Construction and Testing of a radiation-beam powered TA (ThermoAcoustic) washer for grease removal

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Abstract : A small washer powered directly and solely by thermal radiation was constructed and tested to explore the feasibility of using solar energy or other types of thermal radiation for washing and cleaning. In principle, TA (ThermoAcoustic) washers have the benefits of simpler design and operation and fewer energy conversion processes, thus should be more energy efficient and cost less than electric washing/cleaning systems. The prototype TA converter we constructed could sustain itself with consistent fluid oscillations for more than 20 minutes when powered by either concentrated solar radiation or an IR (infrared) heater. The frequencies of water oscillations in the wash chamber ranged from 2.6 to 3.6 Hz. The overall conversion efficiency was lower than the typical efficiencies of TA engines. Change in water temperature had little effect on the oscillatory flow in the TA washer due to its low efficiency. On the other hand higher water temperatures enhanced grease removal considerably in our tests. Methods for measuring the overall conversion efficiency, frictional loss, and grease removal of the TA washing system we designed were developed and discussed.

Key Words : ThermoAcoustic, Washer power, Grease removal, TA washing system, Radiation-beam

1. Introduction

A great deal of research has been performed on integrated energy systems that utilize different forms of energy and multiple methods and stages of energy conversion to sustain

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cost-efficiency and a reduction of CO_2 emissions in the environment. Solar radiation is the largest and most abundant source of free energy available on the planet. A great portion of the sun's energy can be harnessed to provide much needed power through several distinct applications, the largest being electrical power generation through Photovoltaic (PV) solar cells or solar heat engines, and thermal heating through Solar Thermal Plants (STPs). These methods have proven to be very effective in producing next to zero CO_2 emissions and requiring minimal maintenance [Giostri et al., 2012]. However, the world continues to grapple with building solar powered constructs that can compete with the current costs of the earth's natural resources. The goal of this investigation is to explore the feasibility of utilizing solar energy or other free or inexpensive thermal radiations as the sole-provider in thermo-acoustic washing applications.

Thermo-acoustics is the science that studies the conversion between heat and acoustic energy. The use of the thermo-acoustic effect and principle has been studied in various forms and applications [Rott 1975 & 1980; Swift 1988; Chen et al. 2012; Chun et al. 2012]. One important element of the thermo-acoustic effect is the generation of sound waves. The sound waves converted from heat can be used directly for dry cleaning, heat-pumping, or sono-assisted food or material processing, or as the energy input to a piston-cylinder device or a piezoelectric converter for mechanical or electrical power

generation. Solar-powered water pumps using the TA effect have been tested for developing countries and areas where gasoline or electricity is rare or expensive, and/or conventional water pumps are too costly to purchase and maintain.

In the present investigation, a small washer powered directly and solely by thermal radiation was constructed and tested to explore the feasibility of using solar energy or other free or inexpensive thermal radiation for washing and cleaning. The motivation of this research is that the energy output of a thermal-to -acoustic energy converter is in the form of sound waves, and flow oscillations are desired in most wet washing or cleaning processes to effectively shake loose and tear away grease or dirt from contaminated surfaces. In principle, TA(ThermoAcoustic) washers have the benefits of simpler design and operation and fewer energy conversion processes, thus should be more energy efficient and cost less than electric washing/cleaning systems. Methods for measuring or evaluating the efficiency, frictional loss, and grease removal of TA washing systems were developed and discussed in this paper.

2. Washer Design and Testing and Evaluation Methods

The TA washer we designed for grease removal is shown schematically in Fig. 1. The TA converter can be any one of the many TA lasers (e.g., the Rijke tube or the stack-in-a-tube TA laser) that have been

successfully developed and tested in the past. The casing of the TA converter must be transparent to allow the medium (typically a porous plug or a stack of tiny flow channels) inside the converter to be heated by a thermal radiation beam.

