Droplet impinging behavior on surfaces
Part I – Hydrogen Peroxide on Aluminium Surface

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Abstract. In the present work the droplet behavior of the hydrogen peroxide (6% by weight) on a aluminum surface is reported. The behavior of hydrogen peroxide droplet is compared with water droplet for the same temperature conditions. Visualization of the droplet falling on a aluminum surface is done using a high speed camera. A data acquisition system is used for measuring the real time temperature. The characterization of droplet dynamics with variation in temperatures is detailed. The results reveal that with increase in temperature, the droplet splashes in to the ambient like a jet which is unlike water behavior, which when subjected to the same temperature conditions. The behavior of water droplet and hydrogen peroxide droplet after impinging and spreading over the surface and evaporation phenomenon is studied and observed.

1. Introduction

Micro thrusters are required to provide micro thrust of the orders of micro Newtons for nanosatellites. Recent trends in space satellite launches focus more on nanosat models (<20 kg) rather than conventional type. Even conventional satellites need precise positioning which leads to the development of Micro thrusters for micro-propulsion [1]. Cold gas, solid and liquid propellant are most commonly used in micro-propulsion systems. Hydrogen peroxide is one of the most commonly thought fluid for such micro-thrusters which is self decomposable in presence of catalytic chemical reactions. However the behavior of hydrogen peroxide on materials of such propulsion chambers is of immense importance for the design. Hydrogen peroxide was used in previous century in the rocket propulsion. Due to limitations of specific impulse, hydrogen Peroxide was replaced by hydrazine. Now with the launch of nano-satellites and space vehicles there is a requirement of producing controlled yet less thrust for putting them in precise orbit. In order to achieve high maneuverability, accurate positioning and orientation of Nano-satellites and spacecraft there is a requirement of generating precise impulse bit [2, 3]. The importance of using hydrogen peroxide as a monopropellant for micro-attitude control thrusters during space maneuvering was insisted by [4]. Different solutions have been used for characterizing the performances of low-thrust nozzles with hydrogen peroxide type propellants as cold gas [5]. A new type of fuel cell was tested which utilized silver catalyzed nickel foam cathode which was nano-structured in hydrogen peroxide with aluminum. The modified fuel cell along with renewable energy source could produce 20 times more electricity per pound than a conventional battery [6]. The effective electrochemical nature of hydrogen peroxide with electro catalyst made of aluminium was studied in an Al–H₂O₂ semi fuel-cell (SFC) [7]. This was done to determine the reduction of rate of reaction that generated electricity by chemical reactions with hydrogen peroxide and aluminum. In fuel cells, hydrogen peroxide serves two roles. It was used as electrolyte that conduct electricity and also as a cathode that attract electrons towards it. On the other side aluminium is used as anode that repulse electrons. This type of power source also showed more positive results observed in applications such as unmanned underwater vehicles (UUV) with successive dives which lasted up to 36 h duration [8]. As hydrogen peroxide is a well-known oxidizing agent it is being widely utilized for various industries like paper industries for paper pulp bleaching [9]. Bettner et al. [10] used hydrogen peroxide as oxidizer and polyethylene as fuel for hybrid motor configured rocket engine propellers. The above literature shows some of the applications of hyderogen peroxide. The present work is aimed to have an understanding of droplet behavior of hydrogen peroxide when it is made...
to impinge on a aluminum surface in the form of droplets. Thus it serves two purposes. One is high decomposition (giving required thrust) with increase in temperature and the second is cooling the surface by absorbing heat. This method is influenced by parameters such as the droplet size, nature of the fluid, kinetic energy of the impinging fluid, and the rate at which the fluid gets evaporated and these information is reported in the current work.

2. Experimental setup

The experimental set up for the present work is shown in the Fig. 1. In the present experiment a specimen of aluminum of size 5 x 3.3 x 0.7 cm is taken. The average surface roughness ($R_a$) of the specimen is 1.98 μm as measured by a surface profilometer. A small hole of size 1.2 mm is drilled on side of it. A k type thermocouple of size 1mm is inserted in to the hole and a heat sink paste is used to fill the hole. The voltage controlled heater inside a wooden box provides heat flux constantly, whereas the voltage is controlled using a variac. The specimen is arranged on the top of a wooden box which is packed with Mgo powder (magnesium oxide powder) to ensure uniform heat flux. The temperature history is recorded online using NI cDAQ 9174 chassis with NI 9203 high speed temperature module data acquisition system. Droplets are made to fall from a fixed height. The droplet is made to fall from a needle attached to a syringe pump. The position of the needle is fixed in such a way that the drop falls on the metal surface just above the place where the thermocouple is fixed. The gap between the thermocouple and the top surface on which the drop falls is 3 mm. A high speed camera (with a tripod stand) is held in front of the specimen in order to capture the droplet behavior. The frame rate of the camera is adjusted such that the droplet is viewed clearly. The high speed images are recorded in pc using Streampix software. Uniform illumination is provided by a light source which is arranged at proper height from the metal surface by a stand. The high speed camera (Basler CMOS Model No:acA2000 monochrome, with a zooming lens Navitar zoom 18-108mm) is capable of taking around 1500 frames per second at a 30 X 30 Resolution.

