*As. J. Energy Env.* **2007**, 08(04), 635-644

*Asian Journal on Energy and Environment*

**ISSN 1513-4121**

Available online at www.asian-energy-journal.info

# Application of Particle Image Velocimetry to Analyse Thermal Performance of LPG Cooking Burners

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**Abstract:** Thermal performance of three different types of liquefied petroleum gas (LPG) domestic cooking burners, i.e. a conventional radial flow, a vertical flow and a swirling flow were analyzed by means of Particle Image Velocimetry (PIV). PI V diagnostics can explain the burners' performance from their corresponding flow fields at an impingement area. With the difference of flow patterns, larger attacked area to the impingement surface increased the heat transfer time i.e. higher thermal efficiency. Dynamics properties i.e. velocity magnitude and turbulent intensity at the in vicinity of the pan's bottom well correlated with thermal efficiency of the three burners. Even for the same type of burner with difficulty in distinguishing their difference by the naked-eye, with a powerful of this technique, heat transfer characteristics are clearly explained. The main objective of this work is to firstly apply a PIV technique as a tool for analyzing thermal performance of LPG cooking burners.

**Keywords:** Cooking Burner, Thermal Performance, PIV, Impinging Flame, Fluid Mechanic

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## Introduction

With an increasing trend of energy consumption in domestic [1], about 59% of the total LPG was consumed by a household sector. LPG cooking burner is an important appliance for household living, which provides a good combustion with high safety. However, almost cooking burner manufactures in domestic are manufacturing their burners based on experiences rather than scientific reasons. Therefore, performance of the burners is a crucial issue concerned by the domestic consumers. PIV is now widely applied to study flow field of many areas of research. It is a non-intrusive technique which provided an advantage of ability to measure two-dimensional instantaneous velocity filed. It was rapidly applied to the combustion research, an important flame characteristic could be observed. Flame front position could also be detected by means of PIV [2], the interaction of two-phase vortex was investigated by group of Lemaire [3], flame extinction zone was shown at the highly strain rate region. Lim [4] measured the velocity and strain rate field to clarify the mechanism of $NO_x$ reduction in an opposed impinging jet combustor using PIV technique. However, most PIV applications on combustion were deal with turbulent flows. Cooking burner is one of an important application of laminar partially premixed flame. Larass [5] and Lacour [6] introduce this technique to the investigation of the laminar partially premixed flame. Larass application is a measurement velocity field in the slot burner which was applied to the domestic boiler, while Lacour introduce PIV technique to measured velocity in the domestic cooking burner. However, both of them designed the new burner as a two-dimensional slot and a force aspiration; not the real using ones. The most closely application to the present work is done by the group of Donovan [7]; by introducing PIV technique to measure the fluid flow for the free jet and for the jet in its impingement configuration. The local velocity and turbulence intensity profiles are in qualitative agreement with heat transfer distributions. Therefore, the objective of this work is to applied PIV technique to investigate the flow filed of the domestic LPG cooking burner which available in the country. The velocity field and its calculated dynamics properties i.e. velocity and turbulence intensity could be used to explain the performance of each cooking burner type. With a better understanding in their heat transfer characteristic of each burner, suggestion for the burner improvement can be made to the burner industries.

## Methodology

### *Performance test*

Test of thermal efficiency and CO emission was performed basing on European Standard [8, 9]. Fig. 1 shows three different types of the tested burners, i.e. a conventional radial flow, a vertical flow and a swirling flow, which are characterized by flow pattern of the main burner ports.

