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Improvement of thermal efficiency and emission of domestic gas burner using swirling flow design

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ABSTRACT

An experimental work was carried out to investigate the possibility of improving the performance of the domestic gas burners using liquefied petroleum gas (40% C_3H_8 and 60% C_4H_{10}) as a gaseous fuel through inducing swirling flow. The effect of varying the swirling angle of the outer cap burner on the burner performance was investigated using four burners with four different ring caps having different swirling angles. The swirling angles selected were (5^0, 8^0, 10^0, and 16^0). The results were compared with the original conventional radial flow burner having no swirl angle. This original burner is a commercial domestic gas burner of conventional radial flow utilizing its original cap of foreign origin acquired from an appliance shop which is commonly used in cooking. The conventional burner exit fuel/air mixture ring with no swirl angle is used to be a reference burner for this investigation.

The experiments were conducted in three phases. The first phase was performed to study the effect of swirling flow on the impingement heat flux from the flames at three flame heights (h=10, 26 and 40mm) at fuel volume flow rate $3.5*10^{-5}$ m^3/s (2.1 l/min) corresponding to thermal input 3.48 kw. The second phase was applied to study the effect of varying both of the swirling angles and the fuel volume flow rate on both of the impingement heat flux and the thermal efficiency of the domestic gas burner using the five burner caps mentioned above. The fuel volume flow rate was varied from $2*10^{-5}$ to $3.5*10^{-5}$ m^3/s (1.2 to 2.1 l/min.). The thermal efficiency was studied using open, totally-confined and semi-confined flames. The third phase was carried out for studying the effect of swirling flow on the flame appearance (color and length), the flame temperature distribution and exhaust gas concentrations.

The experimental results showed that increasing the fuel volume flow rate had two opposite effects on the thermal efficiency. The thermal efficiency increased as the fuel flow rate increased to $2.67*10^{-5}$ m^3/s (1.6 l/min.) while as the fuel volume flow rate increased beyond this value the thermal efficiency decreased. The maximum increase in thermal efficiency was 47.4% using the swirl burner of 16^o swirl angle at semi-confined flame compared to that of the conventional radial flow burner at open flame.

Also, the experimental results showed that in the range of outer ring cap swirling angles (5^o to 16^o), as the swirling angle increased, the thermal efficiency increased at all fuel volume flow rates. It confirmed that the induction of swirling flow had a

great effect on enhancing the impingement heat flux at three flame heights (h=10, 26 and 40mm). The maximum gain in the thermal efficiency was 43% using the swirl burner of 16^{o} swirl angle compared to that of the conventional radial flow burner at semi-confined flame. The previous results clarified that using the semi-confined flame had a pronounced effect on the enhancement of the thermal efficiency.

Also, the results gave an indication about the improvement of the mixing between air and fuel according to the induction of swirling flow led to somewhat higher burning rates that forming more bluish and shorter flame. The results presented also, that the good mixture formed more favorable combustion conditions with high heat release rates producing high average flame temperature and low CO concentrations with slightly high NO_x concentrations at all the flame heights.

Nomenclatures

C.V	:	Calorific value of fuel, kJ/kg.
C_w	:	The water specific heat, 4.18 kJ/kg ^{o}c.
d	:	Fuel port diameter, mm.
$(F/A)_{st}$	:	The stoichiometric fuel to air ratio.
h	:	Vertical distance measured from the burner tip, mm.
I_i	:	The inner swirler tangential momentum, kg.m/s^2.
I_o	:	The outer swirler tangential momentum, kg.m/s^2.
q``	:	Impingement heat flux, kw/m^2.
p	:	Pressure, static pressure, Pa.
Pr	:	Prandtl number.
r	:	Burner radial distance , mm.
Re	:	Reynolds number, dimensionless, $(\rho.v.d)/\mu$.
S	:	(Swirl number): defined as the ratio of the axial flux of angular (swirl) momentum "G_ϕ" to the axial momentum flux "G_x" multiplied by a characteristic length "L", dimensionless.
T_f	:	Flame temperature, K.
T_{th}	:	Thermocouple temperature, ^{o}c.
T_{wi}	:	Cooling water inlet temperature, K.
T_{wo}	:	Cooling water outlet temperature, k.
v	:	Velocity (m/s).
α	:	(Swirling angle): defined as the angle between the projection of both the port axes and the radius axes on the burner top surface plane.
β	:	(Inclination angle): defined as the angle between the projection of both the port axes and the burner plane on the radius plane.
σ	:	Stefan-Boltzmann constant, 5.67×10^{-8} W/(m^2.K^4).
ε	:	Flame emissivity, dimensionless.
μ	:	Absolute viscosity, kg/m.s.
ρ	:	Density, kg/m^3.
η_{th}	:	Thermal efficiency.
θ	:	Swirl vane angle measured from horizontal plane.
$\emptyset_o$	:	Overall Equivalence ratio, dimensionless which is the ratio between the stoichiometric air to fuel ratio to the actual air to fuel ratio.

