Performance and Diagnostic by PIV of LPG Cooking Burners in Thailand

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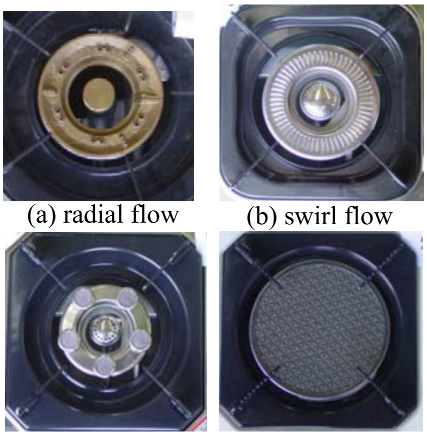
Abstract: A comparative study on performance, in terms of thermal efficiency (η_{th}) and emission of pollutant (CO), of domestic liquefied petroleum gas (LPG) cooking burners available in Thailand has been carried out. About 400 burners were statically sampled from local manufacturers, and categorized into four types; a radial flow, a swirling flow, a vertical flow and a porous radian burner. European standard was used as a reference for the testing. Among the burners, the swirling flow burners yield the most preferable thermal performance with highest thermal efficiency (η_{th} > 55%) and acceptable low CO emissions of less than 1,000 ppm. In contrast, the radial flow burners yield the poorest thermal efficiency (η_{th} < 43%) with the largest span of variation in thermal efficiency despite its lowest CO emission of about 100 ppm. The vertical flow burners and the porous radian burners yield their performance in between the swirling flow and the radial flow burners. The averaged thermal efficiency of the total burners was about 49%. Urgent need for improvement in performance of the burners is placed on the radial flow burners, because of its largest variation in thermal efficiency and CO emissions. Two particular radial flow burners having large difference in thermal efficiency but almost the same CO emission were selected for diagnostic using Particle Imaged Velocimetry technique (PIV), so as to explore the flow field of the combustion flames at the heat transfer surface. Difference in heat transfer characteristic of the two burners could be justified by the difference in the measured flow field. Suggestions were made for further improvement of the burners.
Keywords: LPG cooking burners, Thermal efficiency, CO emissions, PIV

1. Introduction

Liquefied petroleum gas (LPG) cooking burner is widely used in household around the World because it is well known for convenience for use and clean combustion. In addition, the LPG is also convenience for transportation and storage with high safety provided by sufficient precaution and safety measures. The LPG cooking burner is thus received much more attention than it used to be for use in household sector so long as efficient energy utilization and green environment is concerned. Thailand has no exception with the total amount as high as 59% of the total LPG consumption of the country being occupied by the household sector in the year 2005 [1]. This figure shows an increasing trend with an increasing in the number of the population of the country. Unfortunately, most of the LPG cooking burners available in the country are made basing on experiences rather than scientific reasons. Several important parameters affecting the burners' performance, such as variation in composition of LPG [2], geometry of mixing tubes [3], burner ports area and configuration [4], burner-to-plate spacing or heating height and so on are not taken into consideration during the design of the burners. As a consequent, a large number of poor performance burners are manufactured each year, but this is extremely undesirable in view of efficient energy utilization and clean environment.

The goal of this work is to justify base-line performance of the LPG cooking burners which are available in the country. Improvement in performance of selected poor burners using PIV is also a highlight of the present study. PIV diagnostics is a whole-flow-field technique providing instantaneous velocity vector measurements in a cross-section of a flow. This technique is now widely applied to the combustion research. Lacour *et al* [5] introduced the PIV technique to study flame stability of a domestic natural gas burner. However, they considered only a force aspirating burner not a self aspirating one as is normally used in the conventional cooking burner. Since flow field can be well correlated with the corresponding heat transfer characteristic, an application of PIV to study a flow field of an impinging flame of the self-aspirating cooking burner is very important in view of diagnostic of performance of the burner.



(a) radial flow (b) swirl flow

(c) vertical flow (d) porous radiant burner (PRB)

Fig. 1. Photographs of tested cooking burners.