(a) Radial flow burner (No.1) (b) Radial flow burner (No.2) (c) Vertical flow burner (d) Swirling flow burner

**Fig. 1** Photographs of the tested burners (top view)

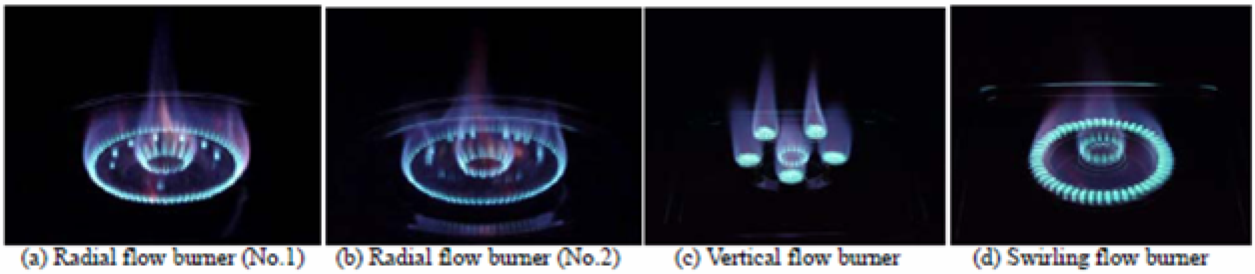


**Fig.** 2 Photographs of free flame.

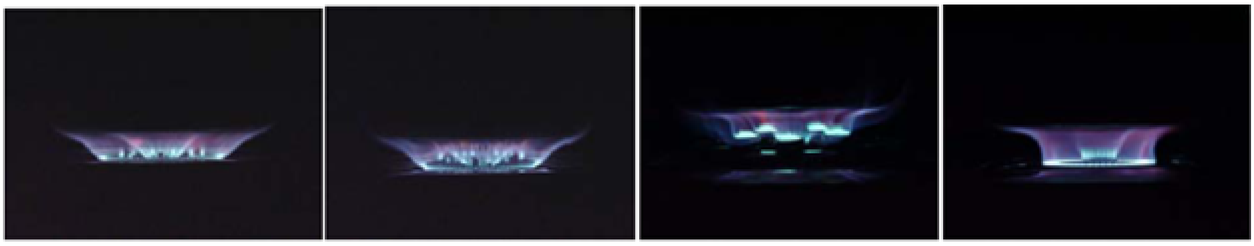

**Fig.3** Photographs of impinging flame.

CO emission were studied to understand what stay behind their difference in performance. All burners are the self-aspirating and operated at relatively low pressure and thermal capacities of less than 280 $mmH_2O$ and 5 kW, respectively. Figs. 2 and 3, respectively, illustrate typical true color photographs of free flame and impinging flame with the pan's bottom surface of the tested burners. In radial flow type, the slot ports of the outer ring are constructed in the radial direction. Therefore, most area of flame is directed and flows out in radial direction. Vertical flow burner is designed by combining several circular nozzles burner, i.e. five, six or larger. The flames flow vertically downstream and impinge on the target. Port configuration and the exit port of swirling flow burner are designed to produce the centrifugal flow. Blue flame color of the three burner types show good combustion achieved. However, looking of these flame photographs is difficult to know how difference of their thermal efficiencies. It seems to be nothing different between them.

***Thermal efficiency test***

The burner is adjusted to its nominal rate. Aluminum pans are used which have a matt base, polished sides. The pans are filled with the quantity of water corresponding to the specified heat input [9]. The initial temperature should be 20±1$^0$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 70 K. It is then considered that the hot condition has been reached. Then the pan previously used is replaced with the standard pan containing the corresponding mass of water at 20±1$^0$C. As soon as the water temperature reaches 70 K above its initial value, the burner is extinguished and the gas consumption and maximum water temperature attained are measured. The efficiency is given by:

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

where $V_{mes}$ is thermal efficiency (%), $M$ is mass of water (kg), $CP$ is specific heat of water, $t_1$ is the initial water temperature ($^0$C), $t_2$ is the final water temperature ($^0$C), $VC$ is the volume of gas burned ($m^3$) at reference condition (1013.25 mbar, 15$^o$C). The volume of gas consumed determined from the volume measured 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 volume of gas measured ($m^3$), *pa* is atmospheric pressure (mbar), *p* is supply gas pressure (mbar), *pw* is partial pressure (mbar) of water vapor in gas, $t_g$ is gas temperature at the point of measurement heat input ($^0C$), *H* is net calorific value of gas ($MJ/m^3$) at reference condition. Based on the reference standard, shall not be less than 50%.

