A numerical study of propane-air combustion in meso-scale tube combustors with concentric rings

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Abstract

Dwindling energy resources and strong demand for better power sources as compared to conventional batteries have sparked research interest in micro power generation. The invention of state-of-the-art electronic devices requires more energy capacity, shorter charging period and light in weight, characteristics of which batteries lack. Therefore, in recent years micro power generation systems have been seen as a potential alternative to batteries owing to the obvious advantages that it has. It is essential to fully understand the underlying factors that affect the combustion stability in meso and micro-scale combustors. One of the popular methods to examine these factors is by performing numerical simulations. This paper demonstrates an axisymmetric two-dimensional steady state numerical simulation of propane-air combustion in meso-scale cylindrical tube combustors with concentric rings. The inner diameter of the tube is set to 3.5 mm and the wall thickness is specified to 0.7 mm. The concentric rings are placed between the unburned and burned gas region. The main function of these rings is to act as a flame holder where a stable flame can be easily established. The wall thermal conductivity in the unburned and burned gas region is varied from 1 W/m/K to 1000 W/m/K and the results in terms of gas, inner wall, outer wall surface temperature distribution, the blowout limits and combustion efficiency are analyzed and presented. In addition, the effect of the inlet velocity and the equivalence ratio is also investigated. The results show that the inlet velocity and equivalence ratio have significant impacts on the flame temperature, which in turn change the wall temperature distribution. Although the wall thermal conductivity has minimal effect on the flame temperature, both inner and outer wall surface temperature are greatly affected. Consequently, this variation of wall temperature contributes to the significant changes on the blowout limits. It is also shown that the combustion efficiency is influenced by the wall thermal conductivity of the combustors.

Key words: Micro power generation, Micro and meso-scale combustors, Numerical simulations, Blowout limits

1. Introduction

Meso and micro-scale combustion phenomena are the key components in micro power generation. An experimental study has shown that flame stabilization in a confined space or a narrow channel is achievable (Miesse, et al., 2004). However, the difficulty of sustaining a stable flame for a micro combustor due to its high surface to volume ratio is a major issue in micro combustion (Suenaga, et al., 2011; Maruta, 2011). This high ratio causes a large portion of heat loss from the flame to the wall, which leads to thermal quenching (Kaisare, et al., 2012). In recent years, numerical simulations have been utilized as prominent methods to study the combustion feasibility in meso and micro-scale channels. By performing the verification, any newly designed of micro combustors can be thoroughly studied and optimized (Kurdyumov, et al., 2009).

As early as in 2000s, Computational Fluid Dynamics (CFD) has been utilized to numerically investigate the flame propagation in micro-burners. Raimondeau et al. (2002) demonstrated methane (CH_4) combustion in a two-dimensional tubular micro combustor, which was modeled using a detailed multi-component transport and gas chemistry. The results show that the effect of reactants pre-heating and insulations allows the flame to propagate even in micro channels. Furthermore, initial heat losses and wall radical quenching are the main parameters that determine the flame propagation in such micro burners.

In order to provide a better understanding to the underlying fundamentals of the combustion of gaseous hydrocarbon fuels like propane (C_3H_8) and methane (CH_4) in micro-burners, numerical simulations using commercial software were conducted. For instance, FLUENT software has been used to investigate the effect of wall conductivity, burner dimensions and external heat losses on combustion characteristics in meso-scale burners, which modeled as two parallel plates (Norton and Vlachos, 2003, 2004). In their work, combustion chemistry with one-step irreversible reaction mechanism was employed. This chemistry is deemed sufficient to demonstrate flame dynamics behavior. It was highlighted that propane-air micro-flames are more stable than methane-air flames. The lower ignition temperature of propane fuel contributes to this flame stability enhancement. A similar reaction mechanism is used by Feng et al. (2010) to numerically solve methane-air combustion in a circular tube combustor. Factors affecting the flame temperature like the combustor size, inlet velocity and equivalence ratio were studied. Their results indicate that the equivalence ratio of the mixture and the burner dimension can be considered as important parameters to the flame temperature. Next, Li et al. (2009) presented their findings on methane-air combustion using detailed combustion chemistry with 25-reversible reaction mechanism in two-dimensional (2-D) cylindrical tubes and parallel plates. The partial oxidation that involves in the reaction process can be well represented by the detailed mechanism. Their studies show that proper material selections can be performed if the flame temperature in the combustor is known.

