EFFECTS OF SCALE ON SWISS-ROLL HEAT-RECIRCULATING COMBUSTORS

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Abstract: A numerical study of the effects of length scale on Swiss-roll heat-recirculating combustor was conducted. Geometrically identical but different sizes 3D Swiss-roll combustors were simulated via FLUENT. It was found at low Reynolds number (Re), smaller-scale combustors actually showed better performance (in terms of having lower lean extinction limits at the same Re) due to less heat loss and internal wall-to-wall radiation effects, whereas at high Re, larger-scale combustors showed better performance due to longer residence time. When the flow rate was too low (low Re), a negative effect of the Number of Transfer Units (NTU) of spiral heat exchangers described by Strenger et al. (1990) also affected the performance. These results provide insight into the design of the small scale combustors and the optimal choice of their operation condition.

Keywords: heat-recirculating combustor, Swiss-roll combustor, micro combustion

INTRODUCTION

Hydrocarbon fuels contain about 50 times more energy density per unit mass than the state-of-art batteries. Therefore, many researchers have tried to extend the use of hydrocarbon fuel in electrical power generation from large scale (in terms of volume and power range) to smaller scale where the conventional methods, such as internal combustion engine, are not applicable due to heat and friction losses. To overcome these issues, many groups have tried to use heat-recirculating combustors, which are able to recycle some of the thermal energy to the reactants via a heat exchanger to minimize the impact of heat loss, and then use thermoelectric material to convert thermal energy to electricity without moving parts. Among different heat-recirculating combustors, the Swiss-roll combustor [1, 2], which recirculates the heat via a spiral counter-flow heat exchanger, is considered very thermally efficient due to the large ratio of heat exchange to heat loss area. However, due to complexity of the interaction between heat transfer and chemical reaction, how to design the combustor especially for small scale application is not straightforward. Therefore, to properly apply Swiss-roll combustors, it is necessary to obtain further understanding of its performance at different scales.

Due to the difficulties of manufacturing device of different sizes that are otherwise identical, a numerical model becomes a convenient and powerful tool to evaluate performance before physical devices are built. In addition, simulation can be employed to identify the appropriate dimensionless parameters. In this work, a 3D numerical model of Swiss-roll combustor developed by Chen and Ronney (2011) was applied to perform the scale analysis and identify dimensionless parameters that affect the performance for different scale combustors.

NUMERICAL MODEL

Three different scales (full: 5 cm tall, 3.5 mm channel width; half: 2.5 cm tall, 1.75 mm channel width; double: 10 cm tall, 7 mm channel width) but geometrically identical 3D numerical models of 3.5 turn Swiss-roll combustors were constructed using FLUENT (Figure 1). The computational domain includes the gaseous reactants and products, solid combustor walls and insulation. A coupled convective (U_E = 10 W/m^2-K) and radiative (ε = 0.8 and 1 for wall and insulation separately) boundary condition was used to describe the external heat loss. The Reynolds Stress Model (RSM) was applied to simulate the turbulence effects on heat transfer. 1-step finite rate chemistry (for propane-air mixtures) with activation energy 40 kcale/mole and pre-exponential term 9×10^9 in m-sec-kmole units (calibrated by experiment at one point (Re ~ 1000)) was used to describe the chemical reaction. Details of the model and the validation with experiments can be found in [6].

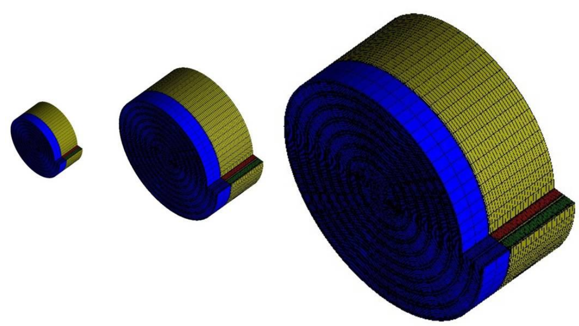

Fig. 1: Three different scale but geometrically identical 3.5-turn 3D numerical models of Swiss-roll combustors (Half, Full, and Double).

