

DESIGN, FABRICATION, AND DEMONSTRATION OF A MEMS STEAM GENERATOR FOR EJECTOR PUMP APPLICATIONS

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Abstract: The design, fabrication, and successful demonstration of a microfabricated steam generator based on the homogeneous catalytic decomposition of hydrogen peroxide are presented. The device consists of a mixer, a reactor, and a nozzle, and it produces a jet of high-speed steam that can be used for driving ejector pumps and microthrusters. Numerically-implemented coupled chemical, thermal, and fluidic modeling was used to design the device, which was then fabricated via bulk micromachining and enclosed in a thermally insulating package. The device operated successfully with 90% peroxide catalyzed by ferrous chloride tetrahydrate solution. Visual inspection of the device confirms full liquid vaporization.

Keywords: steam, hydrogen peroxide, catalyst, reactor, nozzle, ejector pump, microrocket, microfabrication

INTRODUCTION

MEMS ejector pumps offer a promising approach to microscale vacuum gas pumping for moderate pressure rises [1]. Compared to existing MEMS gas pumps, ejector pumps allow much higher flow rates, along with robust operation and no moving parts. In an ejector pump, a high-speed gas stream (the motive flow) entrains and mixes with a low speed stream (the suction flow). The suction fluid is pumped via the conversion of part of the mixed flow's kinetic energy into pressure rise. Steam chemically generated from a liquid precursor is often used for the motive fluid source since it offers significant advantages over compressed air (which needs a reservoir with a large volume) and over steam generated by vaporizing a water reservoir (which requires an external heat source and suffers from a long start-up time).

Aqueous high test hydrogen peroxide is a non-toxic and green candidate for the chemical generation of steam. Hydrogen peroxide decomposes catalytically to produce oxygen gas, water, and heat that subsequently vaporizes the water. A microscale device that generates steam via this approach can thus be integrated into a MEMS ejector pump to provide the motive fluid. Closely related devices can also be used for thrust generation in microrockets [2].

Previous attempts at demonstrating microscale steam generators based on the above approach have generally been unsuccessful [2, 3]. One of the challenges is that, as the device is downscaled, the ratio of surface area to volume increases. Therefore, the heat losses become significant compared to the heat generated by the exothermic reaction inside the device, and the energy remaining inside may not be sufficient for sustaining the reaction and vaporizing

the water. The effects of boundary layers also become more pronounced and can lead to significant deviations from inviscid behavior. Finally, prior devices have typically used a heterogeneous catalyst coated on the device walls, which necessitates very narrow flow channels to maximize the reaction surface area; this makes the device prone to clogging. Such a static catalyst layer is also susceptible to poisoning and eventually becoming ineffective.

In the current work, the above challenges are addressed by using multi-domain physical modeling to simulate the reacting flows and evaluate the heat losses from the device. The results guide the design of both a MEMS device that decomposes hydrogen peroxide using a homogeneous catalyst and a package with sufficiently high thermal resistance to enable full peroxide decomposition and complete water vaporization. The model includes the effects of boundary layers in the flow; these effects are compensated for in the design. Finally, by using a continually-supplied homogeneous liquid catalyst, the poisoning problem of heterogeneous catalysts is eliminated, at the expense of adding a mixer section for the peroxide and catalyst streams.

CONCEPT AND MODELING

The steam generator consists of three sections: a mixer, a reactor, and a nozzle, as shown in Fig. 1.

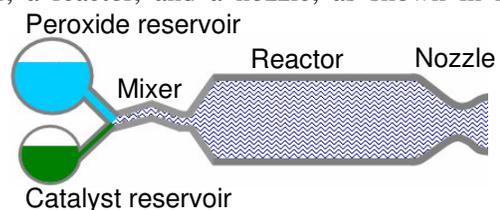


Fig. 1: Schematic of device

Mixer

The mixer is designed to achieve full mixing of the peroxide and catalyst streams before they enter the reactor. Four mixers are used in parallel to minimize the pressure drop across the device and hence the supply pressure required. The geometry of each of these mixers is shown in Fig. 2. The mixer channels are sized to achieve “engulfment flow” following the work of Krockman et al. [4] who demonstrated that mixing in this flow regime is significantly faster than in other regimes typical of microflows. The design also includes wall protrusions and zigzag corners which have been shown to enhance micromixing [5, 6]. A CFD package (ADINA) is finally used to simulate the flow in the mixer and to verify sufficient mixing [7].

