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Effects of Air Preheating on Double-Swirling Stabilised Flames

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ABSTRACT: The use of air swirling with fuel to stabilise flames in industrial burners or in gas-turbine engines has become widely practiced, but limitations concerning the levels of intensities of swirlings remain a problem. Previously, it was observed that at highly intensive swirlings[1], double swirlings could create opposing movements which reduced the net momentum, and suppressed the intensity of swirlings. However, it could not explain the results of the reduction in intensities of swirlings. Therefore, in this investigation, the primary objectives are to establish such results, as well as to provide supports for the previous study. Experimental set-up was the same as before, except for the introduction of double swirlings in the environment of increased temperatures. The present study showed that air preheating produced results consistent with the experiments using ambient air temperature. Preheating had the effect of lowering the lean flammability limit, by 40% in some cases. The flame in its physical characteristics was smaller. The composition of blue flames increased. The concentration of carbon monoxide was reduced, for some instances by 50%.

KEYWORDS: air preheating, double swirling, stabilised flames, industrial burners, gas-turbine engines.

INTRODUCTION

At present, the use of heat from industrial burners has become very popular, because of it easily constructed structure and its efficiency. However, in general, the quality of the mixing of air and fuel is still deficient to the mixture derived from swirlings. As such, swirl technique has become, a standard in industrial burners. Nonetheless, some limitations still exist, as cited in past research works by, for example, Leukel[2], Durão et al[3], Milosavljevic[4], Prassas[5], Sivasegaram and Whitelaw[6], and Bhidayasiri[7].

From the limitations of highly intensive swirlings, a zone of reverse flows was created which had the effects of increasing the length of the middle combustion zone, increasing fuel momentum in the middle section, reducing the rate of combustion and inducing unwanted flames. All of these effects impact negatively on applications with high-heat fuels commonly used in the production of heat and electricity[8,9].

From past research of Bhidayasiri[1] on control of double-swirling stabilised flames, it was found that flows of counter-swirlings could reduce intensities produced by swirlings, as well as the net momentum of swirl. However, it was only preliminary finding and had some limitations about equipments, so the results were not conclusive on improving combustion by the use of swirlings. Therefore, in this study, improvement was made to the quality of the mixture by increasing the air temperature or preheating before the occurrence of combustion. The presumption was that the variation of air temperature had impact on the reaction rate and led to more complete reaction, because preheating raised air temperature to levels close to that existing in the ideal reaction, according to stoichiometry[10,11]. The higher air temperature could have led to the clearer impacts of the direction of air-flow, in agreement with the previous results showing that preheating in gas-turbine chamber reduced oscillations in combustion chamber up to a factor of four.

FLOW CONFIGURATIONS, INSTRUMENTS AND UNCERTAINTIES

The experimental set-up was an industrial burner model modified from the small industrial burner used in the study of Bhidayasiri et al[12,13] as shown in Figure 1. The burner was composed of a chamber which was divided into upper and lower sections, attached to each other by screw connection. By flipping the upper chamber, counter-swirl flow could be configurated. Therefore, air flowing from the two chambers could be controlled, in the same direction (co-swirl) or in opposite direction (counter-swirl). The intensity of the swirlings could also be controlled independently of each other by adjusting the proportion of the axial and tangential flows. At the exits of the chambers, the openings were reduced to the shape of bottleneck, or cone, such that air flow speed was raised to the appropriate level before it was mixed with fuel injected from the center of the cross-sectional space at the quarl, or diffuser. The ignition caused combustion from the quarl or the areas nearby.

The two chambers had cylindrical shapes. The upper chamber had a diameter of 273 mm connecting to the cone part together with the exit to the quarl, which had a diameter of 73 mm and a length of 50 mm. The lower chamber also had the same diameter as the upper, but with a cone with a reduced diameter of 37 mm and the exit to the same plane, led by the upper, so that the distance to the quarl was 321 mm. In each chamber, there was a swirler, which was made up of four 24 mm long tangential inlets and four 24 mm long axial inlets . The inlets were located circumferentially around the chambers.

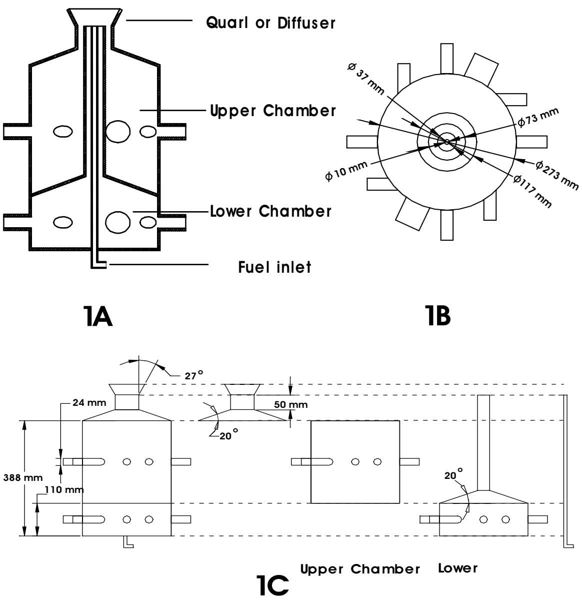


Fig 1. Industrial burner model; Cross section (1A), Top view (1B) and Side view (1C).