***CO emission test* [8]**
the pan is filled with the quantity of water corresponding to the heat input. The test is carried out with the maximum burner rate. The burner is covered by the hood for collecting the exhaust gases, which is sampled by a probe from an exhaust gas analyzer. Combustion is checked within 15 minutes after ignition and concentration of CO and $CO_2$ are measured. To achieve adequate accuracy, dilution by ambient air should be arranged so that the $CO_2$ content of sample of products of combustion is 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.

***PIV measurement***
Fig. 4 illustrates a simplified schematic diagram of PIV setup to measure the flow velocity at the exit of the tested burners. The instrument consists of a pulsed light source, a Nd: YAG laser, that illuminates the small particles in the fluid for a short 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 cavities are necessary to obtain two laser shots at different time. 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 synchronizer will ensure the synchronization between the CCD camera and the laser.

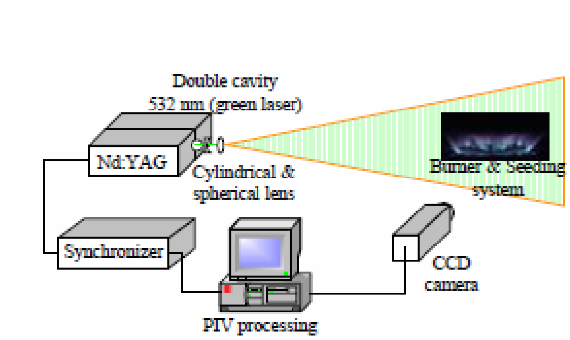


**Fig. 4** Tested burner and PIV setup

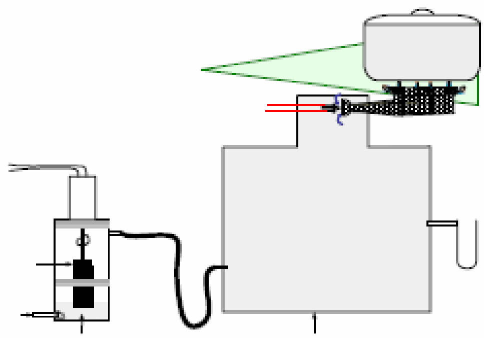

**Fig.5** Schematic diagram of the seeding system

The CCD camera is a Power View 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 load with LPG gas pressure at 280 $mmH_2O$. Since commercial cooking burners are selfaspiration, 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 configuration of the real practical situation of the burners. Thus, the natural entrainment of primary/ secondary air must be conserved. The seeder system as shown in Fig. 5 was employed in the study. The powder of $TiO_2$ particles is dispersed by the rotating brush and mixed with the supplied air at the lower 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 the seeding box. The seeding box that surrounds the inlet of 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 seeder 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.

## Results and Discussion

Two conventional radial flow burners, i.e. No. 1 and No. 2, were selected for PIV diagnostics. Even though they have almost the same flow pattern and CO emissions, large difference in their thermal efficiencies was observed (Table 1). The burner No. 2 has quite high thermal efficiency of about 51.7%, whereas No. 1 has only 41.6%. This is a reason why we perform PIV measurement, so as to understand the flow field and make clear for what reason responsible for the large difference in their thermal efficiencies. To confirm the correlation between thermal efficiencies and corresponding flow filed, vertical flow and swirling flow burners be also investigated.

### *Radial flow burners*

Fig. 6 illustrates enlarged photographs of impinging flames of the radial flow burners No. 1 and No. 2. Fig. 7 shows the corresponding velocity field of the two burners obtained by PIV. Main flame is mostly occupied by the flame issuing from the outer ring burner. Apparently, the burner No. 2 yields a larger angle of attack ($62^o$) of the main flame impinging on the pan's bottom as compared with the burner No. 1 ($52^o$), resulting in more area of heat transfer to the pan bottom and, thus, higher thermal efficiency. By focusing on a 5 mm thickness boundary layer near the pan's bottom of the two burners, time history of the velocity vector at each location of the two burners can be understood as shown in Fig. 8. The burner No. 2 provides a larger velocity magnitude at a deeper location to the pan center (in an increasing x direction) as compared with the burner No. 1, confirming a relatively large angle of attack of the main flame of the burner No. 2.