EFFECTS OF SCALE

The performance (in terms of the lean extinction limits represented by equivalence ratio) of heat-recirculating combustor is largely determined by the amount of "excess enthalpy" obtained by the reactants. This amount is determined by the performance of the heat exchanger and usually characterized by the Number of Transfer Units ($NTU = UA / \dot{m}C_p$). However, in heat-recirculating combustors, Re is used more often since it characterizes the flow field as well as the Nusselt number (Nu) in incompressible flow system, and also, it is more straightforward in terms of flow rate and thermal power output. In addition, at laminar flow region, since Nu ~ Re^0, NTU ~ (L/w) * Re^{-1}, while at turbulence flow region, Nu ~ $Re^{0.8}$, NTU ~ (L/w) * $Re^{-0.2}$, and therefore, similar geometry heat exchangers (with the same L/w) have the same NTU at the same Re.

Figure 2 shows the predicted extinction limit curves for the three different-scale combustors. At the same Re, their performance is not identical even though they have the same NTU as already mentioned. At lower Re, smaller-scale combustors showed better performance (lower lean extinction limits), whereas at higher Re, larger-scale combustors showed better performance. This result implies that Re (or NTU) is not the only dimensionless group that characterizes the performance of heat-recirculating combustors (with similar geometry), and there are some scale-dependent parameters that cause the difference at different Re.

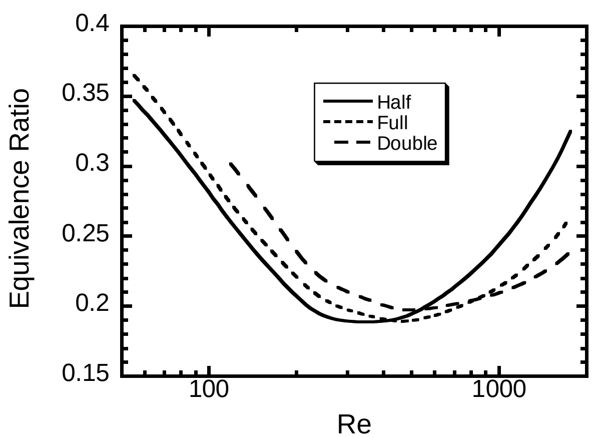

Fig. 2: The extinction limits of three different scale Swiss-roll combustors.

To identify the additional parameters affecting extinction limits, first we focus on the lower Re. Previous studies [4, 5] showed that heat loss and internal wall-to-wall radiation effects significantly affect the extinction limits in this region. The effect of heat loss can be characterized by a dimensionless heat loss coefficient (α), which is the ratio of heat transfer coefficient to environment (U_E, a combination of nature convection and radiation) to heat transfer coefficient inside the channels (U_C). Since U_C (~ k/w) is inversely proportional to length scale, but U_E is independent to length scale [7], different-scale combustors have different α, specifically $\alpha_{Double} : \alpha_{Full} : \alpha_{Half} = 4 : 2 : 1$. Therefore, smaller-scale combustors are subject to less heat loss effects due to smaller α.

For the effect of wall-to-wall radiation, the radiation heat transfer between walls can be estimated by using the infinite parallel walls assumption [8] as $\frac{\varepsilon_i}{2-\varepsilon_i}\sigma A(T_{w1}^4 - T_{w2}^4)$. Thus another dimensionless group, namely the internal radiation coefficient R, can be defined as the ratio of heat transfer coefficient of internal wall-to-wall radiation ($U_R = \frac{\varepsilon_i}{2-\varepsilon_i}\sigma(T_{w1}^2 + T_{w2}^2)(T_{w1} + T_{w2})$) to the convective heat transfer coefficient (U_C). Since again U_C is inversely proportional to length scale but U_R is independent to length scale, different-scale combustors have different R, according to $R_{Double} : R_{Full} : R_{Half} = 4 : 2 : 1$. Smaller scale combustors are thus subject to less wall-to-wall radiation effect due to smaller R. Consequently, the relative values of α and R show that smaller-scale combustors will exhibit better performance at low Re.

On the other hand, at high Re, the extinction limits are caused by insufficient residence time [5]. The Damkohler number (Da), which is the ratio of residence time to reaction time, is used to characterize the time scale. If the residence time is assumed by dividing the diameter of the center combustion chamber by the input flow speed, at the same Re, $Da_{Double} : Da_{Full} : Da_{Half} = 16 : 4 : 1$. Thus, larger-scale combustors have larger Da (more residence time) resulting in better performance at high Re.