The fuel inlet was 10 mm in diameter and located in the lower chamber, inserted from the bottom of the chamber. The end of the fuel inlet was in the same plane as the entrance to the quarl. The cone diffuser expanding into the diffuser at the entrance to the combustion chamber had a diameter of 73 mm. The exit had a diameter of 117 mm and made a 27 degree half-angle.

Air at atmospheric pressure was pressurized, using an air pump (PUMA model PK300) producing maximum air flow of 3805 l/min. The fuel used was liquefied petroleum gas (propane 70% and butane 30%) from the Petroleum Authority of Thailand.

The rate of air flow was measured by two calibrated float-type flow meters, supplied by Bailey Fischer & Porter, and an OMEGA meter, whose deviation were within 5% of values read. All meters were jointly installed with a pressure gauge to standardize the flow rate in the atmospheric pressure.

In studying the impact of air preheating, air was preheated before entering the chamber by connecting air inlet to a heater (Figure 2), providing air temperature up to around 500K. The temperature was measured by a resistant–type thermometer, which was installed at the air inlet exit, to measure air temperature at the exit from the heater. Temperature control of the heater was stabilised by means of thermostat feedback control, with a deviation of less than 3% obtained.

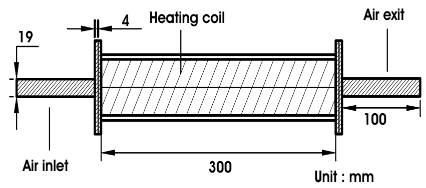


Fig 2. Heater

The measurement of the composition of the exhaust from combustion was conducted in a way which prevented external factors from affecting the products of combustion. A chimney (Figure 3) was constructed around the outlet from the combustion chamber to prevent the air entrainment from the ambient into the chambers. The chimney was made in the shape of cylinder having a radius of 285 mm, a height of 800 mm, and an opening of 150x150 mm^2, for igniting in the center of the cylinder. At the exit, exhaust went through a bottleneck (diameter of 150 mm) which collected the exhaust in the same direction, thus improving the accuracy of the measurement of the gas composition.

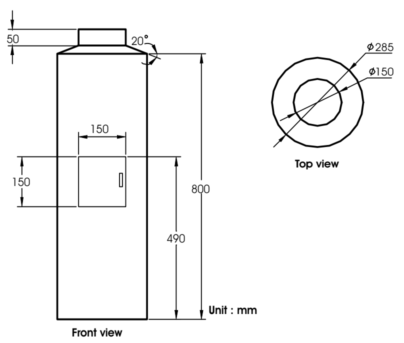


Fig 3. Chimney

List of Symbols

Re	Reynolds number
ϕ	Equivalence ratio defined by actual air/fuel ratio divided by the air/fuel ratio at stoichiometry
CW	co-swirl
CCW	counter-swirl
kPa	kilopascal
W	watt
l/m	litre per minute
K	Kelvin
RT	room temperature

Experimental Results

Results of the experiments are presented in three parts:

Part 1: Lean flammability limit,

Part 2: Physical flame characteristics,

Part 3: Measurements of exhaust gases.

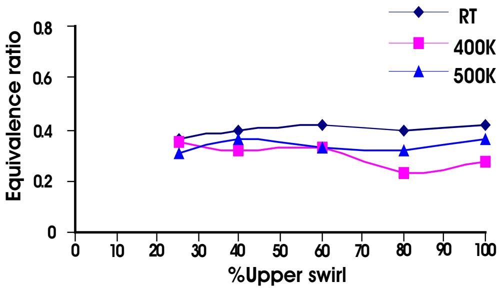
Note: In all of the experiment, the air flow rate into each chamber was set at the constant rate of 900 l/min. The swirl flux was totally dependent on the tangential air flow rate, and the proportion of swirlings was defined by the ratio of the tangential air flow to the total air flow in each chamber.

Lean Flammability Limit

The presumption was that if air temperature was high, the reaction rate would be raised, causing the extent of ignition index to decline. Thus the reaction was more complete because the quantity of fuel needed to maintain the flame stability decreased, which was similar to the techniques used by Feikema[14], and Durbin and Ballal[15]. The experiments were done by connecting the heater to the tangential air inlets to raise temperature levels before entering chamber, and were made with variation of swirl rates in the lower and upper chambers for co-swirl experimentation. Temperatures in the tangential flows were set at 400K and 500K.