2. Methodology

2.1 Performance test

About 400 cooking burners were statically sampled from 13 local manufacturers around the country. Because of practical information from the manufacturers, results obtained from this performance test can be considered as a base-line value of the burner's performance of the country. The performance test comprises thermal efficiency test and CO emissions test, which are based on European standard i.e. EN 203-1:1992 [6] and EN 203-2:1995 [7]. All burners are the self-aspirating burners operating at relatively low gas supply pressure (not more than 280 mmH_2O) with the corresponding heat input of being not more than 5 kW. All burners were categorized into four types basing on configuration of the burner head or flow pattern; i.e. a radial flow, a swirling flow, a vertical flow and a porous radian burner (PRB) as shown in Fig.1.

2.1.1 *Efficiency test*

A burner is adjusted to its maximum heat input at nominal gas supply pressure. Then it is placed on its top by a specified aluminum pan filled with an amount of mass of water corresponding to the specified heat input [8]. The initial temperature of water should be 20±1^{O}C when measured at the center of water, using a mercury thermometer or equivalent, fixed by a correctly adjusted stopper through the lid. The burner is extinguished as soon as the rise in temperature of the water reaches 70K. It is then considered that the hot condition has been reached. Then the pan previously used is replaced with another standard pan containing the same amount of water at 20±1^{O}C. As soon as the water temperature reaches 70K above its initial value, the burner is extinguished and the gas consumption and maximum water temperature attained are recorded. The thermal efficiency is given by equation (1):

$$\eta = \frac{M \times C_P \times (t_2 - t_1)}{V_C \times H} \times 100 \qquad (1)$$

where η is thermal efficiency (%), M is mass of water

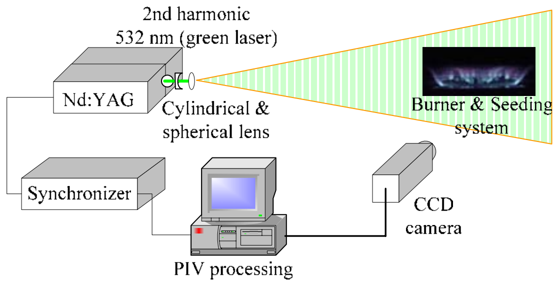


Fig. 2. Test burner and PIV setup.

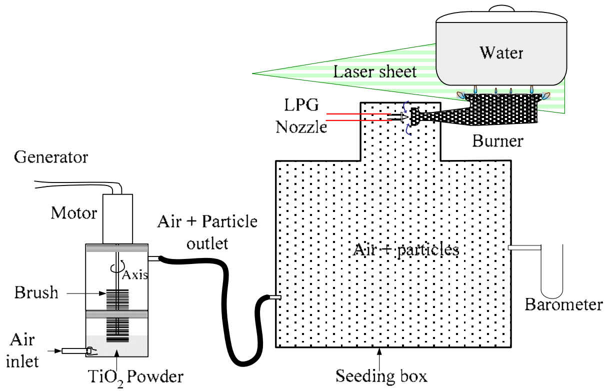


Fig. 3. Schematic of the seeding systems.

(kg), C_P is specific heat at constant pressure of water (kJ/kg K), t_1 is the initial water temperature (^{O}C), t_2 is the final water temperature (^{O}C), H is net calorific value of gas (MJ/m^3) at reference condition (15^{o}C and 1013.25 mbar) and V_C is the volume of gas burned (m^3) corrected to reference condition and is given by

$$V_C = V_{mes} \times \frac{p_a + p - p_w}{1013.25} \times \frac{288.15}{273.15 + t_g} \qquad (2)$$

where V_{mes} is measured volume of gas (m^3), p_a is atmospheric pressure (mbar), p is gas supply pressure (mbar), p_w is saturation pressure (mbar) of steam at t_g, t_g is gas temperature at the point of measurement of V_{mes} (^{O}C). Based on the reference standard, η shall not be less than 50%.

2.1.2 CO emission test [6]

This test is carried out in the same manner as the thermal efficiency test but without temperature measurement. The pan is covered by a specially designed hood for collecting only exhaust gases without mixing with water vapor from the pan before supplying to an exhaust gas analyzer through a sampling probe. Combustion is checked within 15 minutes after ignition and concentration of CO and CO_2 are recorded. To achieve adequate accuracy, dilution by ambient air should be arranged so that the CO_2 content in sampled exhaust gases must be at least 2%. The CO content in the dry, air-free products of combustion shall not exceed 0.10% as is specified by the referred standard.