Table 1: Adjusted values of heat transfer coefficient and emissivity to environment for different scale combustors (bold fonts are the original values) to obtain constant α.

	Half	Full	Double
H_L (W/m^2-K)	**10**	5	2.5
ε (wall)	**0.8**	0.4	0.2
ε (insulation)	**1**	0.5	0.25

Table 2: Adjusted values of internal wall emissivity for different scale combustors (bold font is the original value) to obtain constant R. Note that the wall-to-wall radiation = $\frac{\varepsilon_i}{2-\varepsilon_i}\sigma(T_{w1}^4 - T_{w2}^4)$.

	Half	Full	Double
ε_i	**0.8**	0.5	0.2857

Table 3: Adjusted values of pre-exponential term for different scale combustors (bold font is the original values) to obtain constant Da.

	Half	Full	**Double**
A_P (m-sec-kmole)	1.44E+11	3.6E+10	**9E+9**

If the aforementioned dimensionless groups (α, R, and Da) are sufficient to characterize the performance of Swiss-roll combustors, similar extinction limits should be obtained if these dimensionless groups are the same. While this is difficult to verify via experiments, it can be examined easily via simulation since the material properties can be adjusted artificially. Table 1 to 3 show the adjusted values of the material properties based on the change of length scale so that the three dimensionless groups are the same for different-scale combustors.

The result after the adjusted parameters is shown in figure 3. The extinction limits of the three different scale combustors collapse to a single. This demonstrates that these three dimensionless groups plus Re (or NTU) are sufficient to characterize the performance of different-scale heat-recirculating combustors with similar geometry. Consequently, the lean extinction limits of heat-recirculating combustors with similar geometry are the function of these four dimensionless groups (Φ_{Limits} = f(Re, α, R, Da)). A small discrepancy can be observed at lower end of Re, this may be caused by another dimensionless group, the Biot number (Bi) [5]. Since the wall stream-wise conduction heat loss is relatively small for range of Re studied in this work, this dimensionless groups are not discussed in this work. It must be emphasized that the parameter values listed in table 1 to 3 were adjusted based on the scaling consideration and were not re-adjusted in an empirical fashion to obtain the favorable results shown in figure 3.

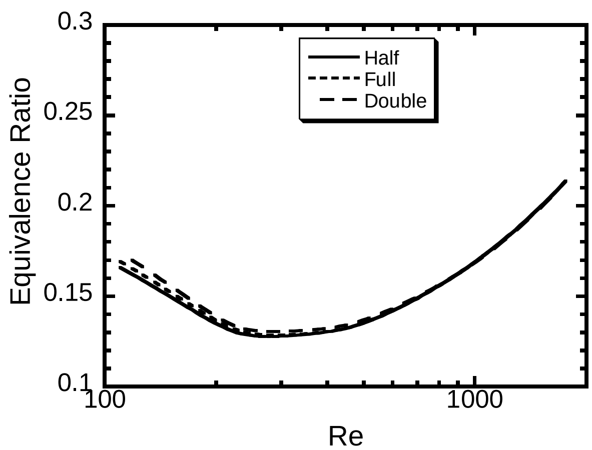

Fig. 3: The extinction limits of three different scale Swiss-roll combustors with constant α, R, and Da.

NEGATIVE EFFECT OF NTU

A special property of spiral heat exchanger pointed out by Strenger et al (1990) is the negative effect of NTU on exchanger performance at large NTU under some circumstances. For conventional counter-flow heat exchanger, if there is no heat loss, a large NTU will always result in better performance. However, for spiral heat exchangers, even without any heat loss to the environment, at small flow rates, increasing NTU via decreasing flow rate may hurt the performance due to "internal heat loss" of the reactants. Figure 4 shows a schematic drawing to explain this phenomenon. When the flow rate and thus the amount of thermal enthalpy input is too small, the inner reactant channels will be hotter than adjacent outer product channels, and the heat will transfer from the reactants to the products in outer channel resulting a decrease on excess enthalpy obtained by the reactants. When this happens, reducing flow rate (increasing NTU) will result more internal heat loss from the reactants, and therefore, the NTU has a negative effect on the performance.