Apart from hydrocarbon fuels, the prediction of premixed flame temperature and flame dynamics in a narrow cylindrical tube with hydrogen as a fuel has been reported by several researchers (Brambilla, et al., 2013; Jejurkar and Mishra, 2011). The effects of various heat transfer conditions on hydrogen combustion have been well discussed by Hua et al. (2005). A detailed reaction mechanism with 19-reversible reaction mechanism was employed to study the combustion stability with and without the presence of wall conduction. Their studies suggest that lower wall thermal conductivity can reduce the heat loss, which results to the enhancement of combustion stability. Nevertheless, the low wall thermal conductivity is likely to cause hot spot on the combustor wall that can decrease the material lifespan.

Numerical simulation was also performed on a more complex combustor geometry like Swiss-roll combustor in order to reduce the occurrence of extinction. Chen and Buckmaster (2004) demonstrated the combustion of the premixed fuel-lean propane-air mixture in a Swiss-roll combustor. The idea of using a flame holder in meso-scale cylindrical tube combustors was first proposed by Mikami et al. (2013). In their experimental work, a stainless steel wire mesh is placed between the burned and unburned gas region. The experimental results show that the flame can be stabilized for both gas and liquid fuel. In fact, it is also demonstrated that flame could be even stabilized in a tube with a diameter below than the classical quenching distance.

In this study, a numerical simulation of propane-air combustion in meso-scale cylindrical tubes with concentric rings is presented. A set of rings is used as a flame holder. The effect of wall thermal conductivities of the unburned and burned regions on flame, inner and outer wall surface temperature distribution was examined. The blowout limits and combustion efficiency with different combination of wall thermal conductivities were also investigated. The surface reaction is excluded in the analysis since materials that can resist radical quenching are now available.

2. Numerical Simulation Setup

A two-dimensional (2-D) steady state numerical simulation was performed using ANSYS Release 14.0 with Fluent 6.3 (ANSYS Inc, 2012). The inner diameter of the combustor is 3.5 mm and the wall is 0.7 mm thick. The wall thickness is modeled as a solid phase where only the energy equation is solved. The total length of the combustor is set to 40 mm. The combustor is divided into two parts namely the unburned and burned gas region by concentric rings.

The concentric rings are modeled as square rectangles with 0.14 mm in length and placed side by side where the location is set to be 30 mm at which is measured from the center of the combustor inlet to the left side of the rings. This value is chosen to ensure that the flow will be fully developed before passing the rings. The wall of the rings is modeled as a thermally thin-wall and its material is stainless steel that has a wall thermal conductivity of 20 W/m/K. One-dimensional (1-D) conductive heat transfer is assumed at the wall of the rings and to model this 1-D heat transfer, a sufficiently small wire thickness is defined to the wall of the rings, which in this case is 0.01 mm. Hence, with this assumption, defining the mesh element inside the rings is not necessary and the total number of mesh element in the computational domain can be reduced. The effect of this thermal conduction is minimal as compared to the thermal conduction via the combustor wall. The main function of the rings is to stabilize the flame before any variation of other

Fig. 1 Schematic of the computational domain (not to scale)

parameters is made. It is widely known that the flame holder prolongs the residence time in the reaction zone that leads to the stable flame. The gap between the rings is set to 0.10 mm to enable the fluid flows and passes through this gap. The fuel type used is propane (C_3H_8)-air mixture. The schematic of the computational domain for this simulation is illustrated in Fig. 1.