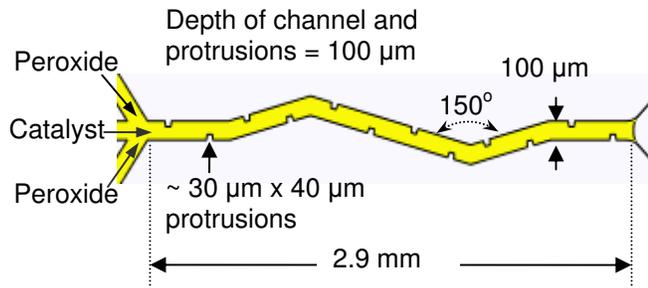
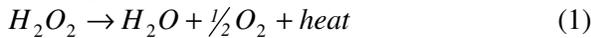


Fig. 2: Mixer design and geometry

Reactor

In the reactor, hydrogen peroxide decomposes to produce water, oxygen gas, and heat, according to the chemical equation:



The reactor is designed to achieve full peroxide decomposition and complete water vaporization using a one dimensional coupled thermochemical flow model. In this model, the mass fraction of the peroxide Y_P , the bulk temperature T , and the quality (i.e. ratio of mass of a given species that is in the gas phase to the total mass of that species) of the water f_w and the peroxide f_p are chosen as the independent or state variables. Based on the variation of these parameters along the reactor, the flow is divided into five stages, as shown in Table 1 (i = increasing, d = decreasing, c = constant at the value shown in parentheses, and $T_{b,w}$ and $T_{b,p}$ are the boiling points of water and peroxide respectively at the reactor pressure). The reaction inside the reactor chamber is assumed to occur at constant pressure because the major pressure drop inside the device occurs in the much narrower mixer channels. All other quantities can be related to the state variables either via constitutive relations (e.g. to find the mixture density

or species’ enthalpies) or via stoichiometry (e.g. to find the mass fractions of the water and oxygen produced). The species mass transport and energy conservation equations are used to solve for the state variables, which are evaluated along the reactor length in each of the five stages using a numerical algorithm. Fig. 3 plots the bulk temperature and peroxide mass fraction versus position along the reactor.

Table 1. Flow stages inside the reactor and the variation of the peroxide mass fraction, temperature, water and peroxide qualities in each stage

Stage	Y_P	T	f_w	f_p
I	d	i	$c(0)$	$c(0)$
II	d	$c(T_{b,w})$	i	$c(0)$
III	d	i	$c(1)$	$c(0)$
IV	d	$c(T_{b,p})$	$c(1)$	i
V	d	i	$c(1)$	$c(1)$

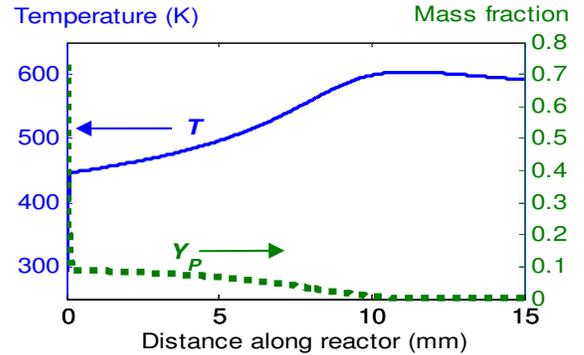


Fig. 3: Variation of temperature T and peroxide mass fraction Y_P versus distance along the reactor

Nozzle

The converging-diverging nozzle for the present demonstration device is designed to eject the superheated flow at atmospheric pressure. The nozzle has a converging section that accelerates the flow to sonic velocity, and then a diverging section that produces supersonic flow. A one-dimensional compressible flow model accounting for heat losses but assuming inviscid behavior is first used to get an approximate geometry; the design is then improved by accounting for the formation of boundary layers and adjusting the nozzle width.