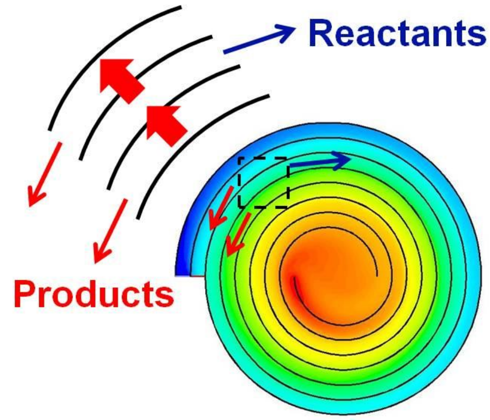

Fig. 4: Schematic diagram to show the heat loss from reactants to outer adjacent products.

Since the performance of Swiss-roll combustor at low Re is dominated by the amount of excess enthalpy, which is determined by the performance of the heat exchanger, this negative effect of NTU effect may cause higher lean extinction limits as Re decreases, even without any heat loss present. To illustrate this point, a 2D simulation without any heat loss to environment, no stream-wise wall conduction (but with radial wise wall conduction to provide heat exchange), and no wall-to-wall radiation heat transfer was built. Figure 5 shows the extinction limits with and without these effects included. When heat loss and stream-wise wall conduction is present, more fuel is required to sustain the reaction as Re decreases (NTU increases) due to the increasing of heat loss effect. However, for the case without any heat loss, the extinction limits also showed a rising trend as Re decreases, which must be caused by the negative effect of NTU.

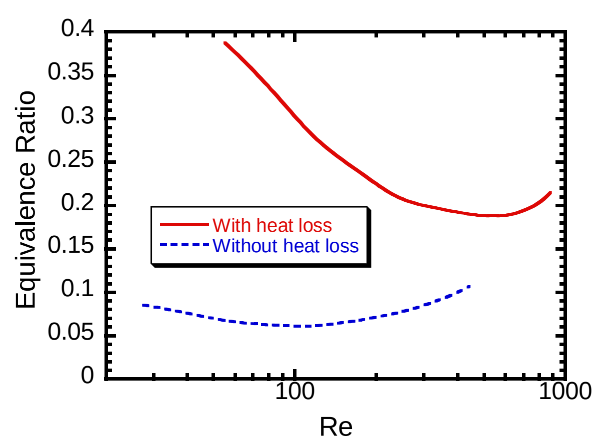

Fig. 5: Simulation results of the extinction limits with and without heat loss at low Re.

CONCLUSION

The extinction limits of heat-recirculating combustors are affected by both the performance of the heat exchanger and the chemical reaction properties. At low Re, smaller-scale combustors show better performance due to a lesser impact of heat loss and wall-to-wall radiation effects resulting more excess enthalpy transferred from the products to reactants. On the other hand at high Re extinction is due to insufficient residence time, thus larger-scale combustors, having longer residence times for the same Re, exhibit better performance.

Though the dual-limit behavior leads to some challenges in determining the extinction limits of heat-recirculating combustors, four dimensionless groups: Re (or NTU), α, R, and Da were found sufficient to characterize their performance. This means of characterization can be used to extrapolate the performance from relatively large laboratory-scale for predicting the behavior of devices for small-scale applications.

A negative effect of NTU in spiral heat exchangers compared to linear exchangers, already known in the heat exchanger literature, was found to affect the performance of Swiss-roll combustors even in the absence of heat losses. This finding suggests that increasing NTU by decreasing flow rate (thus Re) may actually be detrimental to combustor performance.

NOMENCLATURE

A	=	Heat transfer area
A_P	=	Activation energy
α	=	Heat loss coefficient
Bi	=	Biot number
C_p	=	Heat capacity
Da	=	Damkohler number
Φ	=	Equivalence ratio
k	=	Thermal conductivity
L	=	Channel length
ε	=	Emissivity
$\dot{m}$	=	Mass flow rate
NTU	=	Number of Transfer Units
Nu	=	Nusselt number
R	=	Internal radiation coefficient
Re	=	Reynolds number
σ	=	Stefan-Boltzmann constant
T	=	Temperature
U	=	Heat transfer coefficient
w	=	Channel width

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