In this work, Dufour, gas radiation effects and the work done by pressure and viscous force are assumed to be negligible. Norton and Vlachos (2003) have shown that the gas phase radiation has minimal effect on the combustion reactions. Ideal gas law is assumed for the gas density and the specific heat for all the species is calculated using a piecewise-polynomial fit of temperature. The thermodynamics and transport data are obtained from the Fluent internal database (ANSYS Inc, 2012) and Myer (1998).

Meanwhile, reduced one-step propane combustion with five species as suggested by Westbrook and Dryer (1981) is employed as the combustion chemistry,

The species involved are C_3H_8 , O_2 , N_2 , CO_2 and H_2O .

It should be noted that a detailed kinetics mechanism is compulsory if simulations are performed to evaluate flame or emission characteristics. However, since the focus of this study is to examine the trend pattern of the effect of wall thermal conductivity on the combustion stability, the single step mechanism is sufficient. A non-uniform mesh element size is utilized where high mesh concentration is applied in the area surrounding the rings due to the small gap between these rings. The total number of elements is 19482 and employed for all cases. A grid dependent test was performed and revealed that greater number of elements yields no significant advantage in terms of results accuracy.

Boundary conditions are specified as proposed by Norton and Vlachos (2004) and Li et al. (2009) No-slip boundary type condition is applied at the interface between the fluid and the solid wall. The heat flux at this interface is calculated using Fourier's law. Heat transfer by means of convection at the outer surface of the wall is given by:

$$q'' = h (T_W - T_{amb}) \quad (2)$$

where h is the convective heat transfer coefficient, T_W is the outer wall temperature and T_{amb} is the ambient temperature, which is set to 300 K for all cases. The convective heat transfer coefficient (h) is fixed to be at 5 W/m²K, which represents a weak natural convection (Li, et al., 2009).

A thermal insulation (zero heat flux boundary) is applied at both left and right wall edges of the combustor. The wall thermal conductivity for both the unburned gas region (k_u) and the burned gas region (k_b) of the solid wall is varied from 1.0 W/m/K to 1000 W/m/K. The solid zone of k_u and k_b can be established by defining two separate cell zones of the solid wall in the ANSYS-Fluent. In a practical application, this region can be separated by using two composite tubes for the unburned and burned gas region. These tubes can be adhered together using special ceramic adhesive as demonstrated by Mikami et al. (2013). For the outlet boundary condition, a fixed pressure is used while a far-field condition is applied for the species normal to the outlet. This means that a zero diffusive flux of species is assumed at the outlet. An axis boundary condition is established at the centerline so that the calculation can be performed only in the half of the domain. Table 1 below summarizes the numerical model setup while Fig.2 shows the results of grid dependent test with different number of elements.

Table 1 Summary of the model setup

Parameters	Model setup
Solver	Pressure-based, steady-state and axisymmetric
Species model	Laminar finite-rate with stiff chemistry solver
Pressure-velocity coupling	SIMPLE
Spatial discretization	First-order upwind scheme
Density	Ideal gas law
Mixture specific heat	Mixing law
Species specific heat	Piecewise polynomial
Convergence criteria for the scaled residuals	1×10^{-3} for continuity, 1×10^{-3} for velocity 1×10^{-6} for energy and 1×10^{-3} for species equation

Fig. 2 Centerline gas temperature distribution along the axial displacement with different number of elements with $k_u=1$ W/m/K and $k_b=1$ W/m/K for U 0.30 m/s and $\phi=1.0$

A laminar flow of U with a flat velocity profile is applied at the inlet while the inlet feed temperature is maintained at 300 K. At first, the value of U is set to 0.20 m/s and the equivalence ratio (ϕ) of the mixture is initialized to 1. A technique that is called as “cold flow” is employed where the momentum and continuity equation is first solved.