The results with preheating made to lower chamber (Figure 4) were that at the proportion of swirl rate for lower chamber at 100%, the lean flammability limit was lower, compared to the preheating made to the upper chamber. However, if the swirl rate in the upper chamber was higher than 80%, it was found that the lean flammability limit with preheating made to the upper chamber was lower than when preheating was made to the lower chamber. This could be because the upper chamber occupied space around the combustion chamber where highly-swirled flames were stabilised. Therefore, preheating in the upper chamber at the highly-controlled swirl rate increased the effectiveness of preheating by causing better combustion.

When the proportion of swirl in the lower chamber was lowered to 80% (Figure 5), the lean flammability limit with preheating made to lower chamber tended to be lower than at room temperature. This might be because swirlings in the lower chamber were close to



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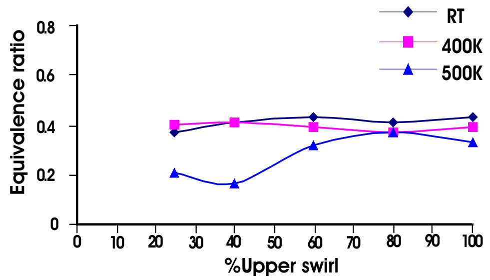
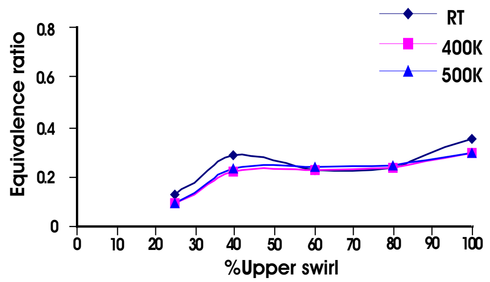


(b)

Fig 4. The lean flammability limit with preheating made to upper or lower chamber at Lower swirl 100% (900 l/min) and Upper swirl from 25% to 100%, Co-swirl, Re = 33000; (a) Preheating made to upper chamber, (b) Preheating made to lower chamber.



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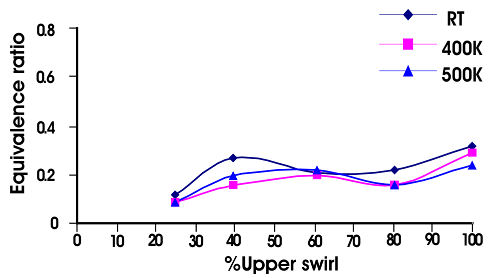

(b)

Fig 5. The lean flammability limit with preheating made to upper or lower chamber at Lower swirl 80% (720 l/min) and Upper swirl from 25% to 100%, Co-swirl, Re = 33000; (a) Preheating made to upper chamber, (b) Preheating made to lower chamber.

the area where flames near extinguishing were stabilised and where temperatures were high enough. Thus, raising temperature in the lower chamber increased the reaction rate more than did raising temperature in the upper chamber, thereby lowering the lean flammability limit yielding lower values.

Moreover, the reduction of the proportion of swirlings in the lower chamber from 100% to 40% (Figures 4, 5, 6 and 7) resulted in the lowering of the lean flammability limit from 0.4 to 0.1. This was different from other cases, in which burners with reduced swirling proportion were used to maintain flame stability and resulted in higher values for the lean limit. The reason was that the flame stabilised near the bottleneck, with some flames lingering in the preheating chamber and swirling around the exit area of the fuel tube. The reduction of swirlings thus caused the flame to stabilise in the quarl and occupied the middle part of the exit area of the fuel tube where the local fuel intensity was close to stoichiometry, thus causing lower average value for the lean flammability limit.

When the proportion of lower chamber's swirl declined to the range 60-40%, preheating in either the upper or lower chamber caused the lean flammability limit to approximate a common value. This might have been caused by the reduction in the proportion of swirlings in the lower chamber which elevated stabilised flames from the exit end of the fuel tube, thus increasing the mixing of air from the two chambers and consequently lowering the temperature from preheating in the lower chamber.

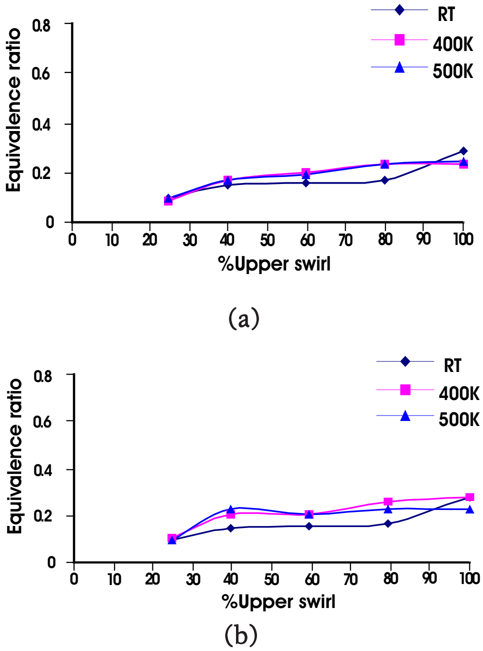

Fig 6. The lean flammability limit with preheating made to upper or lower chamber at Lower swirl 60% (540 l/min) and Upper swirl from 25% to 100%, Co-swirl, Re = 33000; (a) Preheating made to upper chamber, (b) Preheating made to lower chamber.

