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EXPERIMENTAL INVESTIGATION OF HEAT TRANSFER AND THERMAL EFFICIENCY FOR LEAN COMBUSTION OF LPG GAS HYPERMIXING WITH SUPER HEATED STEAM ON SWIRLING SURFACE CONFIGURATION

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ABSTRACT

The present work introduces the use of steam injection technology with an advanced design based on "hyper mixing" with LPG fuel and swirling air as lean combustion burned on swirling surface furnace. The effect of steam injection and swirling surface on the thermal efficiency, heat transfer rate, heat release rate and exhaust gases emission are presented. In this concept, the twisted tape of swirling surface is optimized at twist ratio, $Y = 0.6$ for the inner surface of furnace and $Y = 0.25$ for the cupper tubes of water cooling and steam injection is performed. The experiments were carried out at Reynolds number ranging from 50000 to 120000 for air at 20 °C and different air mass flow rate in the range from2kg/h to 25 kg/h while the temperature of combustion was650 C°. The experimental results indicated that the increase in heat transfer rate and thermal efficiency by using swirling surface is greater than its respective value of plain surface by 25% and more increase by 50% by using steam injection at the same Reynolds number. The fuel consumption is decreased also NOx emission decreased as results of steam injection by 40%. The thermal efficiency increased as the heat release rates decreased.

KEY WORDS

LPG lean combustion, swirling surface, steam injection, heat transfer, exhaust gases emission.

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NOMENCLATURE

Symbol	Description	Unit
A	Heat transfer area	m^2
a	Cross area of air hose	m^2
Cp	Specific heat capacity	kJ/kgK
D	Cylinder diameter	M
dh	Hydraulic hose diameter	m
d	Hose diameter	m
H	Heat transfer coefficient	W/m^2K
K	Thermal conductivity	W/mK
Lc	The length of water cooling tube	M
L_{cv}	Lower calorific value of LPG gas	kJ/kg
M	Mass flow rate	Kg/s
Nu	Nusselt number	
P	Pressure	Pa
Q	Heat transfer rate	W
R	Gas constant	KJ/kg.K
Re	Reynolds number	
r	Radius of water cooling tube	m
T	Temperature	K
U	Average axial velocity	m/s
Vc	Volume of water heated cylinder Twist	m3
Y	ratio	
Ρ	Density	Kg/m3
μ	Dynamic viscosity	Kg/m.s
Y	Kinematics viscosity of air	m/s^2
ε	Enhanced effectiveness	
η	Thermal efficiency	
λ	Air / fuel ratio (A/F)	

Subscript

a	Air	W	Water
a_i	Air inlet	W_i	Water in
a_o	Air out	W_o	Water out
m	Mean	HRR	Heat release rate
c	Cylinder	LPG	Liquefied petrol gas
f	Fuel	PL	Plain surface
g	Combustion gases	P.F	Pattern factor
g_i	Combustion gasses in	SW	Swirling surface
g_o	Combustion gasses out	ST	Steam

INTRODTUCION

Lean combustion is employed in nearly all combustion technology sectors, including gas turbines, boilers, furnaces, and internal combustion engines. This wide range of applications attempts to take advantage of the fact that combustion processes operating under lean conditions can have very low emissions and high efficiency. Many investigations have been performed to study the heat transfer, thermal efficiency and the emissions of lean combustion. Elnajjar et al. [1] study the effect of LPG fuel with different propane to butane volume ratio compositions on the performance of dual fuel engine under variable operational, the data indicates that different LPG fuel composition has minimal effect on the engine efficiency and has strong impact on the levels of generated combustion noise. Weigandet et al. [2] has performed comprehensive experimental investigations on premixed swirling CH4 /air flames at atmospheric pressure in a gas turbine. Experiments showed that the heat release rate varied by more than a factor of 6. The measurements revealed in homogeneities of the premixedness and periodic variations of the fuel/air ratio. Noor et al. [3] found that combustion is still very important to generate energy. Moderate or Intense Low-oxygen Dilution (MILD) combustion is one of the best new technologies for clean and efficient combustion. EKalil et al. [4] distributed combustion offers significant potential for improved performance and near zero emission for gas turbine applications. Results showed very low levels of NO and CO emissions at an equivalence ratio of0.6 and a high heat release intensity of 27 MW/m3-atm with preheated air under premixed combustion. SatpalSingh and hashChander [5] study the evaluation of heating capabilities of dual swirling flame under fuel lean conditions. It has seen that the energy efficiency of the dual flame decreases with increase in separation distance and higher firing rate conditions. Selim [6] studied combustion of the dual fuel engine using three different gaseous fuels. The gaseous fuels used are liquefied petroleum gas, pure methane and compressed natural gas mixture. Combustion noise, knock and ignition limits are presented for a dual fuel engine running on dual fuels of diesel and three gaseous fuels separately.

