FLOW AND HEAT TRANSFER ANALYSIS ON SPIRAL COUNTER FLOW HEAT RECIRCULATING BURNER

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To my beloved wife, Nina and
newborn princess Miza

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ABSTRACT

In order to establish a performance characterization of spiral counter flow heat recirculating burner, an understanding of the chemical kinetics, heat transfer and flow dynamics aspects of the combustor needs to be developed. Research would be focusing on the micro-scaled square spiral counter flow configuration which is also known as the "Swiss roll" micro-combustor with propane-air mixture as the case study. A two-dimensional Computational Fluid Dynamics (CFD) with propane-air premixed stoichiometric numerical based model is being adopted and focus of the study would be in observing the thermal characteristic (i.e. heat recirculation rate) of the combustor. This is the parameter that characterizes the preheat energy obtained by the incoming reactants through combustion process and its high energy post-combustion products. The performance of the combustor with respect to the thermal characteristic is being analyzed at a range of $40<Re<1000$ steady, laminar and incompressible fluid flow velocity profile. In addition, a parametric study on identifying the effect of different geometrical aspect ratio between channel wall thickness to channel width is also being envisaged. Analysis has shown that a heat recirculation method has managed to produce an excess enthalpy flame beyond the adiabatic flame temperature which leads towards extending the limitation of the combustion process feasibility in a miniaturization of a combustor system.

ABSTRAK

Bagi mewujudkan ciri prestasi penunu aliran bertentangan yang berpusar dengan peredaran semula haba, pemahaman dari aspek kinetik kimia, pemindahan haba dan aliran dinamik pembakar perlu dibangunkan. Penyelidikan ini memberi fokus terhadap penunu aliran bertentangan yang berpusar dengan peredaran semula haba yang berbentuk segi empat dan berskala mikro yang juga dikenali sebagai pembakar berskala mikro "Swiss roll" dengan bahan bakar campuran propana-udara sebagai kes kajian. Kajian melibatkan model berangka pracampur stoikiomterik propana-udara didalam dua dimensi dengan menggunakan kaedah dinamik bendalir berkomputer (CFD) dimana fokus kajian tertumpu kepada ciri terma (kadar peredaran haba) pembakar. Parameter ini menggambarkan tenaga prapanas yang diperolehi oleh bahan bakar sebelum bertindak balas melalui proses pembakaran dimana perolehan tenaga tinggi ini berpunca daripada hasil pembakaran bahan bakar itu sendiri. Prestasi pembakar melalui ciri terma ini dianalisa pada keadaan bendalir yang tak boleh mampat, mantap dan lamina dimana profil halaju sekitar $40<Re<1000$. Selain daripada itu, kajian dalam mengenal pasti kesan perubahan geometri diantara ketebalan dinding saluran dan lebar saluran terhadap ciri terma ini turut dijalankan. Analisa telah membuktikan bahawa kaedah peredaran semula haba berjaya menghasilkan lebihan entalpi yang melebihi suhu nyala adiabatik dimana ia menjurus kepada memanjangkan had kebolehlaksanaan proses pembakaran didalam pengecilan sistem pembakar.

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LIST OF SYMBOLS/ABBREVIATIONS

A	-	Surface area
CFD	-	Computational fluid dynamics
c_p	-	Specific heat at constant pressure
$\boldsymbol{D}$	-	Binary diffusion coefficient
D	-	diameter
d	-	Channel width
EFAB	-	Electrochemical fabrication
h	-	Coefficient of thermal convection
h_f^o	-	Enthalpy of formation
i	-	Species count
k	-	Coefficient of thermal conductivity
L	-	Thickness of channel wall
l	-	Channel length
MEMS	-	Micro-electro-mechanical system
m''	-	Mass flux
m'''	-	Mass production rate per unit volume
N	-	Number of passes
p	-	Pressure
q	-	Heat transfer rate
Re	-	Reynolds number
T	-	Temperature
t	-	Time
V	-	Velocity vector
Y	-	Mass fraction of species
α	-	Thermal radiation absorptivity
ε	-	Thermal radiation emissivity

$\O$	-	Equivalence ratio
ρ	-	Density
υ	-	Kinematic viscosity

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CHAPTER 1

INTRODUCTION

1.1 Background

Evolution of micro-electro-mechanical system (MEMS) development has lead to increasing demands on the essential need to search for a micro-power generation devices that has such a high power density parameter. Battery technology currently has a limited power density to cater for enhancement of MEMS industry power requirement whereby it could be noted that an alkaline battery would only has a specific energy of 0.6 kJ/g and lithium ion battery has an energy storage density of around 1.2 kJ/g [1].

Understanding on this limitation has motivated research activities to look for an micro-scale combustion-based power generation device which is understood that hydrocarbon fuels has a high energy storage capacity that is typically in the range of 45 kJ/g [2]. That is why most vehicles such as automobiles, aircraft and even rocket are relying on the combustion process to propel. Thus, taking the micro-combustor as the alternative solution would lead to a longer operating time of the MEMS devices or a lighter system with the same amount of power capability from those battery solutions. In addition, since it is a refueling based system, a waste disposal will not be an issue [3].

Based on conventional combustion theory, there is a major limitation with regards to the geometrical miniaturization allowable factor namely the quenching distance. This is due to the fact that flames will extinguish upon entering a narrow passageway. In addition, with such miniaturization process, it would lead to a high ratio of surface area to volume. Such a ratio value would prone for a significant heat-loss behavior of the combustor that leads to affect the combustion stability parameter such as the flammability limits or also known as extinction limit and the reaction rate (i.e. ignition energy and time) for self-sustained combustion or decreases the combustion efficiency itself.