Downstream of the TA laser is a wash chamber in which greasy surfaces are to be washed by an oscillatory flow of water (plus a small amount of detergent). One end of the wash chamber is connected to the TA laser and the other end open to the surrounding air. The oscillatory flow of water is driven by the acoustic waves converted from thermal radiation through the use of the TA laser. The heat rejected from the TA laser can be used to raise the water temperature in the wash chamber for enhanced grease removal.
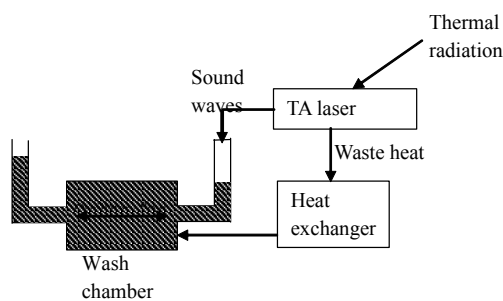

Fig. 1   Conceptual plot of a thermal-radiation powered TA washer for grease removal.

The output energy of a thermal-to-acoustic energy converter is sound waves, which involve pressure and velocity oscillations (except for the pressure nodes where pressure oscillations vanish, and the velocity nodes where velocity oscillations are zero). TA lasers, in principle, are simpler in design and

more energy efficient than other energy converters for the generation of oscillatory flows required in most washing systems. The reason oscillatory flows are often desired in wet washing processes is illustrated in Fig. 2. Grease and dirt on a smooth surface are easy to remove, relatively speaking. The fine cracks and holes in a rough surface make it more difficult to remove grease and dirt due to the additional contact areas as shown in Fig. 2(a). If water is flowing in one direction during washing, only one side of the grease or dirt will be pulled loose by the drag force, as shown in Fig. 2(b). On the other hand, in an oscillatory flow, the drag force on the grease or dirt changes direction alternately, making it much easier and faster to shake loose and wash the grease or dirt away from the rough surface (see Fig. 2(c)). Periodic loading is also a very effective way to weaken a structure or material according to the theory of fatigue.
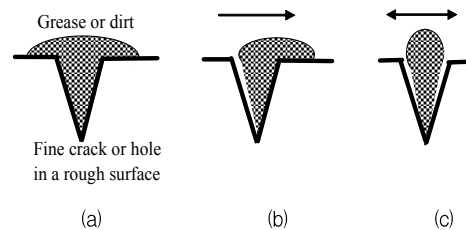

Fig. 2   Grease/dirt removal in oscillatory flow. (a) No flow; (b) Flow in one direction; (c) Oscillatory flow.

In comparison with our TA washer design, a conventional washer utilizes electricity (which is converted from hydraulic, wind, or solar energy, or from heat released in fossil fuel combustions or nuclear reactions) to

power a motor that produces shaft work. The rotating shaft then drives a mechanism to generate the oscillatory flow in the washer. Since such a process involves many energy conversion devices and stages, the conversion efficiency in principle should be lower than the efficiencies of the processes that have fewer energy conversion stages. In addition, the systems involving less stages of energy conversion should be simpler in design and less expensive.

The TA laser and wash chamber of our TA washing system are shown in Fig. 3. The simple TA laser we built was a Pyrex glass tube partially filled with fine steelwool. The wash chamber was made from a combination of plastic and glass tubing and coupling links. The combination of glass and plastic tubes was implemented due to the cost of funding and the reduction of heat loss in the system. A large Fresnel lens was employed in our first prototype TA washer to concentrate solar radiation and focus the sunbeam near one end of the steelwool inside the Pyrex glass tube. The purpose of this test was to demonstrate that the solar-powered TA laser could sustain itself with consistent fluid oscillations over a period of time similar to that of a dishwasher. With 0.025 L (liters) of water in the washer and solar irradiation around 1 kW/m^2 on the lens, we observed steady fluid oscillations at a frequency around 2.6 Hz in the washer. A digital camcorder was employed to monitor the variation of water column height in the vertical tube open to