Abbreviations

LPG	:	Liquefied petroleum gas.
CB	:	Conventional burner
PM	:	Porous medium
RB	:	Radial burner
SB	:	Swirl burner
SPMB	:	Self-aspirating porous medium burner
PRB	:	Porous radiant burner
PRRB	:	Porous radiant recirculated burner

TABLE OF CONTENTS

ACKNOWLEDGEMENT I
ABSTRACT II
NOMENCLATURES IV
ABBREVIATIONS V
TABLE OF CONTENTS VI
CHAPTER (1): INTRODUCTION 1
CHAPTER (2): LITERATURE REVIEW 6
2.1 Introduction 6
2.2 Review of the Previous Work 7
2.2.1 Swirling in the Industrial applications 7
2.2.2 Swirling in the Domestic applications 8
CHAPTER (3): TEST RIG AND EXPERIMENTAL WORK 25
3.1 Introduction 25
3.2 The Burner 27
3.2.1 Burner Head 27
3.2.2 Burner Cap 33
3.2.3 Burner Casing 34
3.3. Fuel Supply System 35
3.3.1 Flame temperature measurements 35
3.3.2 Calibration of the flame thermocouple 36
3.3.3 Estimation of the error in measuring the flame temperature using type S thermocouple 36
3.4 Data Acquisition System 39
3.5 2-D Positioning System 39
3.6 Flame Photographing 39
3.7 Exhaust Gas Analysis 41
CHAPTER (4): EXPERIMENTAL PROCEDURE 43
4.1 Introduction 43
4.2 Experimental Program 43
4.3 The Experimental Procedure 44
4.4 Thermal Efficiency 46
4.4.1. Thermal efficiency calculation 46

4.5 Swirl Number 47
4.5.1. Swirl flow characteristics 47
4.5.2. Generation of the swirl flows 47
4.5.3. Vane swirler characteristics 48
4.5.4. Swirl strength (swirl number) for a single swirler 48
4.5.5. Calculation of the swirl number for each burner 50
4.6 The use of the vatell heat flux 51
CHAPTER (5): RESULTS AND DISCUSSIONS 54
5.1 Introduction 54
5.2 The effect of the swirling flow angle, α, on the impingement heat flux from the produced flame 56
5.2.1 The impingement heat flux from the swirl and the non-swirl burners' flames 56
5.2.2 Impingement heat flux from the produced flame 57
5.3 The effect of the swirling flow angle, α, on the thermal efficiency 67
5.3.1 The thermal efficiency using open flame 67
5.3.2 The thermal efficiency using totally-confined flame 71
5.3.3 The thermal efficiency using semi-confined flame 75
5.4 The effect of the swirling flow angle, α, on the flame shape and color 80
5.5 The effect of the swirling flow angle, α, on the flame length 82
5.6 The effect of the swirling flow angle, α, on the flame temperature 87
5.7 The effect of the swirling flow angle, α, on the exhaust gas analysis 99
5.7.1 The effect of the swirling flow angle, α, on the NOx concentrations 99
5.7.2 The effect of the swirling flow angle, α, on the CO concentrations 109
5.7.3 The effect of the swirling flow angle, α, on the CO_2 concentrations 120
5.7.4 The effect of the swirling flow angle, α, on the O_2 concentrations 131
5.8 The effect of the swirling flow angle, α, on the secondary air entrainment 144
5.8.1 Overall equivalence ratio 144
5.8.2 Primary equivalence ratio 150
CHAPTER (6): CONCLUSIONS 154
6.1 Introduction 154
6.2 Conclusions 155
REFERENCES: 156
APPENDIX (1): CALCULATION OF THE OVERALL EQUIVALENCE RATIO 160
APPENDIX (2): FLAME THERMOCOUPLE CALIBRATION 162