Then, by patching a high temperature around an area that can be defined as patch zone, the energy and species equations are then solved. This patch zone is located at 2 mm from the outlet and should not be placed too close to the outlet since it can result to a reverse gas flow, which negatively affects the ignition process. A sufficiently high temperature of 1700 K is applied on the patch zone to ensure that the fuel-air mixture can be ignited. Once ignited, the flame propagated to the upstream and eventually stabilized near the rings. To obtain the blowout limit, the value of ϕ is first fixed and the value of U is gradually stepped up with 0.01 m/s interval. The corresponding U value that causes the flame to propagate away from the rings and subsequently blown off the tube is considered as the blowout limit. The whole process starting from the cold flow step is repeated to obtain the blowout limits for different values of ϕ .

3. Results and Discussion

3.1 Flame propagation and stabilization

Flame propagation in a narrow channel is a broad subject matter. Investigation of flame propagation characteristics in a narrow channel tube combustor is indeed a formidable task. In order to numerically study the phenomenon of flame propagation inside a meso-scale tube combustor, a detailed kinetics reaction mechanism is required that can lead to a higher computational cost. As mentioned in Section 2, this investigation is mainly on the effect of wall thermal conductivities on the combustion of this type of combustor. Therefore, results shown in Fig. 3 are only limited to demonstrate the capability of the concentric rings.

Fig. 3 Heat of reaction contours with different values of iteration number for $k_u=1$ W/m/K and $k_b=1$ W/m/K, $\phi=1.0$ and $U=0.20$ m/s, (not to scale; for easier visualization, reflection of axis is used in all figures (a) iteration number=185; (b) iteration number=385; (c) iteration number=755; (d) solution converged

The ignition was attained by applying a sufficiently high temperature on the patch zone. This ignition method replicates the experimental condition reported by Mikami et al. (2013). The inlet velocity was set to $U=0.20$ m/s while the equivalence ratio (ϕ) was fixed to 1.0. Since the flame burning velocity is faster than the inlet velocity, the flame propagated towards the inlet once it was ignited. As shown in Fig. 3, the flame stopped to propagate when it reached the rings and stabilized there until a converged solution was achieved. This condition is defined as a stable flame. The concentric rings act as a flame holder by which the flame can be stabilized at a fixed location.

3.2 Flame, gas and wall surface temperature profile

In micro combustors, flame, inner and outer wall temperatures are interdependent to each other. These characteristics are essentially important in a micro power generation research. Yang et al. (2012) suggest that a good combustor for micro power generation application should have a sufficiently high and uniform outer wall surface temperature. As for this simulation study, the wall thermal conductivity values for both the unburned (k_u) and burned (k_b) gas region were varied at 1 W/m/K, 10 W/m/K, 100 W/m/K and 1000 W/m/K. The effect of wall thermal conductivity on the temperature contours of the combustor is shown in Fig.4 while Fig. 5 illustrates the corresponding gas centerline temperature distribution. The flame temperature can be defined as the highest gas temperature recorded along the axial displacement. Figure 4 suggests that the variation of the wall thermal conductivity has a minimal effect on the flame temperature. As the value of k_u and k_b is increased to 10 W/m/K, 100 W/m/K and 1000 W/m/K respectively, there is notably better uniformity of gas and wall temperature distributions in the unburned gas region.

Fig. 4 (a)-(d) Temperature contours with different values of k_u and k_b for $U=0.30$ m/s and $\phi=1.0$ (not to scale; for easier visualization, a reflection of the axis is used in all figures)

Meanwhile, Fig. 5 shows that there is a direct relationship between k_u values and the gas temperature in the unburned gas region particularly from $x=3$ mm onwards. This change is due to the role of the combustor wall as a heat