Thermal management

Thermal management is key to ensuring successful operation of the steam generator. Using the reactor model, the maximum heat loss from the device that can be tolerated without causing incomplete peroxide decomposition or water vaporization was

estimated. Two packaging schemes were then evaluated: suspending the device in air with fluidic connections made via pipes adhered directly to the device surface (e.g. by epoxy), or encasing the device inside a machined package using O-rings and threaded fittings. In the first approach, the flow loses heat by internal forced convection to the device walls and then by external natural convection to the ambient air. This approach provides sufficient thermal insulation due to the low natural convection coefficient, but it was not selected because of robustness considerations. In the second approach, the flow loses heat by internal forced convection to the device walls and then by conduction through the package to the environment. The package material was required to meet the following criteria:

- Melting point greater than 700 K to tolerate the temperatures reached inside the reactor
- Thermal conductivity less than 0.5 W/m-K to limit the heat losses to no more than 25% of the critical value required for successful operation based on the 1-D model
- Machining tolerance sufficiently tight to allow accurate dimensioning of the O-ring gland and successful installation of the O-rings.

Based on these considerations, the package was constructed from a mica-based ceramic composite (Rescor 914, Cotronics Corporation). The package design allows visual access to the device and thermocouple insertion, as shown in. Fig. 4.



Fig. 4: Photograph of package

FABRICATION

The device consists of five layers and it is made of five bonded wafers, as shown in Fig. 5. Layers 1 through 4 are silicon wafers; layer 1 is about 0.5 mm thick and the rest are 1 mm thick. Layer 5 is a blank, 0.5 mm thick Pyrex wafer used for capping the device and providing optical access to the reactor chamber and one of the mixers.

The silicon wafers are processed using contact photolithography and deep reactive ion etching (DRIE). Layer 1 and 3 are fabricated similarly. Layer 1 contains the inlet holes for the peroxide and catalyst streams along with thermocouple insertion holes to

measure the silicon wall temperature, while Layer 3 contains through-holes and some of the reactor and nozzle depths. Layers 2 and 4 are identical and they contain on both sides the relatively shallow mixers in addition to the remaining deep-etched features. The different depths of the mixers and the deep features necessitate a “nested mask” approach using a combination of photoresist and oxide layers as masks. The four patterned silicon layers are then bonded together using silicon direct bonding, and the stack is anodically bonded to the Pyrex wafer and diesawed. A microfabricated device is shown in Fig. 6.

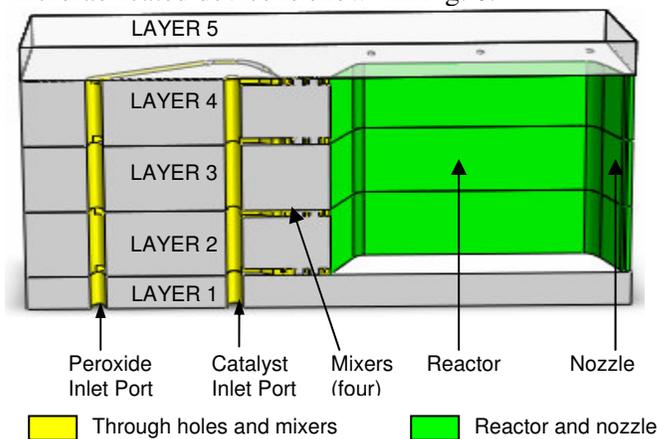


Fig. 5: Schematic cross section of the device



Fig. 6: Photograph of a microfabricated device (42×9 mm)