APPENDIX (3): THE USB-4718 SPECIFICATION 164
APPENDIX (4): GAS ANALYZER SPECIFICATIONS 167
APPENDIX (5): HEAT FLUX CALIBRATION...170
APPENDIX (6): SPECIFICATIONS OF THE GASEOUS FUEL 174
APPENDIX (7): FLAME LENGTH MEASUREMENTS 175
APPENDIX (8): CALCULATION OF THE CONVECTIVE HEAT TRANSFER COEFFICIENT 176
APPENDIX (9): PHOTO COPIES OF THE OUTPUT PAPER SLIP SAMPLES 179
APPENDIX (10): THE HOT WIRE ANEMOMETER SPECIFICATIONS 181
APPENDIX (11): THE UNCERTAINTY OF THE THERMAL EFFICIENCY 182

CHAPTER (1)
INTRODUCTION

The ever increasing demand for higher efficiency and precise controllability coupled with more stringent pollution emission requirements impose considerable pressures on combustion research and development.

The major challenge for best utilization of fossil fuel energy via combustion is focused on environment, efficiency and economics. To meet these requirements, the development of combustion equipment must be directed at environmental compatibility, high efficiency and high intensity in addition to low capital and operating costs [1].

With increasing concern of society for environmental protection, domestic gas burners producing lower pollutant emissions are much desirable. Therefore, more studies on thermal efficiencies and emissions of domestic gas-fired burners have been carried out.

It is well known that the domestic gas burner most widely used is the conventional Bunsen type, i.e. partially aerated. The typical partially aerated burner entrains primary air naturally by a momentum sharing process between the high velocity gas jet and ambient air [2].

Considering that many cooker-top burners being used nowadays, even slight improvements in the thermal performance and reductions of emissions resulting from a better design will have significant impacts on decreasing the world’s fossil-fuel expenditure and environmental degradation.

The fuel commonly used in domestic gas appliances is LPG or natural gas. Liquefied petroleum gas (LPG) is widely used as a fuel in heating processes (especially in domestic heating appliances) throughout the world because its combustion products are relatively clean. However, the indoor air pollution has still been of great concern due to its direct association with people [2].

For domestic cooking applications, LPG (liquefied petroleum gas) is the most commonly used conventional fuel. The combustion in a domestic LPG cooking stove takes place in a gaseous environment, and the flame stabilizes over the surface of the burner. This combustion is known as the free-flame combustion, where convection is the dominant mode of heat transfer. The free-flame combustion is characterized by a thin reaction zone and this result in a sharp temperature gradient across the flame. A thin reaction zone and a sharp temperature gradient are responsible for an inefficient combustion which leads to a higher amount of pollutants formation [3].

Existing domestic gas burners have solely relied on the self-aspirating atmospheric conventional burner with radially flowing ring burner. Most conventional domestic burners have typically relied on open combustion flame, where a large amount of energy loss with the flue gas arises, resulting in relatively low thermal efficiency (<30%). It is clear that if the dispersion of the flame or flue gas to the surroundings can be delayed, then an improvement in thermal efficiency can be achieved [1].

Accordingly, much effort has been expended to obtain higher thermal efficiencies and lower emissions of domestic gas burners for a number of years in view of the desire for energy saving and the requirement for reducing emission.

Direct gas flame impingement is employed in a wide range of industrial and domestic heating processes. By impinging the flame on the target, forced convection greatly enhances the heat transfer rate. So, significant attention has been paid to the heat transfer characteristics of the impinging flame system. [4].

A rapid and high heating rate leading to short processing time is one of the important requirements of heating processes. Direct gas flame impingement heating using hydrocarbon–air or hydrocarbon–oxygen flames is employed in an expanding range of heating processes because of its rapid and high heating rate. The dominant mode of heat transfer is forced convection, and the flames are characterized by their elevated temperatures, which are associated with concentrations of dissociated species, although small but are significant. Recently, rapid heating techniques have become increasingly popular because they offer the possibility of saving energy and improving the quality of the hot product [5].

Experimental studies show that swirl has large-scale effects on flame size, flame shape, flame stability, combustion efficiency and combustion products. Hence for lower environmental pollution of carbon monoxide (CO), more energy saving, high combustion efficiency and stable flame that allow good and safe operation under wide range of air to fuel ratios, swirling motion is required.

