Versatile, fuel-powered active gas mask or room air purifier

Paul D. Ronney, Department of Aerospace and Mechanical Engineering
University of Southern California, Los Angeles, CA 90089-1453
Topic Number: CBDIF-2006-PRO01 (Individual Protection)

Motivation and approach

Practically all chemical and biological warfare agents can be destroyed simply by incineration, as is common in demilitarization efforts. However, in the field an agent dispersed in low concentrations in the air itself, rather than a concentrated agent, must be decontaminated, and this decontaminated air must be breathable. With this motivation, an active gas mask or air purifier using heating of inhaled air to perform decontamination has been studied by MesoSystems, Inc. under the DARPA/DSO Mesoscale Machines Program. This system uses an electrical (or possibly combustion) heat source and a heat exchanger. Because of limited heat exchanger temperature (250˚C – 400˚C), a catalyst is required. Breakdown products of chemical-agent molecules either deposit onto the catalyst as an acid (e.g., phosphoric acid) or are released as acid-gases (e.g., NO/NO2), but the deposited acids accumulate and will eventually degrade catalyst performance. (Released acid gases are not problematic because of the low concentrations involved.)

We propose an alternative approach to chemical and biological agent destruction. Heat-recirculating or "excess enthalpy" burners, first reported by Felix Weinberg at Imperial College (London) in the 1970's, transfer thermal energy from the combustion products to the reactants without mass transfer (thus dilution of reactants), thus the total reactant enthalpy (sum of thermal and chemical enthalpy) can be higher than in the incoming cold reactants and therefore burn mixtures much leaner than the conventional lean flammability limit. The most effective configuration was a "Swiss roll" spiral counter-current heat exchanger with combustion its center. With the Swiss roll, Weinberg demonstrated steady burning with mixtures 5 times less fuel than the lean limit of conventional flames. Thus, *the heat-recirculating burner enables combustion of very lean mixtures containing enough excess oxygen that the exhaust is breathable.* Moreover, the heat transfer from the combustion products back to the reactants heat enables the exhaust temperature to be <u>much</u> lower than the combustion temperature.

Advantages of the proposed approach

Compared to the MesoSystems device or similar approaches, Swiss roll combustors have the following advantages:

- *More complete decontamination of chemical agents*. The Swiss roll design uniquely allows combustion of very lean mixtures, thus air can be uniformly heated to very high temperatures (at least 1177˚C in our tests) via combustion with most of the oxygen left intact for breathing.
- *Virtually instant-on*. The Swiss-roll combustor reaches steady-state temperatures to decontaminate air within a few seconds of being activated. The MesoSystems device requires a separate heat source and heat exchanger that would take much longer to start.
- *Low energy consumption*. The MesoSystems approach emphasizes electrical heating, which virtually rules it out for portable use. (Combustion heat sources are barely alluded to in their public documents.) Again, because of the ability to burn unusually lean fuel-air mixtures, the Swiss roll burner could decontaminate large volumes of air using very little fuel.
- *Fuel flexibility*. Swiss rolls burners can work with any kind of fuel, *including logistics fuels such as JP8*. Catalysts are not needed, thus catalyst poisoning by fuel sulfur is not an issue.
- *Shelf life*. Hydrocarbons have virtually unlimited shelf life compared to batteries.
- *Integrated thermoelectrics*. With DARPA support, we have developed technologies for integrating of Swiss roll burners with thermoelectric elements. This can provide more than enough electrical power needed for air pumping, control electronics, etc., plus surplus power.
- *Side benefits*. The combustor can provide heating and humidification of air as needed.

Example of anticipated performance and challenges

Prof. Ronney's group has over 7 years experience with Swiss roll burners in the context of DARPA/MTO-supported programs on microscale power generation, in sizes from 10 mm to 100 mm, thermal power levels of 1 to 2000 W and combustion temperatures of 60˚C to 1177˚C. Materials including inconel, titanium, ceramics and even plastics have been used. Some examples of experimental and modeling results are shown in Figs. 1 and 2.