the surrounding air. The maximum amplitude of the fluid oscillations (the maximum height water in the vertical tube could reach minus its height before the TA laser was turned on) was measured to be about 0.06 m. The TA laser sustained itself for 23 minutes before the Pyrex glass tube was melted by the concentrated sunbeam.
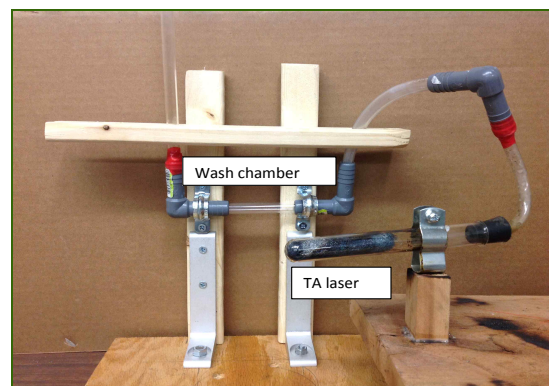

Fig. 3 TA laser and wash chamber.

Due to the continuous change in sun angle and solar intensity, it is difficult to maintain a constant heat input rate for our TA washer. A commercial IR heater was therefore employed in the tests of the second prototype. Shown in Fig. 4 is the experiment setup for the second prototype. The Infrared lamp provided a more accurate and consistent heat input to the washer during experiments and was much safer to use rather than the Fresnel lens. Based on the specifics provided by the IR lamp manufacturer and the heat flux measured by a radiation gauge we designed, the average heat flux at 60 % lamp power level was about 200 kW/m^2 at the focusing point. The

second prototype utilized the same radiation intensity throughout all the experimental tests. This provided greater consistency with our results. The generated fluid oscillations in the wash chamber had a frequency about 3.6 Hz with a maximum amplitude of 0.042 m.
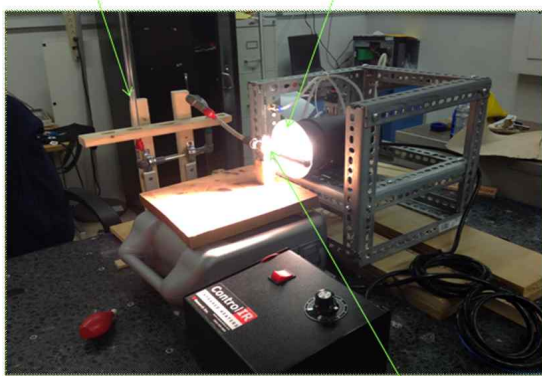
Fig. 4 Steelwool in the TA laser heated by an IR lamp.

The kinetic energy of water oscillations was determined from its maximum amplitude multiplied by water density, the cross section of the vertical tube, and the gravitational acceleration. When the TA washer operation reached its steady state, the useful energy output was balanced by the frictional loss of the oscillatory fluid. We calculated the overall conversion efficiency of the TA washer from the following equation:

Overall efficiency = (frictional loss of water oscillations)/(thermal radiation incident on TA laser)

The frictional loss of water oscillations was determined from the change in water potential energy (which is proportional to the maximum height of water column in the vertical tube open to the air) in successive oscillation cycles after thermal radiation on the TA laser was blocked.

In the grease removal experiments, small volumes ranging from 6.5 to 7.5 x 10^{-8} L of generic-brand vegetable oil were deposited onto a thin steel rod positioned within the wash chamber. Sampled droplets were assumed to be the approximate shape of a sphere and were measured in millimeters. The measured length was assumed to be the diameter of the droplet. The volume of a sphere was determined by the product of four-thirds multiplied by pi and the cubed radius to determine the average amount of oil deposited on the rod surfaces.