VenkateswaraRaol and Rao [7] studied prediction of heat release patterns for modeling diesel engine performance and emissions. They found that diesel engine performance and emissions are modeled using dual Weber function for heat release analysis. Also thermal efficiency, pressure and temperature will increase by increasing the engine speed. Choudhuri and Gollahalli [8] studied the flame luminosity and visible length of a diffusion flame of hydrogen-propane mixtures. They found that the increase of propane concentration the radiation fraction of heat release increases initially at levels above 30% (by volume).The emission indices of NO and NOx decreases and the emission index of CO increases with the increase of propane fraction. Saray [9] studied the present quash-two zone combustion model, combined with the detailed chemical kinetics scheme of a combustion process in dual fuel engines to investigate the combustion phenomenon at part loads. It is found that, both positive effects on the performance and emission parameters, except for Noxofdual fuel engines at part loads. Akpinar [10] studied evaluation of heat transfer and exergy loss in a concentric double pipe exchanger equipped with helical wires. The study indicated that heat transfer rates increased up to 2.46 times and the effectiveness values increased up to 1.16 times with the help of the helical wires. Prager et al. [11] study the structure of n-heptanes /air triple flames in partially – premixed mixing layers. The study shows that a significant reduction in size of the mechanism can be achieved without a significant decrease in accuracy of the edge flame computation. Awad and Gomaa [12] studied heat transfer enhancement and air pollution reduction of exhaust gas stream through swirling recuperator joined with a cyclone-scrubber. The experimental results indicated that the increase in heat transfer rate of the swirling flow is greater than its respective value of plain flow. In the other side the pollution of exhaust gases is greatly reduced by passing exhaust gases into cyclone-scrubber. Abou-Arab et al. [13] studied combustion and heat transfer characteristics for a dual – fuel cylindrical water heater model. They found that the LPG flame gives higher heat release rates within the residence time in the combustor, due to the higher degree of mixing. Also the thermal efficiency increased as the heat release rates decreases at the increase of air fuel ratio. Ohkubo,[14] study low-Noxof combustion technology for micro gas turbine for cogeneration system. It is found that lean combustion with a multistage fuel supply was investigated and NOx emission level is less than 15 ppm. Watcharinet [15] studied the effect of twisted-tap inserts on heat transfer in a tube. He found that a higher heat transfer rates and higher effectiveness of the system than that of plain tube.

The present work studies and optimizes the effect of steam injection and swirling surface of double cylinder combustion chamber on the heat transfer rate, thermal efficiency, specific fuel consumption, heat release rate, and exhaust gas emission of LPG lean combustion system. The results compared with combustion on the plain surface without steam injection at the same condition.

EXPERIMENTAL TEST RIG.

Photograph of the experimental test rig is shown in Fig. (1).The experimental test rig consists of a water cooled cylindrical furnace that operated at atmospheric pressure and could burn gaseous fuel. The experimental work was carried out on a plain surface of a cylindrical furnace first and then carried out on swirling surface of the cylindrical furnace without and with hyper mixing steam injection in the combustion chamber of LPG fuel combustion. The test rig of plain surface as shown in Fig.(2) consists of inner cylindrical furnace is fabricated and assembled from steel cylinder of 250mm inner diameter, 4mm thickness and 1000mm length. An outer steel cylinder of 300 mm inner diameter and 4mm thickness with800 mm length is welded on the inner cylinder and works as cooling water jacket for plain surface furnace. Air is pumped through the combustion chamber by three stage blower fan that was connected to the furnace via a flexible hose. Observation windows and tapping holes were available, to permit the use of measuring probes. Auxiliary systems were designed for the feed and metering of cooling water and gaseous fuel. The cylindrical furnace is connected by spark ignition burner works at maximum temperature of 650 ºC. The test rig of swirling surface as shown in Fig (3) is prepared by a twisted–tap optimized and fabricated from steel strips of thickness 2.0 mm, 60mm width, twisted tap angle 60 degree and welded inthe inner surface of the cylindrical furnace with Y= 0.6. Two cupper tubes of 12 mm inner diameter and 0.4 mm thickness are wrapped and swirled around the outer diameter of the inner cylindrical furnace with twist ratio Y = 0.25 as a coil of water jacket for cooling the furnace and generating steam.

