NUMERICAL AND EXPERIMENTAL STUDY IN SWISS ROLL HEAT-RECIRCULATING BURNER

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Abstract: Swiss roll (or double spiral) burner has been proved as the simplest and most thermal efficient geometry among different heat recirculating burners, and thus it is a considerable candidate as a thermal management device for micro power generation applications. From numerical work, it is found the 3rd dimensional heat loss (toward top and bottom of the burner, Q_L) and wall to wall radiative heat transfer (Q_R) play important roles in lower Reynolds number condition. The numerical model is built by Fluent, with detail conductive and convective equations, temperature dependent solid and fluid properties, and radiation effects. The reaction part is treated as global finite rate reaction mechanism (propane-air 1 step chemistry). The comparison of extinction limit and temperature distributions between numerical model and experimental data shows good agreement with each other. The effect of Q_L is studied experimentally by comparing different thicknesses of insulations. To verify the effect of Q_R, temperature distributions of a titanium burner coated with gold are compared with a bare titanium wall burner.

Keywords: Swiss roll burner, numerical modeling, thermal management, micro combustion

INTRODUCTION

For most of micro power generation methods, a thermal management device is indispensable. It can either provide the working temperature for the energy transducer (such as fuel cell) or supply the thermal power directly to the energy transducer (such as thermal electrical material). Among all the heat sources, combustion is the easiest way to produce heat. However, due to the small size nature of the micro power generation systems, heat loss and maintenance of reaction become major issues in having combustion.

A special burner called Swiss roll heat-recirculating burner (Fig. 1) is a considerable candidate in this application. It basically combines a double spiral heat exchanger, which exchanges the heat from hot product to cold reactant, and a combustion chamber, where the "excess enthalpy" reactant is burned. With the heat recirculated to the reactant, the combustion can sustain in much leaner (or richer) condition than conventional flame. Also, the heat loss is minimized by recirculating the heat, which diffuses from the hottest location of the burner, back to the reaction zone. Consequently, this burner probably is the most thermal efficiently thermal management device in small size application.

Since this burner combines the characteristics of both heat exchanger and combustion chamber, simple theoretical analysis sometimes is hard to cover every aspect (such as radiation, effect of flow field, and etc) and give us quantitatively results. Thus, a 3D numerical model of Swiss roll burner is built to help us understand this non-adiabatic reacting flow system.

According to numerical model, it is found the 3rd dimensional heat loss (Q_L) and wall to wall radiative heat transfer (Q_R) play important roles especially in lower Reynolds number (Re) region. In higher Re region, a centrifugal force induced secondary flow enhances the heat transfer and thus extends the lean extinction limit. Since the lower Re region is more important in micro power generation, here will only focus on the lower Re region. Experiment of different thickness of top and bottom insulations is studied to confirm the effect of Q_L experimentally. Also, temperature distributions of a Titanium burner is compared with a similar burner coated with gold to verify the Q_R effect.

Fig. 1: *An open-top Swiss roll heat-recirculating burner.*

NUMERICAL MODELING

A 3D numerical model of Swiss roll burner with the same size of experiment is built by Fluent package. To save computational time, only half of the burner is included in the computational domain. The mesh geometry file is created in 2D surface of the middle of the burner first by combining several concentric half circles together, and then extruded toward 3rd dimensional direction. The same amount of mesh is distributed on each half circle. In this way, the center domain, where reaction happens at extinction limit, has finest grid size in stream wise direction. And the outer channels have larger grid size which reduces the total amount of grids and thus the computational time can be saved. Figure 2 shows the mesh file.

The model includes temperature dependent fluid and solid properties, radiation effect (Discrete Ordinate model), turbulence effect (Reynolds Stress Model, with low Reynolds number wall treatment). The reaction zone is treated as 1 step finite rate chemistry with pre-exponential term calibrated by experimental data. For the peripheral walls, a heat transfer coefficient 10 W / K-m^2 is used to calculate the convective heat loss. The emissivity of ceramic insulation and metal walls are 1 and 0.8 separately to calculate the radiative heat loss to the environment as well as wall to wall radiative heat transfer.