In lieu with the limitation imposed by the combustion theory with respect to the micro-scale combustor system, a heat recirculation mechanism is adopted as to effectively recirculate the thermal energy from such a high temperature burnt gas (exhaust heat) to the low temperature fresh fuel-air mixture which substantially extend the extinction limit of the hydrocarbons[3]. It is understood that combustion process would experience a finite heat loss that leads of not be able to achieve an adiabatic flame temperature that governs the limitation on the combustion process feasibility. Transferring the exhaust heat from the combustion product would increase the reactants total enthalpy which leads to achieving excess enthalpy flame that is beyond the adiabatic flame temperature. This excess enthalpy flame would then extend the limitation on the flammability limit of the hydrocarbon reactants.

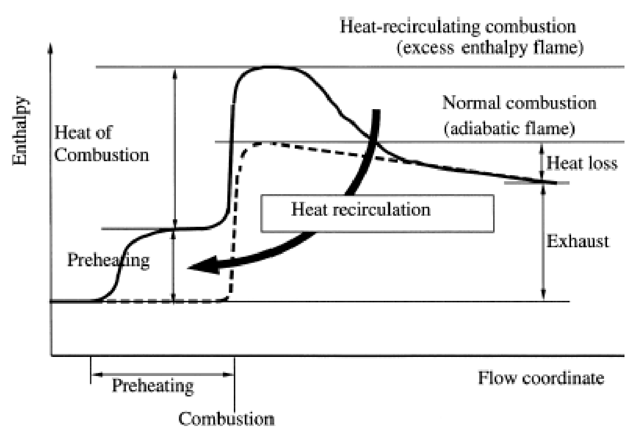

Figure 1.1 Concept of heat recirculation

With the energy optimization strategy is in place, a limitation on the quenching distance has been put up to the test beyond the conventional limit where it is known that quenching distance need to be at least larger than an adiabatic flame thickness which is then dependent on the combustion reaction process. This combustion reaction process in turn has a dependency on the thermal condition of the chamber. Thus, a heat recirculation has substantial benefit of allowing a combustion process to exist at a very low thermal power to attain similar combustion process performance with the non-preheated reactants or better reaction process at similar thermal ignition condition alternately [5].

Looking from a compact and effective heat exchanger design perspective, a spiral, "Swiss roll" with counter flow heat recirculation configuration has been taken by most researchers as the selected configuration to be implemented as the micro-combustor whereby this set of heat exchanger would ensure the post-combustion heated energy is transmitted to the very beginning of the reactants flow passage.

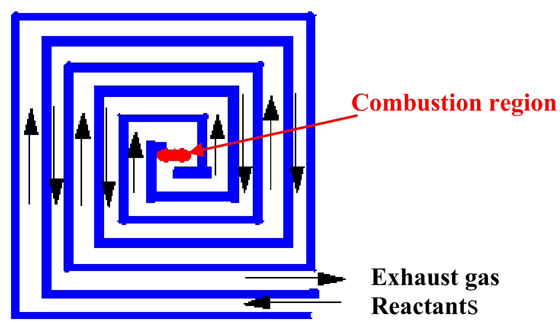

Figure 1.2 "Swiss roll" configuration

1.2 Scope of the Study

In characterizing the optimal design performance of a spiral counter flow heat recirculating burner, there are three (3) major perspectives that need to be accounted which are the chemical kinetics, the heat transfer and the flow dynamics. Based on the past studies on "Swiss roll" configuration, a lot of effort has focused on analyzing the chemical kinetics and associated heat transfer aspect of it. However, none has indulged in terms of characterizing the thermal performance by observing the heat recirculating effectiveness which leads to broaden the range of quenching distance and equivalence ratio spectrum limit as reported from past studies. Below is the conventional limitation on the propane chemical kinetics properties without any pre-heating treatment:

Table 1.1 : Propane limiting combustible properties

	Flammability Limits			Quenching Distance (mm)	
Fuel	**Lean Limit (Ø min)**	**Rich Limit (Ø max)**	**Stoichiometric Mass Air-Fuel Ratio**	**For Ø=1**	**Absolute Minimum**
Propane (C_3H_8)	0.51	2.83	15.6	2	1.8

The principle objective of the research is to study the relationship between geometry and performance of spiral counter flow heat recirculating burner. As heat recirculation is the main driver that established such "excess enthalpy" state to the incoming reactants, it is the author's motivation to study this parameter and adopt it as the performance measurement by following an approach adopted by Shinoda *et al.* [4] in characterizing the heat-recirculating ceramic burner . Thus, a *fractional heat recirculation rate* is taken as the criteria that define the thermal performance of the "Swiss roll" combustor that is being analyzed within the study rather than temperature profile due to its non-representative in characterizing the heat recirculation index [4]. Only one type of fuel being considered that is a propane-air premixed mixture as to have means of validating the results with respect to the experimental work done by Ahn et al [5]. This parameter is studied with respect to different steady, laminar, incompressible fluid flow profile with geometrical manipulation of the aspect ratio between wall thickness to the channel width and to observe the extent of number of spiral loop limitation for effective heat recirculation towards the incoming reactants. In addition, the study is limited to 2-D computational approach with conduction, convection and radiation of heat transfer modes are being considered. Having to understand the heat recirculation profile with respect to different geometrical configuration (i.e. number of spiral loops and aspect ratio) with different fluid flow properties would establish a platform that leads towards design optimization of the combustor for future development.

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