The steam is injected in the furnace from two positions to hyper mix with LPG fuel and air combustion. The cupper tubes are covered by an outer steel tube of thickness 2.0 mm, 300 mm inner diameter and isolated. The cylindrical furnace connected by spark ignition burner works at maximum temperature of 750 C. The compressed air is pumped through the furnace by a three – stage electric blower fan of 2.0 kW power and 60 mm in diameter of inlet air via a flexible hose. Observation windows and taping holes were available to show the flame of combustion process and to permit the use of measuring probes respectively. The other end of the furnace is connected by chimney of L shape with125mm inner diameter and flange coupling as shown in Fig.(3).The cold water flows from desolation water tank at ambient temperature of 20 C. The test rig is controlled by Rota measuring devices as one flow meter installed in the front panel for measuring water mass flow rate and orifice meter for measuring air mass flow rate, LPG rot meter for measuring gas fuel mass flow rate, A Lancôme portable flue gas analyzer is used to measure CO,SO2, and NOx emissions. Twenty–two pre- calibrated K-type thermocouples of 0.3 mm wire diameter, of 1.0 mm probe diameter and of 20 ms response time were used to measure the temperatures at definite locations of (water, steam, air, gas) inlet and outlet temperatures. Thermal anemometer (Testo 415) was used to measure the air velocity. Using a pressure regulating valve, the LPG supply pressure to the burner was kept almost constant at a measured 2.5 m water gauge throughout the experiments. Therefore, air pressure across the burner was also constant and equal 2.5 m water gauge for all runs. All measuring devices are calibrated before using in the test rig. Corrections due to deviation of temperature and pressure from standard values were considered for the gaseous fuel flow meter. The accuracy of temperature measurements was **+/-** 0.5 C°. Corrections due to deviation of Nusselt number suggested to be +/- 100 based on the experimental results. The main components of test rig are shown in Table (1).

TEST PROCEDURE

In the current experimental work, two sets of experiments were carried out as follows:

(1) **In the first set of experiments**, the cylindrical furnace is working without swirling strips (plain surface) and without steam as shown in Fig.(2).The combustion gases are supplied to the inner cylinder furnace at inlet temperature of 400 C. The compressed air is pumped through the furnace at different Reynolds number from 50000 to 120000to change the mass flow rate. The cold water enters the outer tube water jacket at ambient temperature 20 C° at different inlet velocities to change the mass flow rate of water from 9 kg/h to 56 kg/h. The heat is transferred between hot gases and cold water by convection. The measuring results of the temperatures and velocities of water, air and hot gases in and out are measured and recorded under isothermal condition at each test. The inlet and outlet temperatures of both hot gases and water are measured by thermocouple type (K). Orifice meter gave the air mass flow rate in the range of (2 – 25) kg/h at 20 C°. while the flow meter for measuring LPG fuel mass flow rate from 5 to 9.5 kg/h.The temperatures and velocities are measured at different points to find out the average measured values. These values are used as input data to the calculation program to get Nussle number (Nu), Reynolds number (Re), convection heat transfer coefficient(h),the thermal efficiency(**η**) of the furnace, and enhanced effectiveness of furnace(**ε**).

(2) In the second set of experiments, the twisted-tapes is inserted and welded in the inner cylinder of furnace with Y= 0.6, and two cupper tubes of 12mm inner diameter, 0.6mm thickness are wrapped around the outer diameter of cylindrical furnace to generate steam. The steam is injected at 250 C° and hyper mixed with the combustion of LPG gas fuel and air. The combustion gases and steam are supplied to the inner cylinder furnace at inlet temperature of 650 C°. The experiments are carried out with same procedure at the same condition and same measuring devices. The measuring results are recorded and used as input data to the calculation program.

RESULTS AND DISCUSSION

Figure (4) shows that the heat transfers rate by using the swirling surface of furnace at small twist ratio 0.6 and steam injection. It is found that the twisted-tapes inserted and welded in the inner cylinder of furnace gives higher heat transfer rate than that of plain surface. It can cause the swirl and pressure gradient in the radial direction. The boundary layer along the furnace wall would be thinner with the increase of radial swirl and pressure resulting in more heat flow through the fluid. In addition to, the swirl enhances the flow turbulence, which led to even better convection heat transfer. Furthermore, the steam injection can become a significant source of mixing power and becomes possible to increase the mixing heat transfer rates with the products of combustion in the furnace. The mixing power boost provided by the high velocity steam greatly improves the temperature uniformity within the furnace. The improved mixing uniformity can also reduce excess air requirements. The steam injection increases the heat transfer rates by 70% than that of the plain surface and by 40% than that of swirling surface in the furnace at the same Reynolds number.

Figure (5) shows the increase in Reynolds numbers leads to an increase in Nusselt numbers for the swirling flow and planning flow. The corresponding more increase of mean Nusselt number by using hyper mixing steam injection is higher up to 60% than that of plain surface furnace and 30% than that of swirling surface at the same Reynolds number.