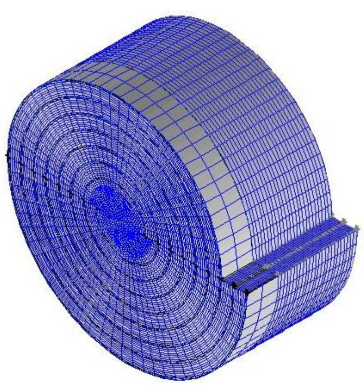

Fig. 2: *The mesh file of 3D Numerical model of Swiss roll burner.*

The result of the numerical model shows good agreement with experimental data of lean extinction limit (Fig. 3). The X axis here is Re defined by channel width and the viscosity in room temperature. It basically means the flow rate of the reactant.

To verify whether the heat transfer effect is properly simulated, 7 thermocouples are installed in different channels (Fig. 4) to monitor their temperature. Figure 5 shows the temperature distribution data of outer thermocouples (T3 to T7) of numerical model match well with experimental data, but T1 and T2 (not shown here) are not consistent with experimental data. This is probably because the over simplified 1- step chemistry used in the model.

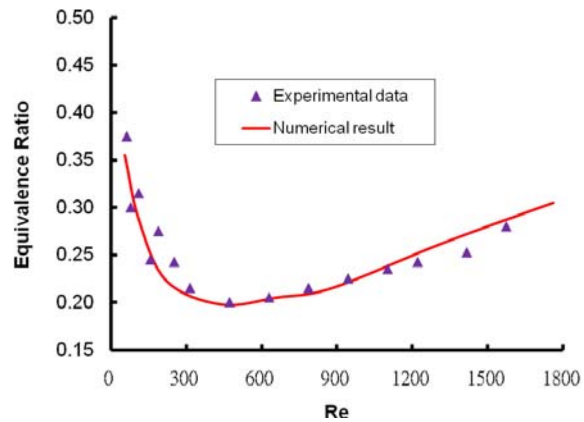

Fig. 3: *Compare extinction limit between numerical data and experimental result.*

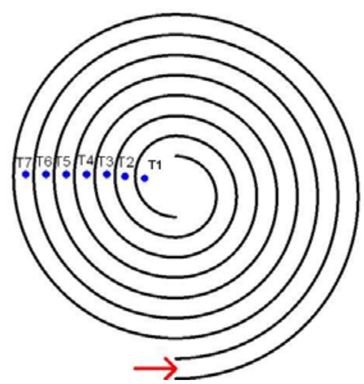

Fig. 4: *The location of thermocouples in the Swiss roll burner.*

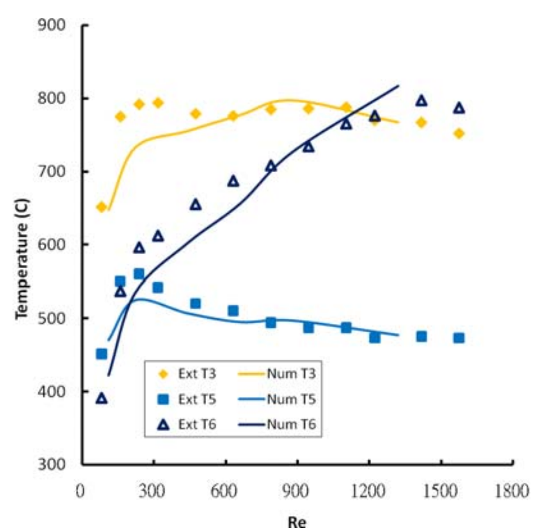

Fig. 5: *Compare numerical temperature distribution data with experimental results.*

Figure 6 shows the ratio of Q_L to total heat release of chemical enthalpy (Q_C). The Q_L in the lower Re is about 40 % of total heat release. As Re increases, the ratio of Q_L to Q_C becomes less and less. However, since in micro power generation system, the lower Re region is relative important, an experiment of different insulation thickness is performed to confirm this effect and it is discussed in next section.