2.2 PIV diagnostic

The PIV setup has been arranged to measure velocity flow field at the exit of the selected two radial flow burners. The complicated systems of PIV setup was simplified by the schematic diagram as shown in Fig. 2. The instrument consists of a pulsed light source, a Nd: YAG laser, that illuminates the small particles in the fluid for a short period of time, and an optical recording medium that records the locations of the particles at each location. The light source is composed of two laser generators and the laser head, BigSky Laser. The two Nd:YAG laser cavity are necessary to obtain two laser shots at different times. Each cavity provides 120 mJ at the maximum energy which can be modified through the Q-switch delay from 0% to 100% of maximum energy. The laser sheet optics is composed of spherical convergent lenses and divergent cylindrical lenses. A pulse generator will ensure the synchronization between camera and laser. The synchronizer is provided with additional input if the experiment needs to be controlled in time (for instance a phase locked experiment in an internal combustion engine) and an additional output if needed (additional camera shutter trigged by laser shots). The camera is a PowerView 2M Plus. It is a two megapixels camera. The camera is compact and cooled by a simple fan. A special feature of this camera is that the CCD sensor is protected from laser reflection by a special coating. The lens is a 28 mm F/2.8 Nikkon. An extension ring is provided and permits to modify the field size. An interferential filter at 532 nm is placed in front of the camera lens to reject visible light at other wavelength than 532 nm. The software provided for the acquisition and the correlation processing is Insight 6 from TSI. Tecplot 10 will be used for vector display and additional post processing such as vorticity or strain visualization. Solid particles of Titanium Dioxide (TiO_2) with diameter of 3 μm are added to the flow of air as the tracer particles. A homogeneous distribution of medium density is desired for high quality PIV recordings in order to obtain optimal results. The burners are performed at maximum heat input with constant LPG gas supply pressure at 280 mmH_2O.

Since commercialized cooking burner is self-aspiration, therefore one of the difficulties of this experiment is the particle seeding system. An importance is to avoid any modification of the gas nozzle and the mixing tube. The velocity measurement must be obtained in the same manner as actual utilization in domestic use of the cooking burner. Thus, the natural entrainment of primary/secondary air must be conserved. Fig. 3 shows a seeding system that is employed in the study. A powder of TiO_2 particles is dispersed by the rotating brush and mixed with the supplied air at the bottom part of seeder. Concentration of particles was controlled by adjusting the rotating speed of the brush. The supplied air will be used as a primary air for combustion and as a carrier medium for carrying the particles to a seeding box. The seeding box that surrounds the mixing tubes of the burner is used to confine the suspended-particles in the primary air. By adjusting the airflow rate in accordance with the air consumed by combustion at the burner, pressure within the seeding box could be maintained at an ambient condition. By this seeding system, the primary air entrained in the mixing tube is thus homogeneously seeded with particles and the entrainment of the primary air is carried out in a natural way.

3. Results and discussion

3.1 Performance test

Frequency distributions of thermal efficiency and CO emission of about 400 burners are shown in Fig 4. The averaged thermal efficiency is 49%, which is slightly lower than the requirement of the referred standard i.e. 50%, whereas the average value of CO emission is about 630 ppm, which is lower than the requirement of the referred standard i.e. 1,000 ppm

Figs. 5 and 6, respectively, show photographs of impinging flame at the bottom of the testing pan for each type of the burners and the corresponding thermal efficiency (η) and CO emissions.

Among the burners, the swirling flow burner yields the highest average thermal efficiency of more than 55% with acceptable average CO emissions of lower than 1,000 ppm. It also yields a minimum span of both thermal efficiency and CO emission. This may be attributed to the swirling flow motion of the flame, yielding an extension of residence time for heat transfer and improvement in turbulence. Even though the swirling flow can enhance mixing, swirl number may not be large enough to entrain more secondary air for more complete combustion.

In contrast, the radial flow burner yields the lowest thermal efficiency of about 43% but with the minimum average CO emissions of about 100 ppm. This may be due to the fact that small nozzles around the circumference of the ring burners produced thin layer of jets that can cause the secondary air to be easily induced to achieve complete combustion. Beside flame jet emerging from the radial flow burner impinges tangentially with the pan's bottom with a few areas of contact and with less quenching effect of flame, thereby reducing in the heating time and thus lowering in thermal efficiency. Despite its relatively low CO emissions, the radial flow burner yields relatively large span of both thermal efficiency and CO emissions and this become one of an important problem of the present study.