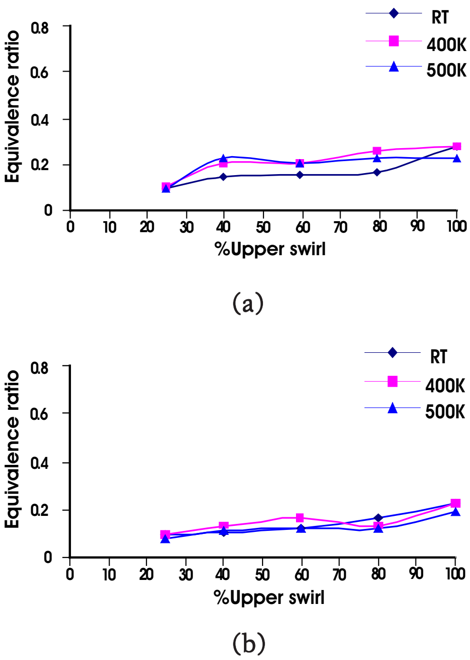

Fig 7. The lean flammability limit with preheating made to upper or lower chamber at Lower swirl 40% (360 l/min) and Upper swirl from 25% to 100%, Co-swirl, Re = 33000; (a) Preheating made to upper chamber, (b) Preheating made to lower chamber.

Moreover, it was found that the impacts of preheating declined. This might have been because the proportion of swirlings in the lower chamber decreased, causing the lowering of the quality of air/fuel mixing as well as the lean flammability limit. Therefore, increasing the air temperature did not have sufficient impact to lower the existing low lean flammability limit.

It was clear that preheating had little impacts when the proportion of swirlings in the lower chamber was less than 40% (figure 8). The lean flammability limit at temperatures of 400K, 500K and room temperature were very similar. The reduction in the proportion of swirlings in the lower chamber to 25% lowered the lean flammability limit, as in earlier experiments, except when the proportion of swirlings in the upper chamber was 25%. When preheating in the upper and lower chambers led to abnormally high lean flammability limit, it was due to the low proportions of swirlings, whether in lower or upper chambers, which triggered use of more fuel to induce stability, and which, in turn, caused high lean limit. But, when the proportion of swirlings in the upper chamber was increased, the lean limit was returned to the same level as for normal conditions with sufficient swirl values.

It was found that when the proportion of swirlings in the lower chamber was less than 40%, the lean flammability limits were close to those of room

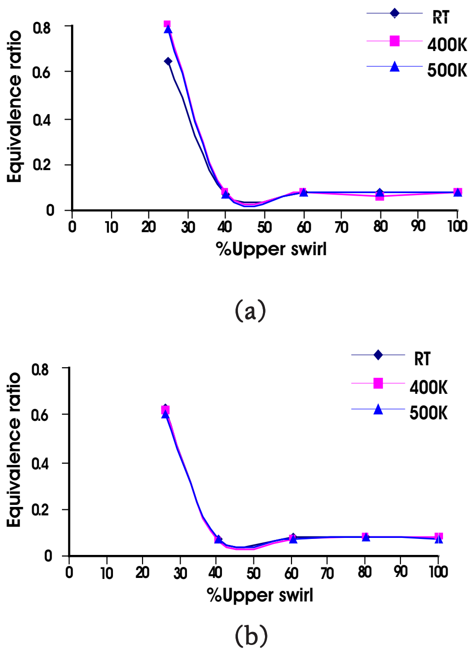

Fig 8. The lean flammability limit with preheating made to upper or lower chamber at Lower swirl 25% (225 l/min) and Upper swirl from 25% to 100%, Co-swirl, Re = 33000; (a) Preheating made to upper chamber, (b) Preheating made to lower chamber.