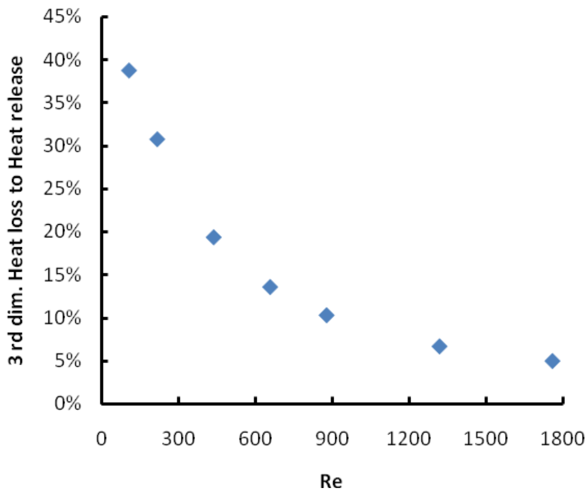

Fig. 6: *The ratio of 3rd dimensional heat loss to heat release vs. Re.*

From numerical model, we can find the effect of wall to wall radiation is actually significant (Fig. 7). The radiative heat transfer is proportional to temperature to the 4th power. Due to the channel walls are hot, 40 ~ 60 % of heat removed from walls is through radiation.

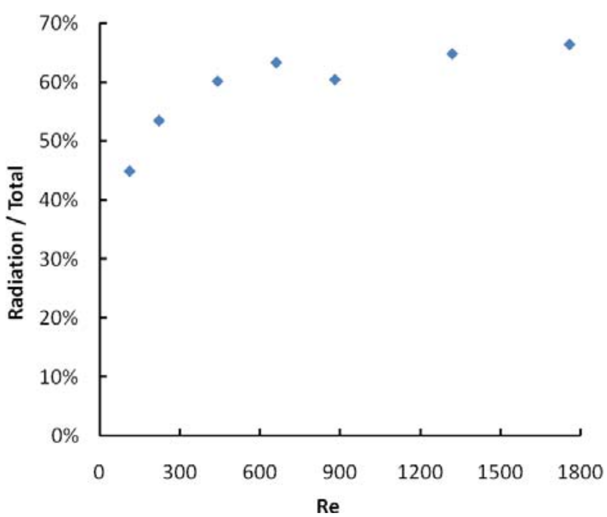

Fig. 7: *The ratio of wall to wall radiative heat transfer to total heat transfer (convective + radiative) from the walls.*

By comparing with 2D Swiss roll burner model from [4], it is found traditional 1 dimensional thermal resistance analysis in the channel flow is not suitable here because of relative fast wall thermal conductivity causing the heat spreads throughout the whole channel height during the heat exchange process. The thermal resistance of 3rd dimensional direction in the channel should be neglected. With modified 3rd dimensional heat loss assumption, a 2D model can replace the 3D model (at least in lower Re region where the flow is very laminar) and save a lot of computational time.

EXPERIMENTAL TEST

From numerical work, it is found the 3rd dimensional heat loss may affect the performance (in terms of lean extinction limit) of Swiss roll burner. To confirm this effect, two different thicknesses of insulations, 0.5 cm and 3 cm, are applied on the same burner separately. Figure 8 shows the result of the effect of different thicknesses insulation on lean extinction limit. However, reducing Q_L can only makes the burner reach to its minimum lean extinction limit at lower Re, but it cannot extend minimum lean extinction limit of the specific burner. To lower minimum lean extinction limit, we should enhance the heat transfer efficiency by increasing the heat transfer area which is not discussed here.