Porous radiant burner yields relatively high averaged value of thermal efficiency of about 47% but with relatively large average CO emissions of about 1,800 ppm. Despite a low convection heat transfer from flame and flue gases caused by the flame shortening, such the relatively high thermal efficiency could be obtained by the infrared burner. This may be attributable to an increase in the overall rate of heat transfer by thermal radiation (depending on the forth power of temperature) from ceramic hot plate to the pan bottom. Since combustion of the radiant burner is mainly depending on the primary aerations in combination with the reaction zone occurring at the downstream surface of ceramic plate, the diffusion of secondary air is, however, hardly to be achieved,

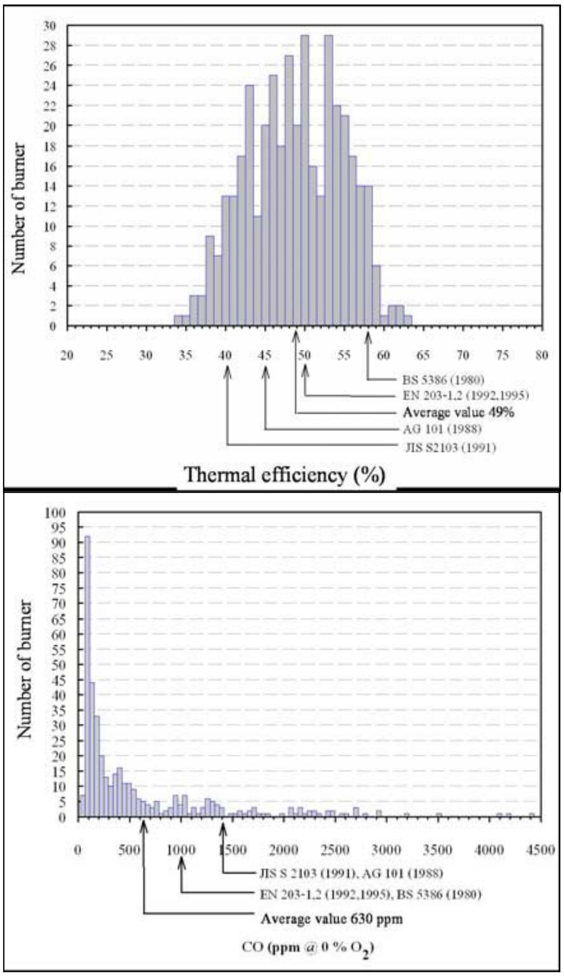
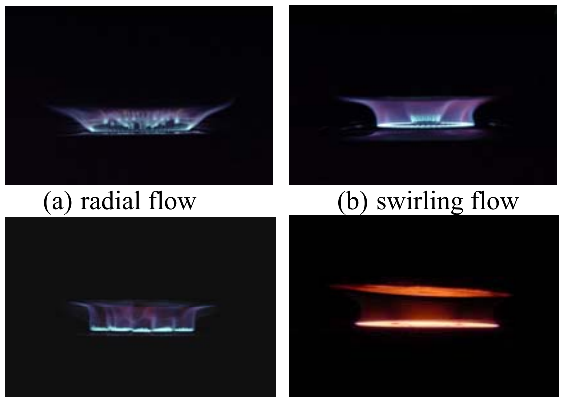


Fig. 4. η (above) and CO emission (below) of LPG cooking burners in Thailand.



(a) radial flow (b) swirling flow

(c) vertical flow (d) PRB

Fig. 5. Photographs of impinging flame.

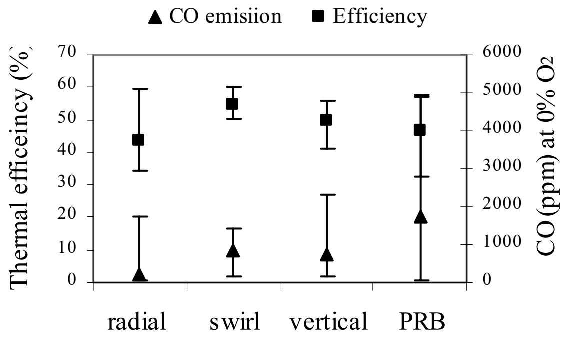


Fig. 6. Thermal efficiency and CO emission of tested cooking burners.

thereby producing the highest CO emissions. The PRB burner shows a trend of large span of both thermal efficiency and CO emissions.