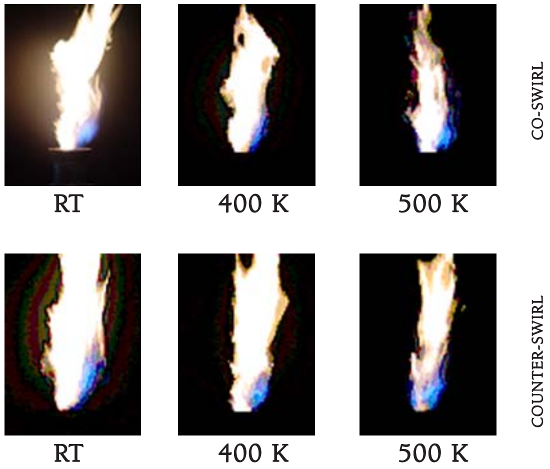

Fig 9. Flame photographs with preheating made to upper chamber, Upper swirl 25%, Lower swirl 40%, Re = 33000, $\phi = 0.5$.

temperature, for both cases of lower and upper chamber preheating. This was because the reduction in the proportion of swirlings in lower chamber caused a change in the influence of higher temperature to change. This changed influence might be weaker only when the proportion of swirlings decreased. This was because the lower swirling proportions lowered further the reaction rate and the lean limit. Increasing air temperature could not have raised the reaction rate. In some cases, it could be conjectured that the swirl intensity would increase the stretch of the flames.

Physical Flame Characteristics

The characteristics of combustion in general were similar to flames without oscillations as in Bhidayasiri et al[12] which found that flames stabilised inside the quarl in areas where flame speed was zero, or at stagnation points. It was believed that the physical characteristics of combustion were the preliminary factors indicating the quality of combustion. As the proportion of swirlings increased, the flames contained more bluish parts, were smaller and more symmetrical.

From past research by Bhidayasiri[1], it was found that co-swirlings yielded better physical flame characteristics than counter-swirlings, except when the proportion of swirlings in the upper and lower chambers was 100%, then counter-swirlings had composition of more bluish flames than co-swirlings, but the flames were larger for cases of co-swirlings. The latter observation could be explained by the fact that co-swirlings caused highly intense swirlings which centrifuged mixture with the swirling air, whereas air-fuel mixture was probably uneven, so the quality of combustion became poorer. Co-swirlings multiplied the impacts of swirlings on flame shapes, and it was normal that intense swirlings would produce shorter flames. It was also found that the change in proportion of swirlings in the upper chamber had impacts on flame characteristics, (Figures 9 and 10). That was because the location of swirlings in the upper chamber transmitted air around the outside of quarl, whereas when integrated, the area was larger than the inside area where swirlings in the lower chamber took place. Therefore, the impacts from swirling in the upper chamber were greater when considered the physical flame characteristics.

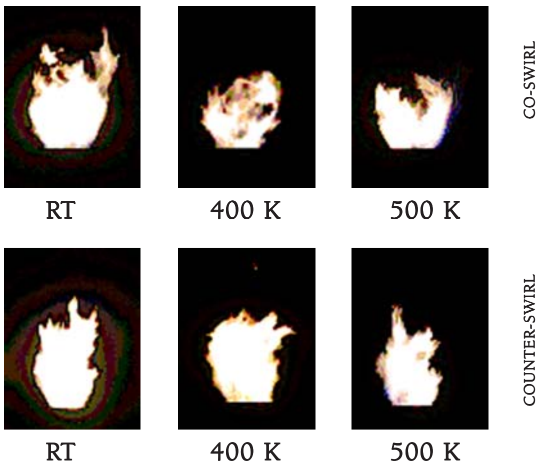

Fig 10. Flame photographs with preheating made to upper chamber, Upper swirl 100%, Lower swirl 40%, Re = 33000, $\phi = 0.5$.

This research was conducted following the research of Bhidayasiri[1]. However, in this present work, preheating was made before entry into chamber in order to find out whether the preheating was important to the direction of swirl flows. The presumption was that, the increase in temperature of the air for combustion, will lead to increased reaction rate, complete combustion, increased heat value and decreased heat loss , which altogether produced better physical characteristics of combustion.

From the experiment, it was found that co-swirlings produced combustion with better properties than counter-swirlings at all proportions of swirlings with preheating in both upper and lower chambers. Flames became smaller and had more bluish parts because lower-chamber swirlings produced influence on mixture in the middle section, which was an important area in the primary zone in relation to mixture quality. When they were co-directed with upper chamber swirlings, they were reinforced to provide good-quality mixture, causing flames to be more stable.

It was further found that preheating before entry to upper chamber had more impacts on the physical flame characteristics of flames than preheating in the lower chamber. That might be because swirlings in the upper chamber affected the outside sections of the mixture, which normally affected the shear layer region and also were close to the locations of flame stability. In summary, preheating before upper chamber was more effective than preheating before the lower chamber.

Measurements of Exhaust Gases

Experiments were conducted to measure the concentrations of CO, CO_2 and O_2 at various proportions of swirlings in both lower and upper chambers and for both co-swirlings and counter-swirlings. A chimney was installed to prevent air entrainment from outside, which would have changed the air-fuel ratio, and to collect exhausts in the same direction. In these experiments, CO values were the primary consideration because burning was most complete if CO in exhausts was least. Preheating was not done for the lower chamber, because past experiments had shown that the proportion of swirlings in the upper chamber was more influential on the physical flame characteristics than the proportion of swirlings in the lower chamber.