Fig. 5 Temperature distribution of gas at the centerline along the axial displacement with different values of k_u and k_b for $U=0.30$ m/s and $\phi=1.0$: (a) $k_u=1$ W/m/K; (b) $k_u=10$ W/m/K; (c) $k_u=100$ W/m/K; (d) $k_u=1000$ W/m/K

conductor. The main method of transferring the heat from the hot burned gas to the unburned reactants in this type of combustor is by the wall conduction. The process of heating up the unburned gas prior to the combustion starts from the inner wall. Thus, the intensity of this process depends on the value of k_u . Figure 6 shows the temperature distribution of inner wall and gas inside the combustor with two different values of k_u and a fixed k_b value. For $k_u=10$ W/m/K, higher inner wall temperature is obtained in the unburned gas region up to $x=29.0$ mm as more heat energy is

distributed to the unburned gas region. Generally, this trend is repeated with a further increment of the k_u value. Nonetheless, using $k_u=1000$ W/m/K is no longer effective in boosting up the unburned gas temperature. The next important criterion for meso and micro scale combustion is the outer wall temperature distribution, which is presented in Fig. 7. Obviously, it is shown in the figure that the combination of low wall thermal conductivities in the unburned and burned gas region leads to steeper temperature gradients.

Fig. 6 Temperature distribution of the inner wall and gas at the centerline along the axial displacement from the inlet with $k_u=1$ W/m/K and $k_u=10$ W/m/K for $k_b=10$ W/m/K, $U=0.30$ m/s and $\phi=1.0$

Fig. 7 Outer wall surface temperature distribution along the axial displacement from the inlet with different values of k_u and k_b for $U=0.30$ m/s and $\phi=1$: (a) $k_u=1$ W/m/K; (b) $k_u=10$ W/m/K; (c) $k_u=100$ W/m/K; (d) $k_u=1000$ W/m/K

According to Norton & Vlachos (2003), such large temperature gradients can significantly reduce the material lifespan. In severe cases, melting of the combustor material might occur. Therefore, to avoid such a problem, a uniform outer wall temperature distribution is desired. This uniform temperature can be achieved by using a high wall thermal conductivity in the unburned (k_u) and burned gas region (k_b). However, it is noted that by utilizing a high value of k_u and k_b , the maximum wall temperature is dramatically reduced. For instance, with $k_u=1000$ W/m/K and $k_b=1000$ W/m/K, the maximum wall temperature is only at 694.7 K. This reduction is mainly due to the heat energy being

distributed to a wider range of area. A lower wall temperature means a reduction of the combustor efficiency in converting heat to electrical energy. As such, a proper consideration is necessary in order to balance between the need of a high performance combustor and a durable combustor.

3.3 Effects of the inlet velocity and equivalence ratio

According to Park et al. (2012), the efficiency of a micro combustor in converting the heat produced from combustion to electrical energy is significantly affected by the inlet velocity. This fact is due to the temperature variation with respect to the inlet velocity. With the elevation of the inlet velocity, more reactant mixture is delivered to the burned region that eventually escalates the reaction rate. Consequently, there is a surge of flame temperature that results to a greater outer wall surface temperature distribution.

Figure 8 depicts the outer wall temperature distribution along the axial displacement with different values of inlet velocity (U) and equivalence ratio (ϕ). As shown in Fig. 8 (a), the increment of the inlet velocity escalates the wall

Fig. 8 Outer wall surface temperature distribution along the axial displacement from the inlet with different U and ϕ for $k_u=1$ W/m/K and $k_p=10$ W/m/K: (a) for different values of U with constant $\phi=1.0$; (b) for different values of ϕ with constant $U=0.20$ m/s

temperature particularly in the burned gas region. This pattern is also valid for larger values of k_u where the increase of wall temperature is more noticeable in the unburned gas region. It is important to note that the process of obtaining a higher outer wall temperature distribution by applying a higher inlet velocity should be prudently performed as blowout might occur.

The other way to elevate the wall temperature without adjusting the inlet velocity is by increasing the equivalence ratio (ϕ). Figure 8(b) clearly shows that a richer fuel-air ratio can result to an increase in the wall temperature due to greater reaction rate. Nevertheless, considering the environment where micro power generators are utilized, combustion of fuel mixture with below the stoichiometric ratio is preferred.