Figure (6) shows the use of small twist ratio Y = 0.6 in the furnace surface leads to increase the heat transfer rate and the corresponding enhanced effectiveness (**ε**) for the furnace than that of plain surface. Furthermore, increase the heat transfer rate and the corresponding effectiveness by using the steam injection than that of plain surface by 50% and that of swirling surface without steam by 25% than that of plain surface at the same Reynolds number.

Fig.(7) shows the experimental variation of gas emission (NOX, CO, SO2) with Reynolds number. It is found that the gas emissions is decreased with the increase of Reynolds number in the lean combustion as a result of excess air in the combustion.

Fig. (8) Shows the experimental variation of gas emission (NOx, CO, SO_2) with steam injection by using hyper steam injection in the combustion chamber of the furnace. It is found that the mixing power boost provided by the high velocity steam greatly improves the temperature uniformity within the furnace reducing peak temperatures, which results in lower NOx formation. The improved mixing uniformity can also reduce excess air and consequently results in lower CO and SO2.The fuel consumption is decreased and also lower NOx emission as results of steam injection by 40%.

Fig. (9) shows the thermal efficiency (**η**) in lean combustion increases with air fuel ratio (A/F) increase at different heat release rate, this may be because the burning velocity is an important factor governing the specific combustion load of a chamber. Furthermore, the burning velocity of spray is significantly affected by turbulence. It is also established that burning velocity increases as mass fuel increases. Also the higher air/fuel ratio improves the combustion efficiency and consequently increases the thermal efficiency.

As air/fuel ratio is further increased a worse pattern factor (P.F), is obtained and incomplete combustion may take place at relatively high air mass flow. Consequently, combustion efficiency decreases, since insufficient time for complete combustion results in a depressed flame temperature. The heat release rate is directly related to burning mass of fuel, flame temperature and consequently combustion efficiency. When heat release rate increases for the same air/fuel ratio, fuel mass flow is increased. However, the air mass flow increases at a relatively lower rate. Hence, combustion efficiency decreases and consequently thermal efficiency decreases.

CONCLUSION

An experimental study has been conducted to investigate the effect of hyper mixed steam and the swirling surface on the heat transfer rate, exhaust gas emissions and effectiveness of the cylindrical furnace. The design is optimized by using a twist tape ratio (twist-tape pitch to cylinder diameter) . The ratio was less than one (Y= 0.6) and two cupper tubes of cold water wrapped(swirled) around the cylindrical furnace for cooling and generating steam injected in the furnace with Y = 0.25 to get a higher heat transfer rate in comparison with the plain tube furnace without steam injection. The present design can improve the heat transfer rate. The enhanced effectiveness and the maximum mean Nusselt number is increased by 50% than that of plain tube furnace. The enhanced effectiveness, Nusselt number increases by increasing the Reynolds number. Also, the thermal efficiency of combustion increases as air/fuel ratio increases and heat release rate decreased. The exhaust gases flow out the furnace with low pollution. The results indicated that the emissions of SO_2& CO and NOx flow out the furnaces decreased by using the steam injection than that without steam injection [12].

REFERENCES

[1] Emad Elnajjar E, et al., Experimental investigation of dual engine performance using variable LPG composition fuel, Renewable Energy (2012), http://dx.doi.org/10.1016/j.renene.2012.09.048.

[2] P.Weigand, et all" Experimental investigation of an oscillating lean premixed CH4/air swirl flame in a gas turbine model combustor", proceedings of the European combustion meeting, 2005. http:// www2.dlr.de/VT

[3] Noor et al. "Experimental investigation of Moderate or low-oxygen Dilution (MILD) combustion", International Journal of Automotive and Mechanical Engineering Vol.6,p730-754, 2012

[4] A.E.E. Khalil et all, "Distributed combustion with swirl for gas turbine applications" 49th AIAA Aerospace sciences Meeting including the new Hoizons Forum and Aerospace Expostion 4-7 January 2011,Orlando, Florida.

[5] Satpal singh and Subhash Chander "Evaluation of Heating Capabilities of Dual Swirling Flame under Fuel Lean Conditions", Open journal of heat, Mass and Momentum transfer, HMMT 2015,3(1):1-13,

[6] Mohamed Y.E. Selim, "The combustion of dual fuel engine using three different gaseous fuels", Energy Conversion and Management" Vol. 45 (2004) p411–425.

[7] B.VenkateswaraRaoI and G. Amba Prasad Rao; “Prediction of heat release patterns for modeling diesel engine performance"; March 2012, IJAET ISSN: 2231-1963 262- Vol.2.