The basic requirements of all combustion processes, whether domestic or industrial, are the same regardless of the mode of the fuel and air supply to the burners or combustors. As an example in gas turbine combustors, these requirements are; adequate mixing between the fuel and the combustion air, the flame stay lighted over a wide range of operating conditions, high combustion efficiency, wide stability limits, low pressure loss, and low emissions.

These requirements constitute also the major concern in designing and operating domestic burners. For these reasons, the combustor design is directed towards obtaining sufficient mixing between the fuel and combustion air, at a stable flow pattern and minimal combustor and flame length as well, and pressure loss.

In all combustion systems, the strong favorable effects of applying swirl to injected air and fuel are strongly motivate the use of swirl promoters as an aid to the stabilization of high intensity combustion process and efficient clean combustion in a variety of practical situations such as gasoline and diesel engines, gas turbines, industrial furnaces, utility boilers, and many other practical heating devices.

The mixing of fuel and oxidizer, convection, diffusion, heat transfer, evaporation and turbulence are usually bond together through strongly coupled interaction in combustion systems. Such phenomena as stability limits are not only dependent upon the fuel and oxidizer chemical properties but also depend upon the gas dynamics of the system and how they affect each other [1].

Considering all the previous requirements, the process of design and selecting a suitable flame stabilization mechanism is important for the attainment of a successful overall performance of the continuous combustion system.

Swirlers are often used to produce high rates of turbulence within the fuel and air mixture through the generation of the internal recirculation by creating a strong vorticity on the burner axis. This is achieved by imparting a tangential momentum to the forward flow by the swirlers system. Swirl increases the mixing through the large turbulence generated in the jet shear layers. It improves also stability through the recirculated hot species and by the effect of the aerodynamic blockage of the recirculation zones. Decreased levels of pollutant emissions are possible from the swirl stabilized combustion with a uniform heat release distribution necessary for the durability of combustion equipment [6].

The effect of swirl on the pollution generation is a function of many parameters. Fuel type, fuel and air supply dynamics injection location, expansion geometries of combustor nozzles, and swirl mode and strength are some of these parameters. For a swirl stabilized combustion of a diffusion flame the increased swirl increases the entrainment rate of the ambient air in a confined configuration and thereby decreases the flame temperature and hence the NO_x formation through the thermal mechanism, [6].

Swirl flows are widely used in industrial burners in order to improve fuel-air mixing and accordingly the flame stabilization. As swirl is introduced in the flow, the tangential component of swirling flow enhances the turbulent mixing of fuel and air, and the swirl-induced recirculation stabilizes the flame. In general, if the swirl strength is strong enough, characterized by the non-dimensional swirl number S, an internal recirculation zone can be established that serves as a reservoir of heat and chemical radicals. The existence and shape of this zone strongly influence the flame stability [6].

Swirl significantly influences the heat and mass transfer in natural flows encountered in many technological applications. Inducing swirl in these processes possesses great potential to extend the residence time and enhance flow mixing by means of the rotational movement of the flow field. However, most of the flow types of domestic gas burners contain no swirl flow [2].

Low-pressure and low-Reynolds-number impinging premixed gas-fired flames are widely used in domestic and light industrial applications because of their excellent heating performance and ability to produce rapid and clean combustion.

Recently, there are increasing efforts on studying the thermal and emission characteristics of such flame jet systems. One major drawback in utilizing the impinging premixed gas-fired flame jet is that a very narrow range exists between the upper and lower flammable limits such that it can only operate stably within rather narrow ranges of Reynolds number and equivalence ratio.

In order to enhance the flammability limits of the flame and thus improve its thermal performance, the method of inducing a swirling flow has been used successfully to the high-pressure and high-Reynolds-number impinging diffusion flame which is applied in many large-scale and heavy-duty industrial applications. However, there were very few reported studies on the induction of a swirling flow to the small-scale, low-pressure and laminar impinging premixed flame.

Although some studies have investigated the effects of a swirling central flame, little attention has been paid to the influence of a radial multi-port burner with superimposed swirl, which is a new burner design with swirling flames in this study.

A considerable amount of published work exists on the development of low emission; energy efficient gas stove burners, whereas the literature on the effects of flow type on burner performance is still very limited.

In this study, it is important to assess the effects of swirl flow on the burner performance and propose suitable design or operational factors for domestic gas burners in case of open flame and confined flame. A novel design of domestic gas burner with swirling flames is proposed, and its thermal efficiency and CO, NO_X emission characteristics in comparison to those of the conventional gas burner without swirling flames are investigated in the present study.