Vertical flow burner is the second highest thermal performance burner with thermal efficiency of about 50% and average CO emissions of about 800 ppm, which is slightly lower than the swirling flow burner. However, it yields relatively large span of performance as compared with the swirling flow burner. Heat transfer of the vertical flow burner mainly comes from a direct impinging of flame to the pan's bottom where a stagnation points exist and thus very high rate of heat transfer to the pan's bottom. However, it has less residence time for heat transfer than the swirling flow. A large diameter of nozzle produces a thick flame jet, which increases the difficulty for diffusion of secondary air to react with the fuel inside the jets. Moreover, high jet velocity causes the mixture rapidly impinging on the pan's bottom before complete combustion was reached, thereby relatively large span of its performance.

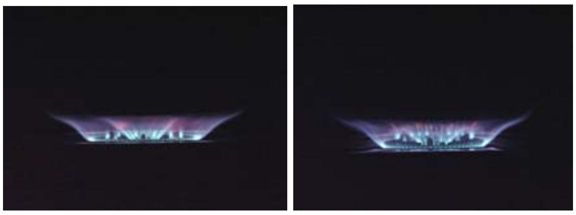
3.2 PIV diagnostics

Two radial flow burners having almost the same CO emission of about 100 ppm but with a large difference in thermal efficiency were typically selected for the PIV diagnostic because of the burner popularity of being used in domestic. One burner has relatively low thermal efficiency of about 42% (hereafter referred to as burner No. 1), whereas the other one has relatively high thermal efficiency of about 52% (hereafter referred to as burner No. 2).

Figs. 7 and 8, respectively, show comparison in photographs of free flame and impinging flames of the two burners taken by a digital camera. These photographs could also be observed by naked eyes with each burner yielding two blue color flame sheaths, i.e. inner flame and outer flame emerging from two separate ring burners irrespective of flame types. This implies premixed combustion flames with nearly complete combustion. However, observation of this type of photographs is not justifiable for the difference in performance of the two burners despite almost the same experimental conditions and CO emissions. It seems to be nothing different between them as observed by naked eyes. However, PIV technique with proper seeding can provide a precise flow field of hot gas impinging on the pan's bottom. In addition, the flow field and the heat transfer characteristics at the pan's bottom have a close correlation with each other. Therefore, difference in thermal efficiency of the two burners could be justified by comparing the impinging flow fields of the two burners obtained by the PIV technique.

Burner No.1 Burner No.2

Fig. 7. Typical free flame. (radial flow)



Burner No.1 Burner No.2

Fig. 8. Typical impinging flame. (radial flow)

Fig. 9 shows comparison in typical averaged velocity flow field of 250 instantaneous images of the impinging flame for each burner. Because of symmetrical flame shape, only one-half of the flames are shown for comparison. Levels of color in the velocity field represent the levels of velocity magnitude, from highest velocity in red to lowest velocity in dark blue color and also vectors represent the direction of flow. The upper dot red line represents the level of pan's bottom (the same heating height of about 3 cm measuring from exit of the outer ring burner to the pan's bottom). Upon impinging on the pan's bottom, hot gases issuing from slot ports of both ring burners of each burner show almost the same flow pattern. However, the burner No. 2 has yielded higher angle of attack of the flow (62°) as compared with burner No.1, which has a smaller angle of attack (52°), the higher the angle of attack, the higher the rate heat transferred to the pan' bottom. Because of a relatively small angle of attack of burner No.1, heat transfer is localized near the rim of the pan bottom, thus less area of heat transfer. In contrast, burner No.2 gives more area of flame contact to the pan's bottom together with an increase in residence time of heat transfer to the pan.