[8] A. Choudhuri and S.R.Gollahalli;“Combustion Characteristics of Hydrogen-Propane Mixtures;” University of Oklahoma; Norman; OK; 73019, 2011**.**

[9] *R.* Khoshbakhti Saray*,* “Enhancement of Combustion Process in Dual Fuel Engine at Part Loads by Using Suitable Techniques**,”** Engine Research / Vol. 14 / spring 2009

[10] R.K. Mandloi et al. "Experimental results given in several literatures have confirmed the reliability and accuracy for predicting the cycles and performance of SI engines running on gasoline and gaseous fuels", International Journal of Engineering Science and Technology Vol. 2(10), 2010, p5907-5919

[11] J.Prager et all, "Structure of n-heptane/air triple flames in partially – premixed mixing layers", Elsevier journal, Combustion and flame, 158 (2011) 2128-2144.

[12] Saad Awad, Mohamed Gomaa, "Heat transfer enhancement and air pollution reduction of exhaust gas stream through swirling recuperator joined with a cyclone-scrubber" Journal of Engineering Sciences, Assiut University, Faculty of Engineering Vol 41 No.4 July 2013,pp1549-1563, Jes@aun.edu.eg .

[13] T.W.Abou-Arab,et al. "Combustion and heat transfer characteristics for water heater model" King Abdul–Aziz University, Jeddah, Saudi-Arabia, fuel Vol. 69 pp(485- 489), April 1990

[14] Yoichiro Ohkubo, "Low- Nox. Combustion Technology of Micro Gas Turbine for Cogeneration System " R&D review of Toyota CRDL, Vol.41 No. 1, pp(12-23), Dec.16, 2005

[15] Watcharin, "Effect of twisted-tap inserts on heat transfer in a tube", "International conference on sustainable Energy and Environment", Bangkok, Thailand,A-030(p),2006

Fig. (1). Photograph of the experimental test rig.

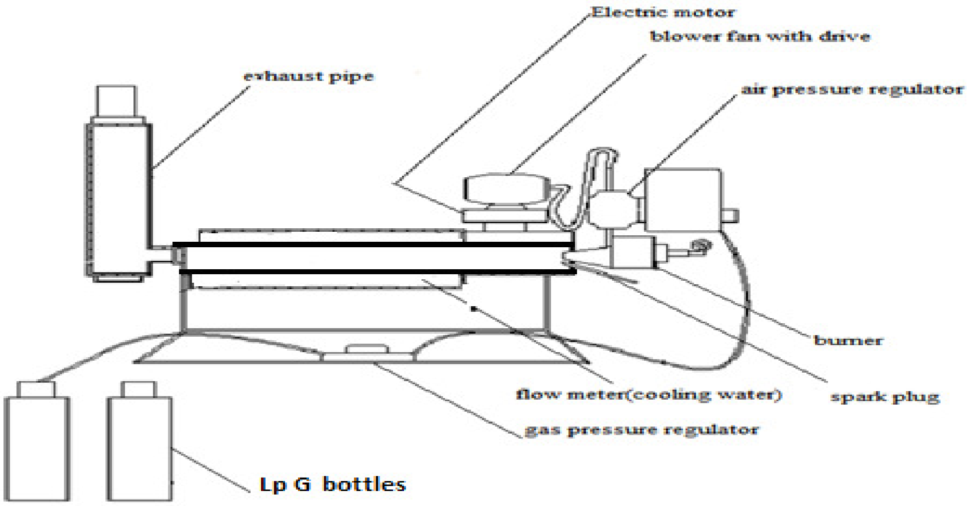

Fig. (2). Experimental test rig of plain surface combustion furnace.

