$  is pressure at the decomposition chamber.