![Figure 1. Experimental set up](image)

Hydrogen peroxide used is 20 volumes of hydrogen peroxide solution which contains 6% of hydrogen peroxide by weight. When Hydrogen peroxide comes in to contact with aluminum surface, aluminum
oxide is formed. Generally for other metals like iron, the oxides formed cause the metal to corrode. However in the present experiment the aluminum oxide formed remain attached to the surface and stops the reaction occurring between Hydrogen peroxide and aluminum metal. Thus a thin layer is formed on the metal to stop the reaction proceeding showing corrosion resistant property of aluminum metal. The layer formed (barrier layer) is observed clearly in the experiment and can be seen in the Fig. 2(a). This layer is visible only at the beginning where evaporation happens and with increase in temperatures due to rapid boiling process the layer was not visible.

![Figure 2](image1.png)  ![Figure 2](image2.png)

**Figure 2.** (a) With slag on Aluminium metal 78°C (b) without slag at 100°C and above

The images which are captured through high speed camera are later analyzed frame by frame using Streampix package. Matlab software is used to process the image in the image processing tool box. A detailed procedure on image processing is explained in part II of this paper. Temperature is raised from 75°C to 118°C by adjusting the variac. At lower surface temperatures from 75 to 90°C, small bubbles are formed inside the droplet and heat transfer is primarily by boiling as shown in Fig. 3. When the droplet is impinged, it spreads along the heated metal as a result of potential energy which is stored in the droplet.

![Figure 3](image3.png)

**Figure 3.** Spreading and bubble formation in droplet
3. Results and Discussion

The droplet absorbs heat and as a result bubbles are formed because of boiling at high temperatures. The phenomenon is different between water and hydrogen peroxide for the same temperature. In hydrogen peroxide because of excessive oxygen the reaction is vigorous and the bubble formed explodes. Instead of normal boiling which is observed in water, the vapor formed splashes out. The phenomenon of splashing occurs above 90°C in hydrogen peroxide while in case of water the process of formation of bubbles and coalescence of bubbles is observed at the same temperature.

![Figure 4. Splashing of droplet at 90°C](image)

Fig. 4 shows the spreading radius and droplet height of the fluid on an aluminium surface. Increase in temperature up to 85°C results in decrease in spreading radius. With further increase in temperature the spreading radius increases.

![Figure 5. Temperature vs spreading radius](image)

The spreading radius is affected by parameters like surface tension, gravity, viscosity and nucleation site density. At initial temperatures of 77°C to 84°C the droplet tends to absorb more amount of heat and there
are bubbles which form uniformly in nucleation sites and depart. There are many smaller bubbles which are formed on the surface and reach top and release the vapor. This results in the liquid radius at the surface getting decreased. However above 84°C the spreading radius is increased. This is because the drop after impingement gets a cloud like appearance. The bubbles formed on the surface coalesce with each other in fraction of seconds and forms a big blanket thereby increasing the spreading radius. This phenomenon is observed till surface temperatures of 102°C. However beyond this temperature there are no more bubble formation and there is a thin vapor film which covers the surface on which the liquid drop starts floating. The radius of this drop decreases and hence the spreading radius also decreases. Hydrogen peroxide is 40% denser than water and is more viscous when compared with water (for any concentration of hydrogen peroxide and water), thus its spreading radius increases because of low viscosity up to certain high temperatures. The results of Fig. 5 show that with increase in temperature up to 84°C the drop radius decreases. The height of the drop in that case remains the same. If it is a single phase fluid the drop height is supposed to decrease with increase in drop radius. However formation of bubble results in increase in height of drop since the vapor formed occupies more space. Beyond 85°C because of vapor blanket formation the height of the drop increases rapidly. After attaining 95°C the average height of the droplet decreases because there will be a rapid explosion of the bubbles through which the vapor escapes. The oscillating nature is as result of formation and escape of vapor blankets.