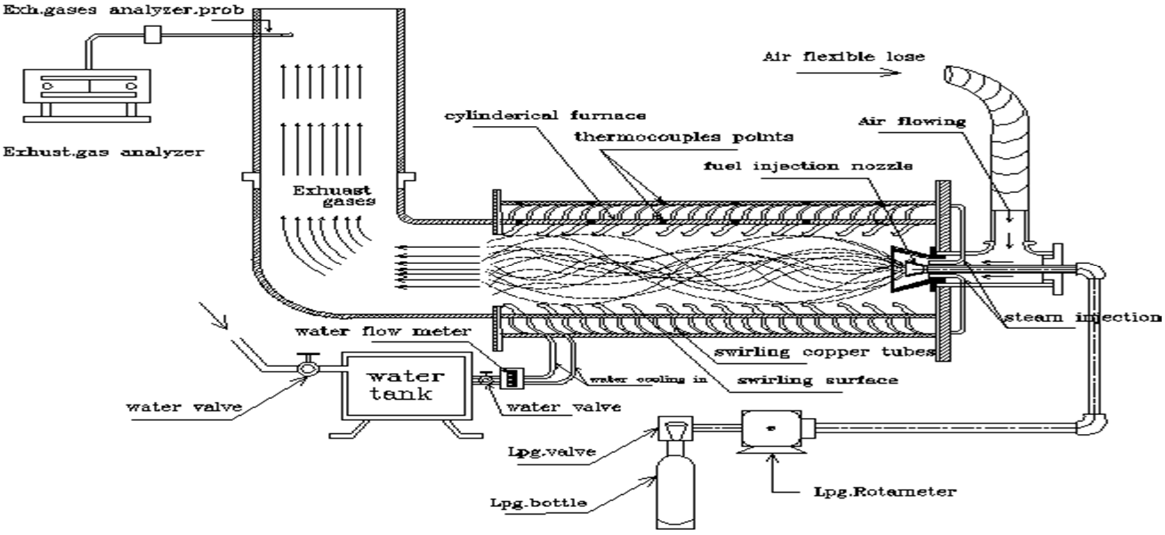

Fig. (3). Complete section of test rig with swirling surface and steam injection in furnace.

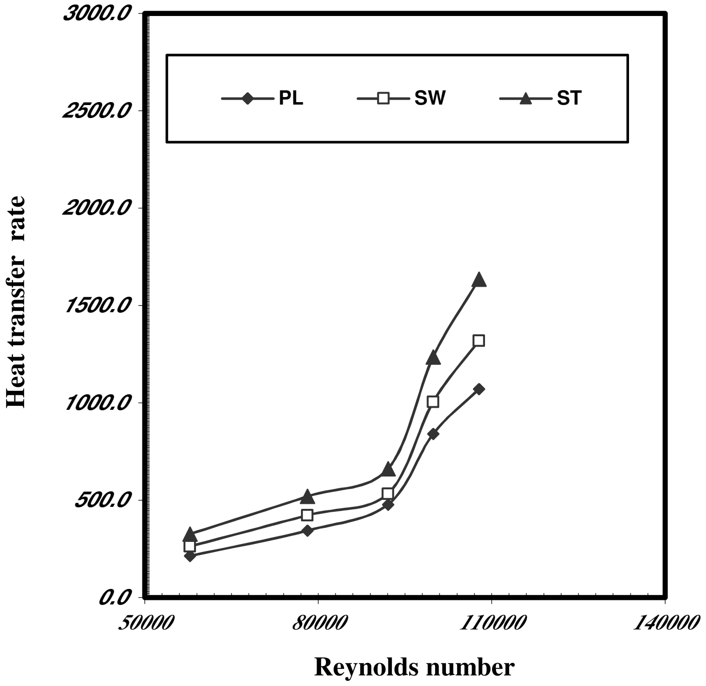

Fig. (4). Experimental comparison of furnace heat transfer rate for plain surface & swirling surface and steam injection versus Reynolds number.

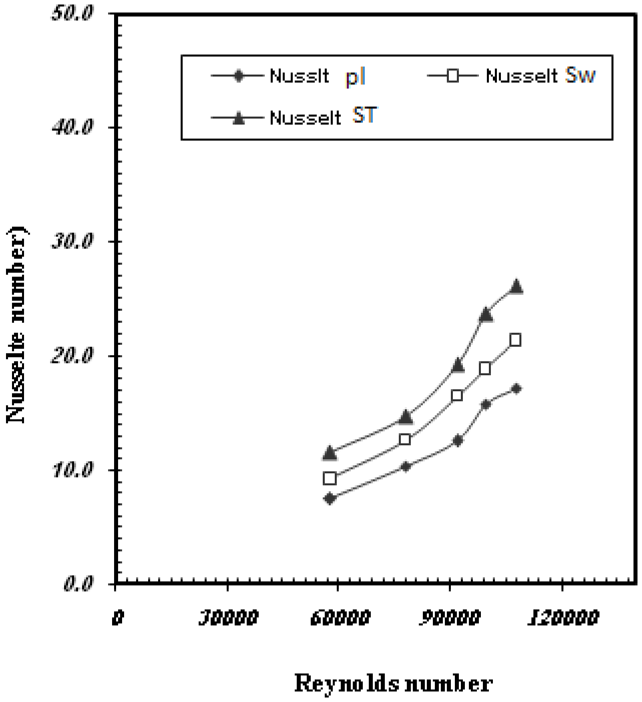

Fig. (5). Experimental comparison of Nussle number for plain surface & swirling surface and steam injection versus Reynolds number.