As an example of the application of Swiss roll burners to agent destruction, consider the 7 cm x 7 cm x 5 cm inconel device reported in Fig. 1. This device has a volume of 245 cm^3, which is less than a C2A1 cartridge (4" diameter x 3" tall = 618 cm^3) and weighs about 150 grams (but can be made much lighter using titanium instead of inconel.) At the highest Reynolds number shown, the air flow rate is 97.5 standard liters per minute, and the propane concentration at the lean flammability limit is 0.80%, resulting in an exhaust O_2 concentration of 16.7% compared to 21% at ambient conditions. Moreover, much higher flow rates are possible and in fact lead to even higher exhaust oxygen concentrations. The fuel (propane or butane) flow rate is only 1.5 grams per minute (thermal power 1100 W). For this condition the combustion temperature is 1177˚C, far exceeding that needed to destroy any chemical or biological agent without a catalyst. The exhaust temperature is only 67˚C, hence that only modest external heat exchange is needed to cool the exhaust to safe levels for respiration. CO and NO were not found in the exhaust even though we could detect down to at least 10 ppm, which is well below OSHA exposure limits. The pumping power required to move 97.5 SLPM through the burner is only 1.7 watts (pressure drop 25 mm H_2O). The BAA requirement is that the device consume less than 100 Watts of electrical power, however, this device could actually *generate* nearly 100 Watts of power with thermoelectric elements despite the relatively low conversion efficiency of thermoelectrics.

The most significant challenge to producing breathable exhaust is CO_2. The long-term exposure standard for CO_2 without adverse effect is 0.5%, although levels up to several percent are tolerated for short periods of time. In the above example, the exhaust CO_2 level is 2.4%, but Weinberg has reported (in burners with more turns) values as low as 1.0%. Thus, further improvements in lean flammability limit are desirable for decreased CO_2 and increased O_2 exhaust concentrations.

Work statement

In the first year we will design and build a burner specifically intended for chemical and biological agent destruction. Using gaseous fuels (e.g. propane, butane), we will determine the effectiveness of the Swiss roll combustor for destroying surrogate chemical agents such as Dowanol DM (a surrogate for mustard gas (HD)), diglyme (sarin (GB) surrogate) and tetraglyme (VX surrogate) and reduce the lean limit with improved heat exchangers and insulation to further increase O_2 exhaust levels and decrease CO_2 exhaust levels. Prof. Ronney's laboratory is equipped with gas chromatographs for measuring destruction efficiency. In the second year we will we will develop a logistics fuel (e.g. JP8) burner, integrate the balance of plant using thermoelectric power generation for the air pump and fuel metering and characterize the complete system under simulated field-like conditions. Throughout the project, state-of-the-art computer simulations (see Fig. 2) will be used to guide the design, development and testing process.

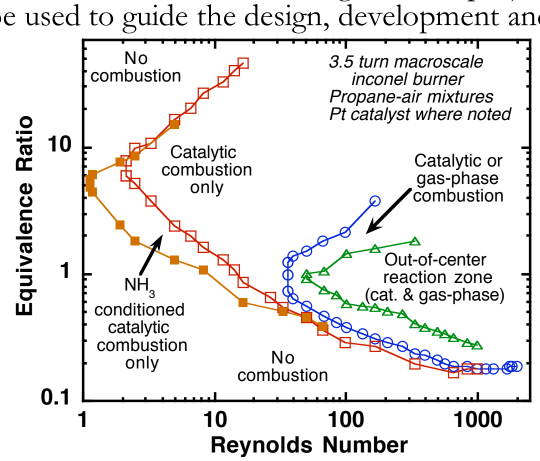

Figure 1. Extinction limits of propane-air mixtures in a 7 cm x 7 cm x 5 cm Swiss roll burner. The case mentioned in the text corresponds to Re = 2184.

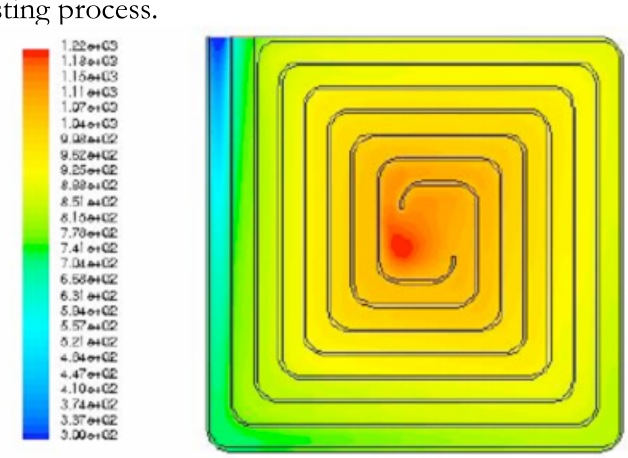

Figure 2. Example of computed temperatures in a Swiss roll combustor including conductive, convective and radiative heat transfer and chemical reaction.