From the experiments, when the proportion of swirlings in the lower chamber was reduced from 100% to 25%, the concentrations of CO declined consistently, from 630 ppm to 300 ppm, on average, for both co-swirlings and counter-swirlings, (Figures 11-14). This is because decreased swirlings in the lower chamber, caused the movement of stabilised flames to the quarl, which supported better combustion. The concentrations of CO in exhausts thus declined. It was further found that the direction of swirlings affected the influence of preheating in different ways. For counter-swirlings, preheating to 400K or 500K yielded more CO in the exhausts than combustion at room temperature. No satisfactory explanation for that had yet been found.

However, when the proportion of swirlings in the upper chamber was increased (from 60% to 100%), it was found that in counter-swirlings, the concentration of CO increased consistently, which might have been because of the impacts of swirlings in the upper chamber where flames stabilised. When the proportion of swirlings increased, the momentum from swirlings from the lower chamber was offset near the entrance of the fuel tube, thus, reducing the quality of air-fuel mixture. This was clearly evident in the proportion of swirlings in the upper and lower chambers which had values of 100% (Figure 11). Counter-swirlings, clearly, generated more CO in exhausts, because counter-swirlings in both chambers offset each other such that the intensities of swirlings were not sufficient to induce air and fuel to mix in reasonable quality; combustion, therefore, was poorer. However, when the proportion of swirlings in the lower chamber was decreased, by increasing the flow in the axial direction, and the proportion of swirl in the upper chamber remained at high values(Figures 12-14), the concentrations of CO were lowered by around 50 %. This was probably due to the weaker influence of the momentum offsetting, when swirl intensities reduced. Therefore, this lower momentum offset was more useful in the ecological sense than those of highly counter-swirling flows.

In co-swirlings, it was found that preheating to 500K reduced CO concentrations with a factor of around two, compared with combustion at room temperature, when the proportion of swirlings in the upper chamber was increased beyond 60%. The increased proportion of swirlings was caused by an increase in heated air tangentially sent into the chamber, which supported good combustion. Preheating air to 400K did not lead to noticeable changes, probably because temperature was not high enough to enhance the reaction rate.

When the proportion of swirlings in the upper and lower chambers had large values (100%)(Figure 11), the concentration of CO increased, perhaps, from the impacts of excessive swirlings, causing return flows to the bottleneck, and worsening the mixing of fuel and air. However, when the proportion of swirlings in the lower chamber was reduced, the concentration of CO decreased, perhaps because of the reduction in the proportion of swirlings which lowered the base of flames to the inside of quarl close to where air was

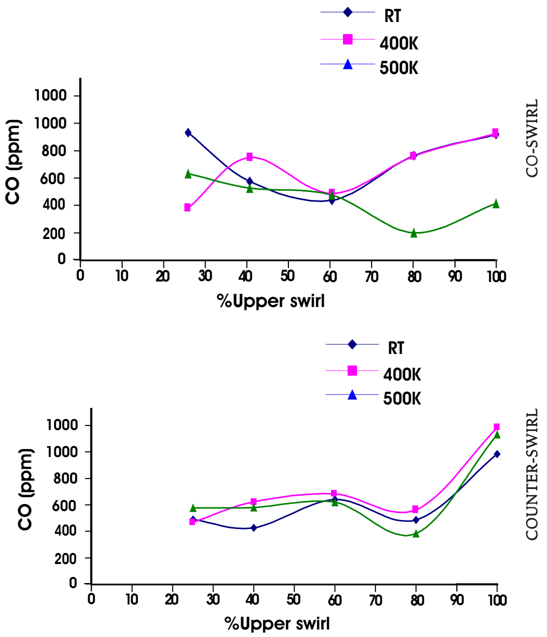

Fig 11. The concentration of carbon monoxide with preheating made to upper chamber at Lower swirl 100% (900 l/min), ϕ = 0.5, Re = 33000.

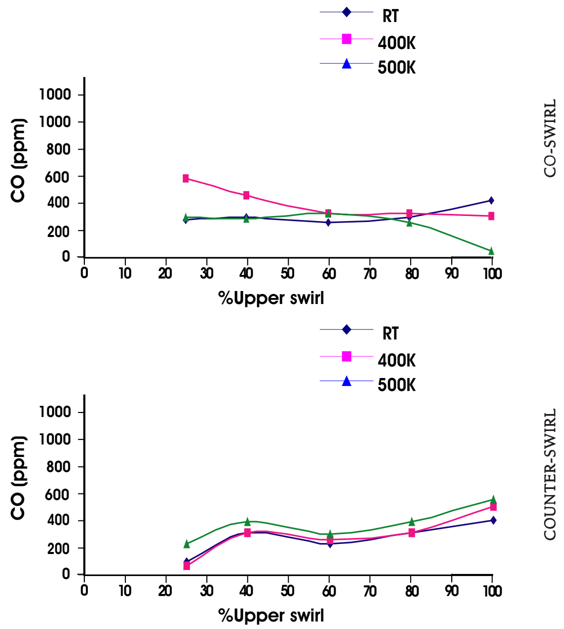

Fig 13. The concentration of carbon monoxide with preheating made to upper chamber at Lower swirl 40% (360 l/min), ϕ = 0.5, Re = 33000.