Due to the hydrophobic interactions between the vegetable oil and the aqueous solution, experimental trials included both single and multiple droplets on the surface. Multiple droplets had the potential to be disturbed on the rod surface and combine with neighboring droplets. Therefore, initial testing was done with single droplets. The addition of the aqueous solution into the wash chamber periodically disturbed the original position of the observed droplet. This condition made it difficult at first to determine an accurate percentage of grease removal. Tests were discounted if the added water in the system relocated the sampled oil droplet on the surface of the rod. The repetitive attempts to minimize this disturbance of a single droplet became very time consuming and negatively impacted the success rate of our

TA washer. The testing of multiple droplets was then implemented to help improve the success rate. The dimensions were measured out on each droplet of oil before washing. Of the sampled droplets that remained on the rod surface after a wash cycle, their dimensions were measured out to determine the final volume of the oil remaining. Percent removal was determined by dividing the final volume by initial volume multiplying by 100.

Measurements of the droplets in millimeters were recorded with the use of a linear tool, which did not account for the elongation of the oil droplet on the rod surface. Therefore, the percentages calculated were not exact measurements of volume and were considered more as an approximation in quarter intervals of 25%, 50%, 75%, and 100%. A small amount (3 to 4 x 10^{-8} L) of generic-brand dish soap was measured out and added to the aqueous solution in the wash chamber to assist in the removal of grease deposits on the steel rod surface. Pictures such as those in Fig. 5 were taken before and after washing to determine how many grease deposits had been removed from their original locations and to illustrate how the diameter of a oil droplet was measured to calculate its volume.

A heat exchanger between the TA laser and the wash chamber was not built and incorporated with the washer in the present investigation. The water was heated to the specified temperature via a microwave oven prior to being introduced into the wash chamber.
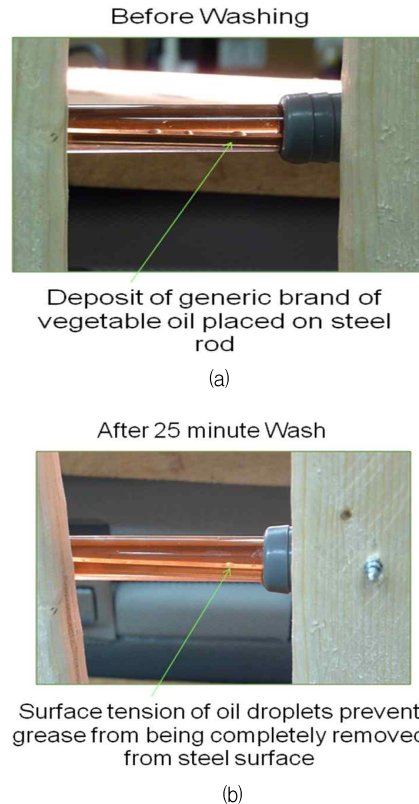
Before Washing

Deposit of generic brand of vegetable oil placed on steel rod

(a)

After 25 minute Wash

Surface tension of oil droplets prevent grease from being completely removed from steel surface

(b)

Fig. 5 Location and volume changes of grease deposits during washing. (a) Before washing; (b) After washing.

3. Results and Discussion

The overall conversion efficiencies of our TA washer measured in different tests are presented in Fig. 6 Since the purpose of this preliminary study is to demonstrate the feasibility of using a radiation beam to operate a washer directly, little attention and effort was spent on fine-tuning and optimizing the TA laser design and operation to improve its efficiency. In addition, the air velocity fluctuations in the TA laser and the water oscillations in the wash chamber were not well matched to efficiently transfer acoustic

waves from air to water. Higher heat and frictional losses due to the small size of our TA washer may also contribute to the low conversion efficiency of our TA washer. Conversion efficiencies comparable to those of heat engines have been achieved in well-designed TA lasers. Conversion efficiencies for liquid-piston Stirling engines-TA converters that produce water oscillations in a vertical pipe- are typically between 3 to 6 % [Everbach, Kyei-Manu, and Obodoako 2006]. It is expected the overall efficiency of the TA washing system we designed could be much higher if a more efficient TA laser were employed and the air and water flow oscillations in the TA laser and the wash chamber were carefully matched.