### *High efficiency burners*

Understanding precise flow field of the flame impinging on the heat transfer area is very important in understanding thermal performance of the burners since the heat transfer is well correlated by the flow field. Two more burners, i.e. a vertical flow burner and a swirling flow burner, were also investigated in the same fashion as the radial flow burners No.1 and No. 2, using PIV. Table 1 shows comparison in thermal performance among the three burners. The vertical flow burner and the swirling flow burner can be characterized as high efficiency burners since they yield relatively high thermal efficiency of more than 50% as compared with the radial flow ones. Figs. 9 and 10, respectively, illustrate enlarged photographs of impinging flames and the corresponding velocity fields obtained by averaging 250 instantaneous images fields using PIV of the vertical flow burner and the swirling flow burner. Apparently, the vertical flow burner provides almost $90^o$ angle of attack of the impinging flame on the pan's bottom, yielding a relatively large area of heat transfer and thus relatively high thermal efficiency. On the other hand, the swirling flow burner yields almost the same flow pattern as the vertical flow one but with less angle of attack owing to the angular momentum pushing the flame outward. However, this may be compensated for by an elongated residence time of flame contacting with the pan’s bottom owing to

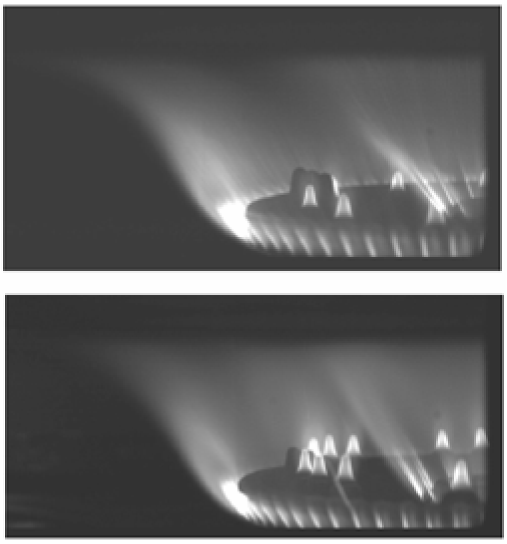

**Fig.6** Comparison of impinging flame between Burner(No.1)(above)and radial flow burner(No.2) (below)

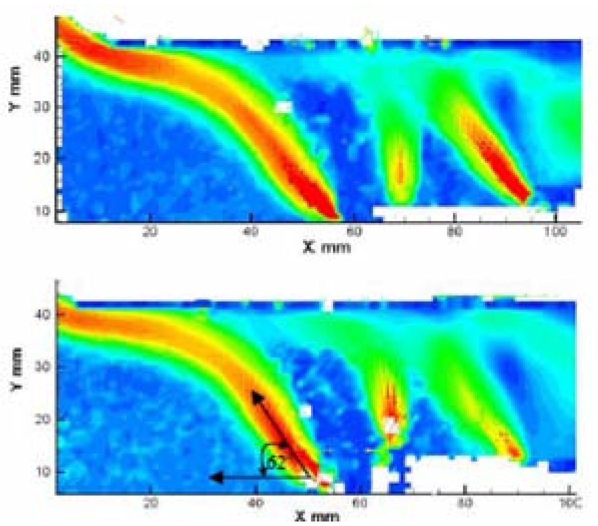


**Fig.7** Comparion of velocity field of impinging radial flow flame between radial flow burner No.1(above)and radial flow burner No.2(below)