heated, thus producing clear results for preheated air (Figure 14). When upper and lower swirlings were low, the quality of air-fuel mixture became poor. This led to incomplete combustion and a high amount of unburned exhausted gas.

When comparing co-swirlings to counter-swirlings, it was found that co-swirlings showed changes resulting from preheating more clearly at every proportion of swirlings. Thus, preheating could help produce good combustion. They were ascertained by the reduction

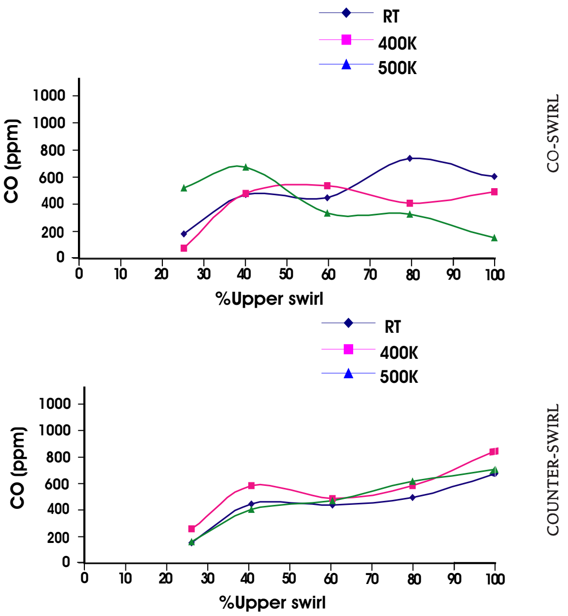

Fig 12. The concentration of carbon monoxide with preheating made to upper chamber at Lower swirl 80% (720 l/min), ϕ = 0.5, Re = 33000.

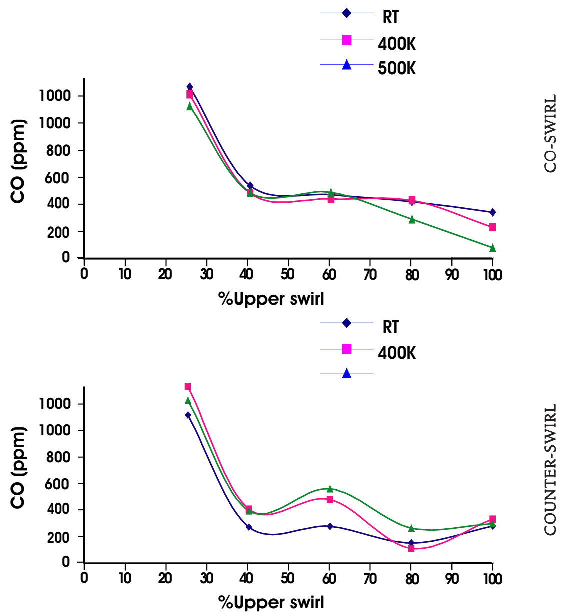

Fig 14. The concentration of carbon monoxide with preheating made to upper chamber at Lower swirl 25% (225 l/min), ϕ = 0.5, Re = 33000.

in the concentration of CO in exhausts. When these were considered together with carbon dioxide and oxygen, they were well correlated and in agreement with theories, except when the proportion of swirlings in upper and lower chambers at value of 25% (Figure 14). Because base of flames rose close to the point where exhausts were measured, and the confined flame was unstable, the measurements were therefore statistically uneven.

In figures 11 and 12, fluctuation of CO emission was observed in case of co-swirlings. This was believed that co-swirlings led to an increase in the momentum in the outer zone compared with counter-swirlings.

Conclusions and Recommendation for Future Work

Considering the lean flammability limit after preheating, it was found that preheating in lower chamber was more influential to the extent of lean limit than preheating in the upper chamber. This was because near extinguishing flames stabilised around the fuel tube, which was located near the exit from lower chamber. It was also found that reducing the proportion of swirlings in lower chamber from 100% to 40% caused a consistent decrease in the lean flammability limit. This was because the position of stabilised flames moved to the stabilisation zone introduced by air from both chambers.

When the proportion of swirlings in the lower chamber declined to the range of 60-40%, it was found that preheating before entry to either one of the chambers led to similar lean limit values. This might have been caused by the reduction in the proportions of swirlings in the lower chamber which elevated stabilised flames above the exit of the fuel tube, and increased the mixing of air from the lower and upper chambers. Therefore, the influence of preheating before lower chamber became less effective, approaching those from preheating before upper chamber.