To quantify dynamic properties of velocity flow field near the impinging surface of the pan's bottom, mean velocity and turbulence intensity are averaged and compared within a 5 mm thick boundary layer near the pan's bottom ranging from the outer rim of the pan to its center for the two burners as shown in Fig.10 and Tab. 1. Turbulent intensity can be computed from the velocity flow field in the considered boundary layer and is defined by:

$$I = 100\% \times \frac{StdDev}{|Mean\ Velocity|} \quad (3)$$

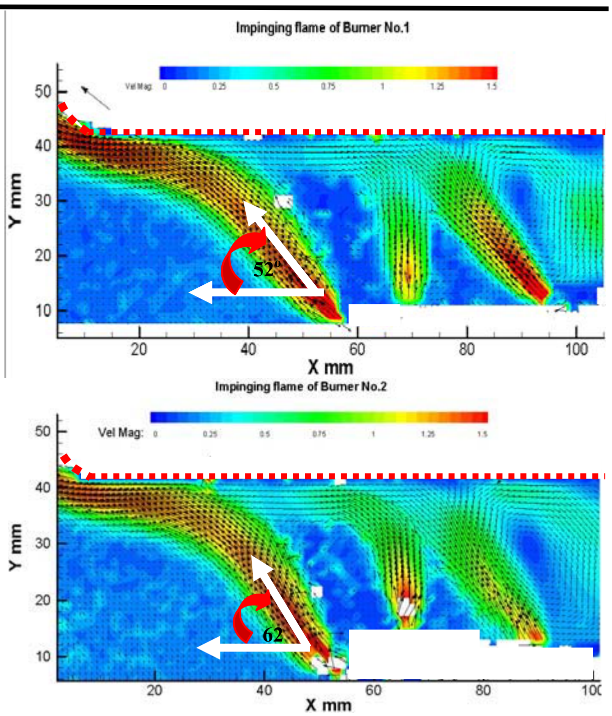


Fig. 9. Typical velocity field of impinging flame for burner No1 (top) and burner No2 (below).

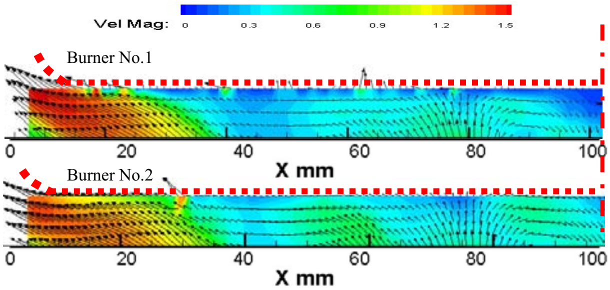


Fig. 10. Comparison in velocity field.

Tab. 1. Comparison in dynamic properties.

Dynamic properties	Burner No.1	Burner No.2
Mean velocity (m/s)	0.53	0.63
Total Turbulent	0.13	0.15

where *StdDev* is standard deviation of velocity magnitude and |Mean velocity| is an averaged velocity magnitude in the boundary layer. This turbulent intensity is equivalent to the Root Mean Square of the velocity fluctuations. Undoubtedly, the burner No. 2 has shown superior dynamic properties as compared with burner No. 1 and also shown a well agreement with the measured thermal efficiencies. In other word, the velocity magnitude and turbulent intensity at the vicinity of the pan's bottom have a close correlation with thermal efficiency of the two burners.

4. Conclusion

4.1 Thermal efficiency and carbon monoxide (CO) emissions of about 400 LPG cooking burners available in Thailand were investigated basing on the EN 203-1:1992 and EN 203-2:1995 standards.

4.2 Results have shown that the averaged thermal efficiency is 49%, which is slightly lower than the requirement of the referred standard i.e. 50%, whereas the average value of CO emission is about 630 ppm, which is lower than the requirement of the referred standard i.e. 1,000 ppm

4.3 Port configuration or flow pattern of burners strongly affected the burner performance. Among the considered burners, the swirling flow burners yield the most preferable burner performance followed by the vertical flow burners, the porous radian burners and the radial flow burner, which yield the poorest thermal efficiency (η<43%) but with the lowest CO emissions. Despite its low CO emissions, the radial flow burner yields relatively large span of thermal efficiency, which can make it no more attractive for use in domestic owing to inefficient utilization of energy.

4.4 PIV is an important tool for study and diagnostic in burner performance without conducting a rigorous parametric experimental study, which is very time-consuming. PIV can provide an overall and accurate picture of flow field at the pan's bottom, which can not be observed by naked eyes. Better understanding in the flow field leads to a more efficient controlling of the rate of heat transfer to thermal load with minimal emission of pollutants.

Acknowledgements

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