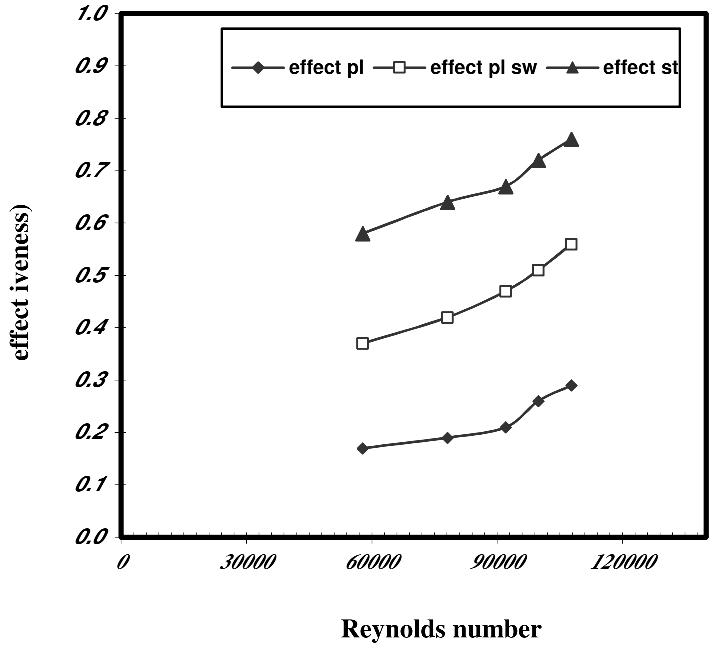

Fig. (6). Experimental comparison of furnace effectiveness for plain surface & swirling surface and steam injection versus Reynolds number.

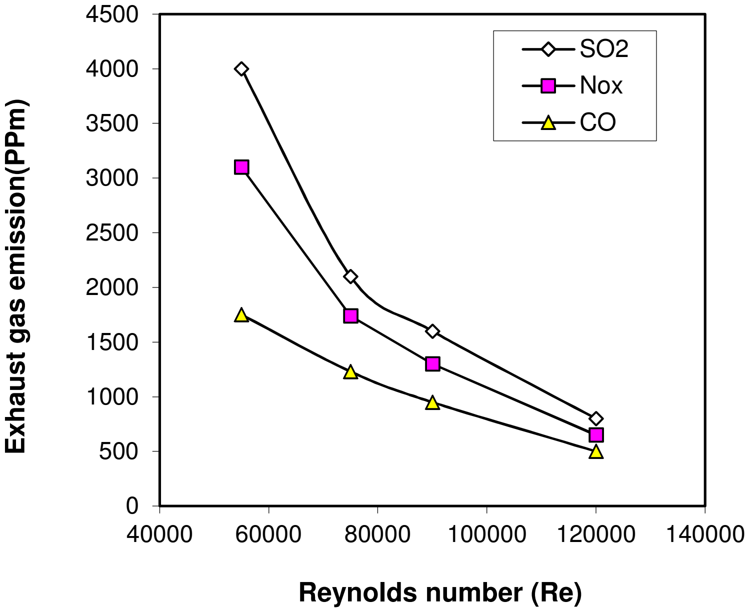

Fig. (7). Experimental variation of exhaust gases emission for swirling surface without steam injection of furnace.

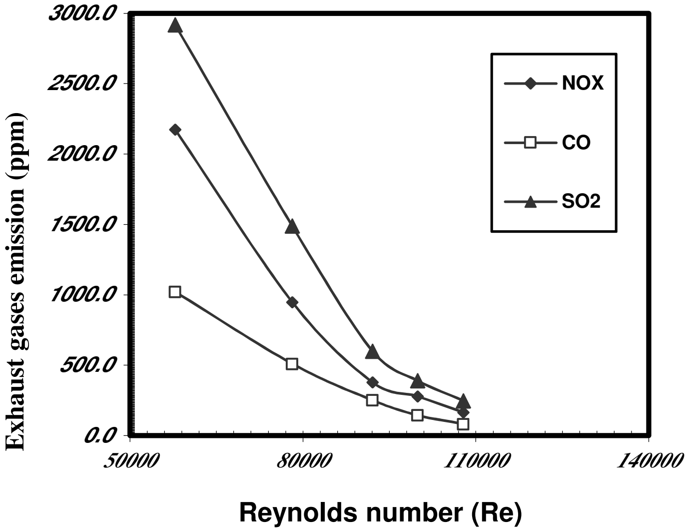

Fig. (8). Experimental variation of exhaust gases emission for swirling surface with steam injection of furnace**.**