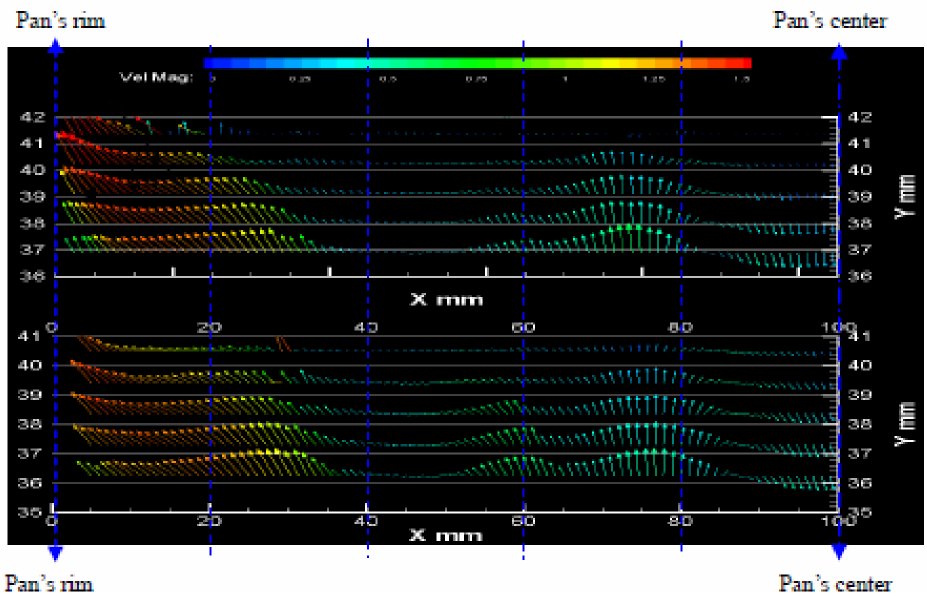


**Fig. 8** Comparison of velocity field in a 5 mm thickness boundary layer near the pan’s bottom of the impinging flame between radial flow burner (No.1) (above) and radial flow burner (No.2) (below) the swirling flow motion of the flame, resulting in maximum thermal efficiency among the three burners. Focusing on a 5 mm thickness boundary layer near the impinging surface of the pan’s bottom of the tested burners as shown in Fig. 11, it is confirmed that the vertical flow burner and the swirling flow burner provide more velocity vector in the vicinity of the pan’s center as compared with the two radial flow burners of No. 1 and No. 2. Thus, more area of heat transfer to the pan’s bottom accompanied by relatively high thermal efficiency can be achieved by the vertical flow burner and the swirling flow burner since the rate of heat transferred to the pan’s bottom is proportional to the pan's exposed area to

the flame, the more area of heat transfer at the pan's bottom, the higher the thermal efficiency. This is an advantage of the vertical flow burner and the swirling flow burner over the radial flow burner, which is highly recommended to the burner manufacturers in the design of their cooking burners. Difference between the pan temperature and the mean fluid temperature is also an important factor controlling thermal efficiency of the burners. Velocity of the gas over the pan's bottom is also a major contributing to enhance the rate of heat transfer. Therefore, dynamic values of these impingement zones were also calculated and compared as shown in Table 2. For each kind of convection heat transfer, the fluid flow can be either laminar or turbulent. For laminar flow of fluid over solid surface, steady boundary layer formations takes place through which conductive heat transfer occur. This reduces convective heat transfer rate. In contrast to the larminar flow, turbulent flow forms when the boundary layer is shedding or breaking due to higher velocities or rough geometries. This enhances the heat transfer [10]. Therefore, high velocity magnitude at high Reynolds number increases convection heat transfer coefficient, and also increase Nusselt number at the impingement area of pan's bottom.