The viscosity of water decreases with temperature considerably in the temperature range (25 to 70 ℃) we tested. The small variations of conversion efficiencies in Fig. 6 implied the frictional loss of water flow did not play an important role in the energy conversion process of our TA washer. This observation suggests that, the major causes of the low conversion efficiency are the inefficient thermal-to-acoustic energy conversion in the TA laser, and the mismatch between air and water oscillations.
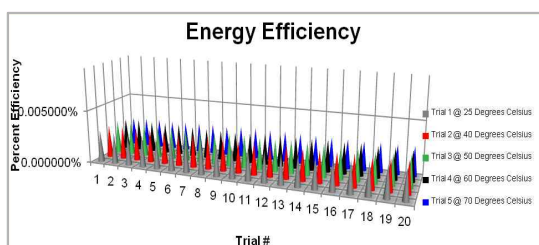
While the water temperature was found to have little effect on the conversion efficiency of the TA washer we built, it had a profound influence on grease removal in our experiments. Shown in Fig. 7 is the % of grease removal after 25 minutes of washing.

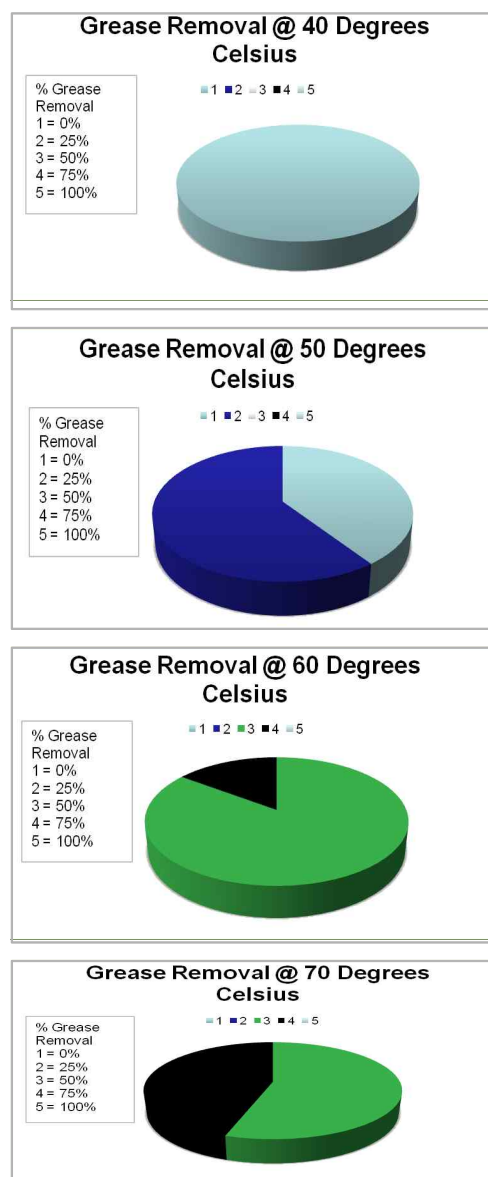Fig. 6 Overall conversion efficiencies.

Fig. 7 Effect of water temperature on grease removal.

Since the kinetic energy of water oscillations was found to be about the same for different water temperatures, Fig. 7 implies the decrease in viscosity of the grease was greater than the decrease in water viscosity as temperature increased.

4. Conclusions

TA washing/cleaning systems powered directly and solely by thermal radiation such as concentrated solar energy were proven to be a feasible alternative to electric washers. More efficient TA laser design and operation, as well as fine-tuning and better matching between the air and water flow oscillations are needed to improve the overall efficiency of the prototype TA washer we built. Grease removal can be considerably enhanced if heat rejected from thermal-to-acoustic energy conversion is used to raise the washing temperature.

Acknowledgments

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