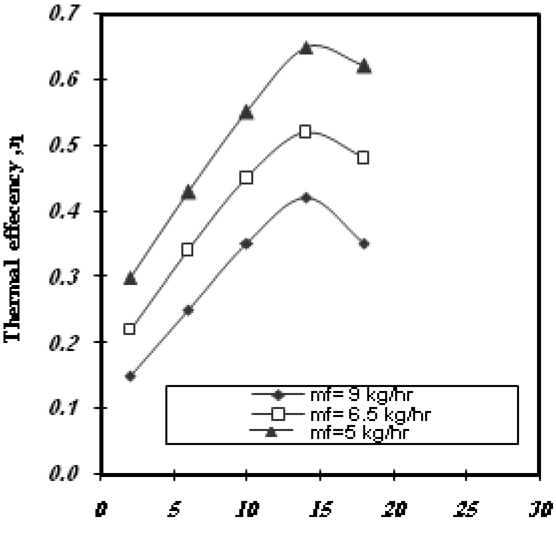

Fig. (9). Variation of thermal efficiency of the furnace versus air fuel ratio of lean combustion at various fuel consumption rate.

Table (1). Main components of the test rig.

1	LPG fuel gas bottle.	10	Two channel filter.
2	Cylinder of plan and swirl surface furnace.	11	Counter flow meter.
3	Spark ignition burner.	12	Oscilloscope.
4	Electrical blower 2.0 kW.	13	Rota meters and U tube manometer.
5	Air pressure regulator.	14	Air flexible hose.
6	Cooling water cupper tubes.	15	Desolating water tank.
7	Exhaust pipe.	16	flue gas analyzer.
8	Gas pressure regulator.	17	Thermal anemometer Testo 415.
9	LPG gas hoses.		

APPENDIX

DATA REDUCTION EQUATIONS

Heat transfer analysis through the combustion process inside a water-cooled heater involves calculation of the following parameters expressed as follows [13,15]:

Plain Surface without Steam Injection Calculations:

The pressure of airflow

$$P = \rho_a *.R.* Ta \quad (1)$$

$M_a = \rho_a * \grave{u}a *.\alpha$, $\alpha = \pi/4(d)^2$, and air/fuel ratio $(\lambda) = M_a / M_f$,

d is the diameter of air hose.

The Reynolds number:

$$Re = \frac{\rho a * \grave{u}a * d}{\mu} \quad (2)$$

The heat transfer to the water heater walls (Q_w) for plain surface is calculated by:

$$Q_w = m_w * cp_w * (T_{wi} - T_{wo}), \quad (3)$$

The heat lost in combustion gases of LPG (**Q_f**):

$$Q_f = (m_f + m_a) * cp_g *(Tgm - Tai), \qquad Tgm = (Tgo + Tgi)/2 \quad (4)$$

The thermal efficiency of furnace for plain surface $\eta = Q_w/Q_f$ (5)

The heat release rate: (HRR) = M_f * LCV / Vc (6)

Vc = $\frac{\pi}{4}(Do - Di)^2 * \mathrm{Lc}$,

where Vc is the volume of water heated, in the cylinder of water jacket, Di and Do are the inner and outer radius of water heater cylinder, Lc is the water heater cylinder length, and LCV is the lower calorific value of LPG gas fuel.

Swirling Flow of Water Heater and Swirling Surface of Combustion Flow Calculations:

The heat transfer to the water heater walls (Q_w) is calculated by:

Q_w = h *A * (T_{wall} - T_b), $T_{wall} > T_b$ (7)

T_b = [T_{wo} + T_{wi}] / 2,

where T_{wall} is the average local wall temperatures and measured at the outer wall surface of the inner tube at four points, lined between the inlet and exit of the inner tubes.

The average heat transfer coefficient is calculated from the energy balance and estimated as follows:

h = M_f *cp *(Tg- Ta) / A * (T_{wall} - T_b) (8)

The mean value of the Nussle number is calculated based on the mean wall temperature (T_{wall}) and mean water temperature (T_w mean) measured at six points on the outer

Nu = h*dh / k (9)

Where, h and k are the mean heat transfer coefficient and mean thermal conductivity of the air respectively at all thermocouple location. The local thermal conductivity k of the air is calculated from the fluid properties at the local mean bulk fluid temperature. The enhanced effectiveness (**ε**) at constant pumping power is the ratio of the convective heat transfer coefficient of the furnace with twisted tape to the plain furnace,

Vc = $(ri)^2 * \mathrm{Lc}$,

where Vc is the volume of water heated cupper tubes, and ri is the inner radius of cupper tubes,

ε = h swirl / h plain , **ε** = 0.836 Re ^0.17 Y-0.38 (10)

where Y furnace = pitch/ cylinder diameter = 0.6
Y water heater = pitch/ cylinder diameter = 0.25
Worse Pattern factor (P.F) = (Tg max. –Tg avg) / ($T_{g\ avg}$ -$T_{g\ min}$).