4. Comparison of nucleation site density

Hydrogen peroxide (H₂O₂) is less stable than water. It self decomposes and with increase in temperature the number of nucleation sites is more in H₂O₂ when compared to water. This is visible from Fig. 6 (a) & 6 (b) which compares the nucleation site density of water and hydrogen per oxide for the same temperature. Nucleation spots mainly affect the transition of liquid to vapor. More the nucleation points faster will the evaporation. In Water, bubbling will occur at nucleation points and when the vapor pressure is high enough to overcome the surface tension of liquid, vaporization occurs. H₂O₂ on the other hand due to its high nucleation spots will form a cloud of bubbles which will encompass into large cloud like structure due to its surface tension. Decomposition of H₂O₂ will result in nascent oxygen which is highly combustible hence will produce a thrust force. The nucleation cloud decreases in size with increase in temperature and at certain temperature there will be appearance of flashing i.e. the liquid as soon as touching the surface vaporizes. At this flashing point the thrust will be the maximum.

![Figure 6. Nucleation spots at 78°C for a) H₂O b) H₂O₂](image-url)
when observed will look like floating in air. The thermal currents flow towards less temperature area. Due
to gravity and self-weight of the drop, it will touch the surface and gets vaporized after some delay. Water
though has lesser boiling point than Hydrogen peroxide, due to its stability will have lesser pushing force.
on the other hand H₂O₂ will form a cloud like structure mainly consisting of the trapped vapors in the
bubble and have greater pushing force which is a primary requirement for producing the necessary micro
thrust. These results are shown in Figure 7 which compares the vaporizing behavior of water and hydrogen
peroxide at 102°C.

![Image](image_url)

(a) ![Image](image_url) (b)

**Figure 7.** At 102°C (a) H₂O Liquid splashing in water (b) H₂O₂ Vapor cloud formation

5. Conclusions

The droplet behavior of hydrogen peroxide (6% by weight) on a aluminum surface is reported. The
results are compared with water droplet for the same temperature conditions. Visualization of the
droplet falling on a aluminum surface is done using a high speed camera. A data acquisition system is used
for measuring the real time temperature. The results reveal that with increase in temperature, the droplet
splashes in to the ambient like a jet which is unlike water behavior, which when subjected to the same
temperature conditions. The decomposition of the hydrogen peroxide is very rapid at high temperatures.

References:

[1] Darren L Hitt, Charles M Zakrzewski and Michael A Thomas, 2001, “MEMS-based satellite
micropropulsion via catalyzed hydrogen peroxide decomposition”, *Smart Materials And Structures, Vol. 10*, 1163–1175.

[2] Tae Goo Kang, Sang Wook Kim, Young Ho Cho, High-Impulse, Low-Power, 2002,"Digital
microthrusters using low boiling temperature liquid propellant with high viscosity fluid plug”,
*Sensors and actuators, Vol. 97-98*, 659–664.

[3] David H. Lewis Jr., Siegfried W. Janson, Ronald B. Cohen, Erik K. Antonsson, 2000, “Digital
micropropulsion”, *Sensors and actuators, Vol. 80*, 143–154.
[4] E.V. Mukerjee, A.P. Wallace, K.Y. Yan, D.W. Howard, R.L. Smith, S.D. Collins, 2000, “Vaporizing liquid microthruster”, Sensors and actuators, Vol. 83, 231–236.

[5] Claudio Lugini, Marcello Romano, 2009, “A ballistic-pendulum test stand to characterize small cold-gas thruster nozzles”, Acta Astronautica, Vol. 64, 615-625.

[6] Weiqian Yang, Shaohua Yang, Wei Sun ,Gongquan Sun, Qin Xin, 2006, “Nanostructured silver catalyzed nickel foam cathode for an aluminum–hydrogen peroxide fuel cell”, Journal of Power Sources, Vol. 160 (2), 1420–1424.

[7] David J. Brodrecht, John J. Rusek, 2003, “Aluminum–hydrogen peroxide fuel-cell studies”, Applied Energy, Vol. 74, Issues 1–2, 113–124.

[8] Oistein Hasvold, Kjell Havard Johansen, Ole Mollestad, Sissel Forseth, Nils Storkersen, 1999, “The alkaline aluminium/hydrogen peroxide power source in the Hugin II unmanned underwater vehicle”, Journal of Power Sources, Vol. 80, Issues 1–2, 254–260.

[9] Claustre Prat, Manuel Vicente, Santiago Esplugas, 1998, “Treatment of bleaching waters in the paper industry by hydrogen peroxide and ultraviolet radiation”, Water Research, Vol. 22 (6), 663-668

[10] Bettner M and Humble R, 1998, “Polyethylene and hydrogen peroxide hybrid testing at the United States Air Force Academy” Proc. 1st Annual Hydrogen Peroxide Conference, University of Surrey