It was found that preheating of swirlings before the upper chamber had more impacts on physical flame characteristics than preheating before the lower chamber. This was because the exit area from the upper chamber was more spacious than that from lower chamber and closer to the location of swirl-induced stabilisation zone unlike that where of near-extinguishing flame stabilised. Co-swirlings produced better physical characteristics than counter-swirlings. When considered together with the extent of ignition when preheated, it was found that physical flame characteristics and the lean flammability limit were related to each other in the same manner as when these properties were measured at room temperature.

When considering the composition of exhausts after preheating, it was found that preheating of co-swirlings had favorable impacts on the composition of exhausts, compared to preheating of counter-swirlings. It was seen that CO concentrations declined. Compositions of exhausts at room temperature were similar for both co-swirlings and counter-swirlings. When considered together with physical flame characteristics and the lean limit, it was found that the most appropriate formula was with co-swirlings at 40% swirlings in the lower chamber and 80% swirlings in the upper chamber, which produced short, more-bluish flames that are symmetrical around the vertical axis. Also, the low lean limit and low concentration of CO yielded the type of flames desired.

From the experiments conducted, the differences of the impacts of co-swirlings and counter-swirlings were not clearly distinguishable in some cases. This was, perhaps, because swirlings in the chambers were segregated and allowed very little collisions. Offsetting of the momentum, therefore, was small and, in some cases, negligible. Air inlets in the directions of the radius and tangents were also installed on the same planes, reducing the intensities of swirlings because of air-flow offsets. Therefore, future improvements should be done to combine the chamber to allow air-flow collision and to change the air inlets to different planes to increase swirl intensities. A future study should be made to study local heat values in combustion process to support more results from these experiments.

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References

1. Bhidayasiri, R. (2003) Control of Double-Swirling Stabilised Flames. *Internal Report*, Mechanical Engineering Dept. Mahidol University.
2. Leukel, W. (1968) Swirl Intensities, Swirl Types and Energy Losses of Different Swirl Generating Devices. *International Flame Research Foundation*, Ijmuiden, Doc. No. G02/a/16
3. Durão, D.F.G., Heitor, M.V. and Moreira, A.L.N. (1992) On the Stabilisation of Flames on Multijet Industrial Burners. *Experimental Thermal and Fluid Science* **5**, 736-46
4. Milosavljevic, V. (1993) Natural Gas, Kerosene and Pulverised Fuel Fired Swirl Burners. *Ph.D. Thesis*, Imperial College, University of London
5. Prassas, I (1998) Combustion of Pulverised Coal in Swirl Burners. *Ph.D. Thesis*, Imperial College, University of London

6. Sivasegaram, S. and Whitelaw, J.H. (1991) The Influence of Swirl on Oscillations in Ducted Premixed Flames. *Combustion and Flame* **85**, 195-205
7. Bhidayasiri, R (1998) Control of Combustion. *Ph.D. Thesis*, Imperial College of Science Technology and Medicine, University of London
8. Bhidayasiri, R (2001) Oscillations in Ducted Swirl-Stabilised Flames. *Proceedings of ASME Fluids Engineering Division Summer Meeting*, FEDSM2001-18200
9. Bhidayasiri, R, Sivasegaram, S and Whitelaw, J H (2001) Control of Combustion and NOx Emission in Open and Ducted Flames. *Environment Combustion and Technology* **2**, 229-54
10. Claypole, T.C. and Syred, N. (1980) The effect of Swirl Burner Aerodynamics on NOx Formation. *18th Symposium (International) on Combustion*, The Combustion Institute, 81-90
11. Bowman, C.T. (1992) Control of Combustion-Generated Nitrogen Oxide Emissions: Technology Driven by Regulation", *24th Symposium (International) on Combustion*, The Combustion Institute, 859-78
12. Bhidayasiri, R, Sivasegaram, S and Whitelaw, J H (1997) Control of Flow Boundary Conditions on the Stability of Quarl-Stabilised Flames. *Combustion Science and Technology* **123**, 185-205
13. Bhidayasiri, R, Sivasegaram, S and Whitelaw, J H (1997) Control of Combustion and Emissions in Open and Ducted Flames. *Proceedings of the Fourth International Conference on Technologies and Combustion for a Clean Environment* **2**, Paper 29.1
14. Feikema, D., Chen, R-H and Driscoll, J.F. (1990) Enhancement of Flame Blowout Limits by the Use of Swirl. *Combustion and Flame* **80**, 183-95
15. Durbin, M.D. and Ballal, D.R. (1996) Studies of Lean Blowout in a Step Swirl Combustor. *Journal of Engineering for gas Turbines and Power* **118**, 72-7