**Table 1** Thermal performance of the tested burners

| Burner type | Radial flow (No.1) | Radial flow (No.2) | Vertical flow | Swirling flow |
|---|---|---|---|---|
| Thermal efficiency, % | 41.6 | 51.7 | 54.2 | 56.2 |
| CO, ppm | 80 | 120 | 800 | 800 |

**Table 2** Dynamic properties at the impingement region

| Dynamic properties | Mean values of flow fields near the impingement surface | | | |
|---|---|---|---|---|
| | Radial flow (No.1) | Radial flow (No.2) | Vertical flow | Swirling flow |
| Velocity magnitude (m/s) | 0.53 | 0.63 | 0.67 | 0.68 |
| Turbulent intensity | 0.13 | 0.15 | 0.15 | 0.25 |
| Vorticity | -39.97 | -29.48 | -124.32 | -61.49 |
| Strain rate | 15.7 | 12.67 | 59.53 | 30.39 |

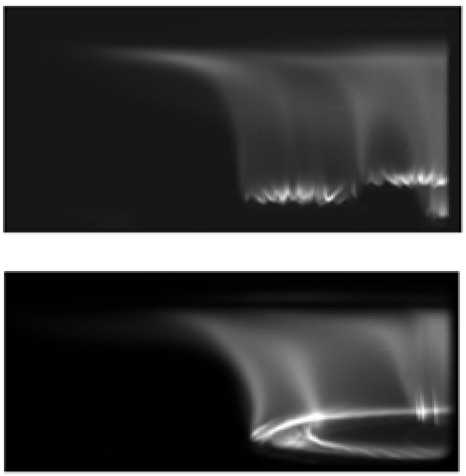

**Fig. 9** Comparison of impinging flame of the vertical flow burner (above) and the swirling flow burner (below)

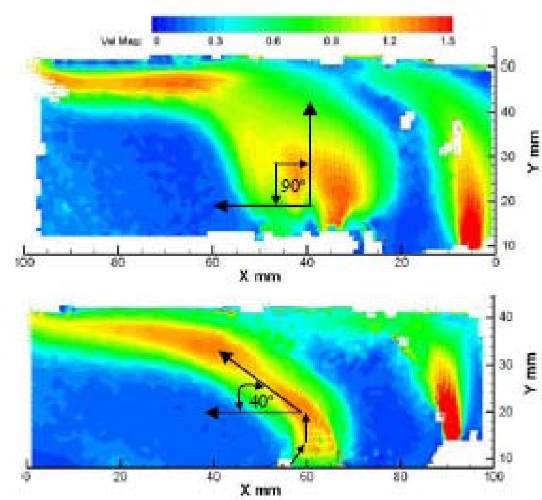


**Fig. 10** Comparison of velocity field of the vertical flame burner (above) and the swirling flame burner (below)

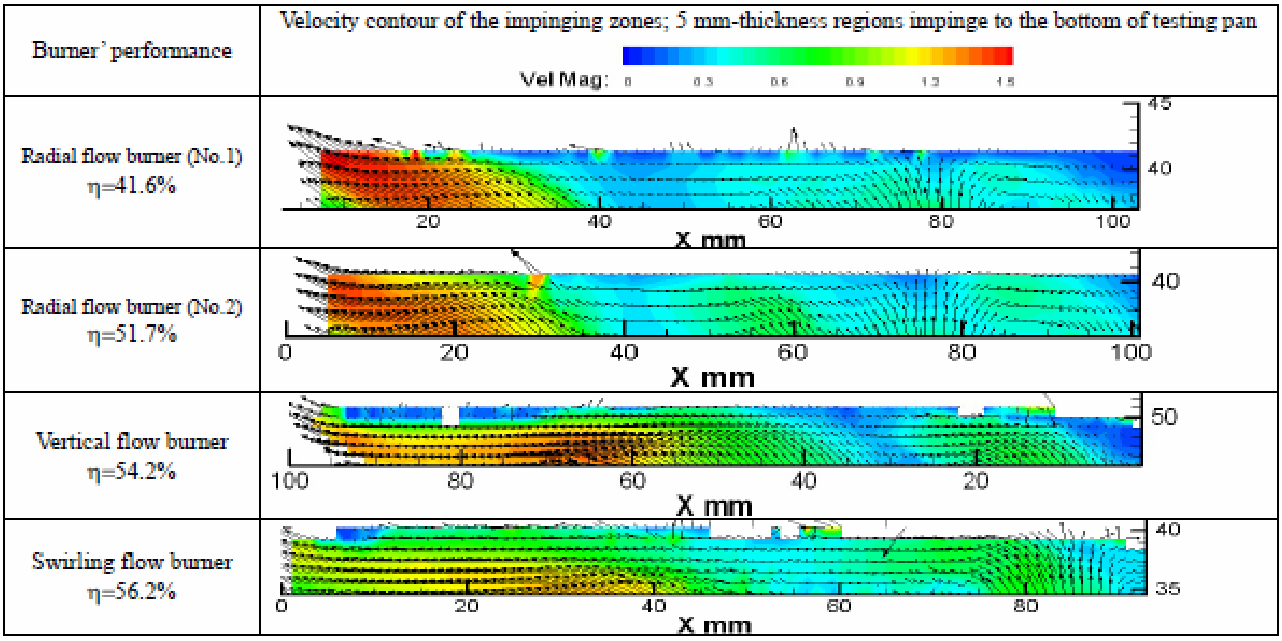


**Fig. 11** Comparison of thermal efficiency and velocity field at the impingement surface of the pan's bottom

The other two terms which correlated to the combustion are the vorticity and the strain rate. The vorticity field is computed with the derivatives of each velocity component ($V_x$ and $V_y$):

$$\omega = \frac{1}{2}\left(\frac{\partial V_y}{\partial x} - \frac{\partial V_x}{\partial y}\right)$$

The vorticity is negative for clockwise rotating vortices and positive for anticlockwise rotating vortices. The strain field, which are represented by the velocity gradient along x and y axes, indicate a degree of distortion defined as:

$$S_{xy} = \frac{1}{2}\left(\frac{\partial V_x}{\partial y} + \frac{\partial V_y}{\partial x}\right) \qquad (4)$$

Thus, the strain rate is one of the important parameters which represent the flame structure characteristics. High strain rate extends the flame area, which might cause the extinction of flame. Vorticity gives rise to turbulence, which is chaotic but has structure. It is generated by the density gradients i.e. the largest density gradient corresponds to a larger of intense vorticity generation. Vorticity is reasonably well correlated with the reaction zone. The high vorticity does not imply that vertical eddies