TESTING AND DEMONSTRATION

High test hydrogen peroxide (90% solution purchased from FMC Chemicals) and ferrous chloride tetrahydrate solution (solid purchased from Sigma Aldrich and dissolved in DI water at 80% of saturation) are used to test the device. Syringe pumps (Chemyx Inc.) with stainless steel syringes are used to feed both streams to the package. Hydrogen peroxide at this concentration is a very strong oxidizer with the capability to cause a fire or a detonation in a closed system if contaminated. Therefore, several measures are taken to ensure safety. All components that come in contact with the peroxide during the experiment are made from compatible materials: Teflon and its derivatives, PEEK, passivated stainless steel (passivation achieved by immersion in 70% HNO₃ followed by conditioning with 30% H₂O₂), Viton, or Chemraz. The fluid path of each stream also contains

a pressure relief valve (Swagelok) that is activated when the system pressure exceeds 150 psi. Finally, check valves (Upchurch Scientific) are installed close to the package to prevent the flow of either stream into the piping of the other during startup.

The syringe pump flow rates are set at 5 mL/min for the peroxide and 0.5 mL/min for the ferrous chloride catalyst, and the pumps are turned on. Frame-grabs of the device during operation are shown in Fig. 7. First, a short transient period exists in which the device walls heat up. During this period, some liquid is present in the effluent in addition to the gas, as shown in Fig. 7a. After the device walls reach the high temperature dictated by the reaction, steady state conditions prevail and the effluent is completely gaseous. This is shown in Fig. 7b.

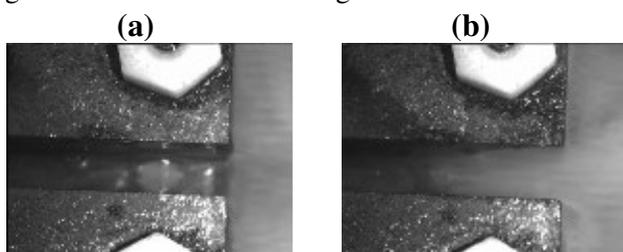


Fig. 7. Frame-grabs of the device during operation, showing a) the transient period in which some of the effluent is still liquid, and b) the steady state period in which the effluent is completely gaseous. Flow is from left to right.

The performance of the system is evaluated based on two criteria: the complete decomposition of the peroxide, and the complete vaporization of the water produced by the reaction. Visual inspection of the steam exiting the nozzle confirms the second criterion. In addition, there is a coupling between the phase of the products present at the exit of the nozzle and the mass fraction of the peroxide decomposed. The model predicts that when the products become completely gaseous, the remaining peroxide concentration is at most about 10%. Therefore, complete water vaporization indicates full or almost full peroxide decomposition, supporting the first criterion, and hence confirming the successful operation of the device.

CONCLUSION

In this work, the design, fabrication, and demonstration of a MEMS steam generator based on the catalytic decomposition of hydrogen peroxide have been reported. This is the first device of its kind in the literature to produce a completely gaseous effluent. Full effluent vaporization makes the device very useful for driving MEMS ejector pumps after

adjusting the nozzle to match the exit pressure to the upstream pumping pressure. The device can also be used as part of a microthruster after adjusting the nozzle to accelerate the flow to the desired speed. Future work will include refractive index analysis to quantify the degree of peroxide decomposition and temperature measurements to compare the experimental results with the developed model.

ACKNOWLEDGEMENTS

The authors thank Kimberlee Collins for the CFD simulation of the mixer. Microfabrication was carried out at the Microsystems Technology Laboratories (MTL) at MIT. This work was supported in part by the Tactical Technology Office at the Defense Advanced Research Projects Agency (DARPA), in part by the Missile Defense Agency (MDA), and in part by the Air Force Research Laboratory through DARPA Order T171/00, Program Code: 4G10, issued by the DARPA Contracts Management Office under Contract MDA972-04-C-0140. The views and conclusions that are contained in this document are those of the authors and should not be interpreted as representing the official policies, either expressed or implied, of the DARPA or the U.S. Government.

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