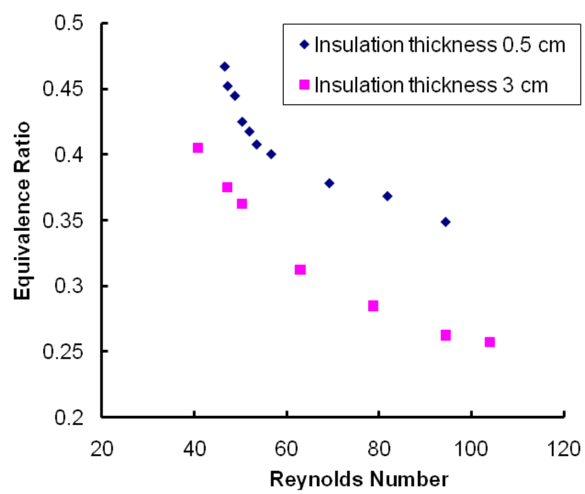

Fig. 8: *Comparison of extinction limits between 0.5 cm and 3 cm thickness insulations.*

The numerical model also shows that the Q_R is around 40 ~ 60 % of total heat transfer from the walls. This radiative heat transfer is actually not good for heat recirculation since the emissivity of gas is very low and thus it is hard to receive this part of heat. Thus, Q_R is actually a loss which provides a channel to loss heat from center hot reaction zone.

To verify the effect of Q_R experimentally, the temperature distributions of a titanium burner coated with gold is compared with a bare titanium burner. The preliminary experiment is conducted by using electrical heating wire as a heat source instead of combustion flame to avoid the hot flame temperature damaging the gold coated walls. The amount of electrical power used here is 40 W which is about 2.2 % propane at Re = 39. Figure 9 shows the comparison of the temperature distributions of the two burners with 40 W thermal power and Re = 47 condition.

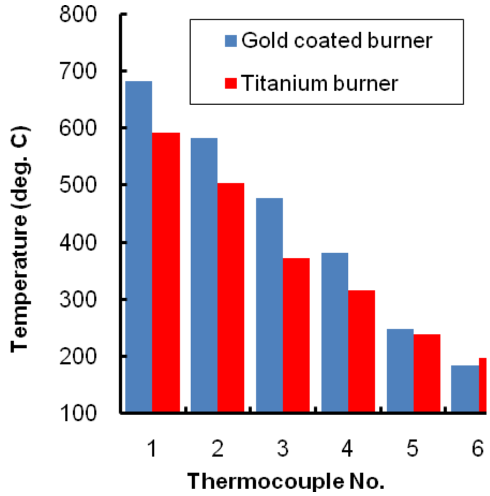

Fig. 9: *Temperature distribution of burner coated with gold and bare titanium wall. The heat source used here is electrical heating wire with 40W power consumption and Re is 47 for both cases.*

CONCLUSION

A 3D numerical model of Swiss roll burner is successfully built and matched well with experimental results. The numerical model can also give us several quantitative data which is difficult to obtain from experimental methods or theoretical analysis. This data can help us further improve the design of the burner.

The effect of 3^{rd} dimensional heat loss on the extinction limit is confirmed both numerically and experimentally. It is shown that reducing 3^{rd} dimensional heat loss can make the burner reach to its minimum lean extinction limit in much lower Re, which means less fuel is needed to provide the necessary thermal power or working temperature.

Preliminary experiment about wall to wall radiation effect shows reducing emissivity will increases the temperature at each channels. However, since the amount of thermal power used here is small, the difference is not significant.

The minimum Re number of gas phase combustion sustained in Swiss roll burner is limited due to the nature of high activation energy and flame propagation. If the upstream velocity is too slow, flame will shoot out easily since stronger mixture is needed to sustain the reaction in the lower Re and thus causes faster flame speed than upstream velocity. Putting catalyst in the center to lower activation energy and also change the reaction type to surface reaction can significantly reduce the minimum Re. This part is discussed on [3].

For the future work, it is possible to combine Swiss roll numerical model with simulation of energy transducers and help us design better performance of micro power generation systems.

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