exist within the reaction zone. Rather, high vorticity is related to the shear across the reaction zone. As the results of Lemaire, et al [2], they had studied the effect of vortex size in the context of flame surface area evolution and flame extinction. The flame experiences rapid extinction for vortices of high velocity and strength due to increased normal strain rate. These might affect the higher emission of pollutants of the vertical flow burner and the swirling flow burner than the two radial flow burners. The velocity magnitude, turbulent intensity, vorticity and strain rate are well correlated to heat transfer and combustion of impinging flame. Judging from the dynamic properties of the four burners as in Table 2, the swirling flow burner has the highest of both velocity magnitude and turbulent intensity, followed by vertical flow burner, radial flow burner No.2 and No.1, respectively.

## Conclusion

Thermal efficiency of the tested burners is well correlated with the corresponding flow fields obtained by PIV. PIV is a powerful tool for study and diagnostic in difference in performance of the burners, which can not be done by a conventional way. PIV can provide an overall and accurate picture of the 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 maximum thermal efficiency but with minimal emission of pollutants. The swirling flow burner yields the highest thermal efficiency and the corresponding dynamics values of velocity magnitude and turbulent intensity among the tested burners followed by the vertical flow burner and the radial flow burner of No.2 and No.1, respectively. Port configuration design of the burners is a very important factor controlling the flow direction of flame, areas of the flame impingement and thus affecting the rate of heat transfer and thermal efficiency. Swirling flow exit port is the best configuration to enhance heat transfer to the load. Even for the same radial flow burner, angle of the burner's port plays an important role in controlling thermal efficiency provided that combustion is completed.

## Acknowledgments

This work at the Combustion and Engine Research Laboratory (CERL), King Mongkut's University of Technology Thonburi (KMUTT) was sponsored by the Joint Graduate School of Energy and Environment (JGSEE)

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