3.4 Effects of the wall thermal conductivity on the flame stability and combustion efficiency

In meso and micro-scale combustors, the wall thermal conductivity plays a significant role in determining the flame stability. The axial heat conduction from the burned gas region promotes the pre-heating of the unburned gas that eventually enhances the flame stability. One of the indicators of flame instability in a micro combustor is blowout. In general, blowout occurs when the combustor exit velocity is higher than flame burning velocity (Turns, 2003). It is important to determine the blowout limits for meso and micro-scale combustors so that the operative range can be ascertained.

In this study, the determination of blowout limits is as follow. Firstly, a stable flame is established in the combustor. For all cases, a stable flame can be achieved with the inlet velocity (U) of 0.20 m/s regardless of the equivalence ratio (ϕ) value. Then, the value of U is gradually stepped up with 0.01 m/s interval and further calculation is conducted until a converged solution is achieved. For instance, if increasing the value of U from 0.25 m/s to 0.26 m/s

causes the flame to propagate away from the rings toward the outlet, then $U=0.25$ m/s is considered as the blowout limit. This step is repeated for each case of ϕ and both wall thermal conductivities (k_u and k_b). Figure 9 shows the flame image with a blowout condition while Fig. 10 summarizes the blowout limits with respect to all variable parameters. As depicted in Fig.9, with the value of U increased to 0.42 m/s, the flame is blown out to the tube end resulting to the

Fig. 9 Heat of reaction contours in near blowout condition with different number of iteration for $k_u=100$ W/m/K, $k_b=100$ W/m/K, $\phi=1.0$. This phenomenon of blowout occurs when U was increased from 0.41 m/s to 0.42 m/s: (a) iteration number=100; (b) iteration number=7000; (c) iteration number=9500(not to scale, for easier visualization, reflection of axis is used)

Fig. 10 Blowout limits with different values of k_u , k_b and ϕ (a) $k_b=1$ W/m/K; (b) $k_b=10$ W/m/K; (c) $k_b=100$ W/m/K; (d) $k_b=1000$ W/m/K

flame extinction. Meanwhile, Figure 10 indicates that as k_b is increased from 1 W/m/K to 100 W/m/K, the flame stability is enhanced. In overall, the combustion of mixture that is rich in fuel significantly improves the blowout limits as Mikami et al. (2013) experimentally showed for meso-scale quartz tube combustors with wire mesh. However, there is only a slight improvement in the limit with the use of $k_b=1000$ W/m/K. It is also shown that there is an inverse relationship between the value of k_u and the blowout limits except for $\phi=0.90$ as indicated in Fig. 10 (b) to (d). This reduction of limit is probably due to the variation of pre-heating effect that occurs in the unburned gas region.

Figure 11 presents the temperature distribution along the inner wall with different values of k_u and k_b . It can be seen from the figure that the inner wall temperature at $x=29.5$ mm for $k_u=1$ W/m/K is the highest. This maximum inner

Fig. 11 Inner wall temperature with different values of k_u for $U=0.30$ m/s and $\phi=1.0$; (a) $k_b=1$ W/m/K; (b) $k_b=10$ W/m/K; (c) $k_b=100$ W/m/K; (d) $k_b=1000$ W/m/K

wall temperature is still within the unburned gas region. Figure 12(a) depicts the numerical value of inner wall temperature at $x=29.5$ mm while Fig. 12(b) shows the blowout limits for $\phi=1.0$. The highest inner wall temperature is recorded to be 848.7 K while the maximum blow out limits is 0.52 m/s. Clearly, Fig. 12 suggests that the blowout limits is affected by the inner wall temperature, particularly in the small area just before the ring position. The increased inner wall temperature at such a position conceivably increases the local burning velocity at the flame attachment region. The use of a bigger k_u value can result to a lower temperature in this area. Consequently, the blowout limit is decreased. However, it is observed from the results that for the combustor with $k_b=1$ W/m/K, the blowout limit does not change dramatically with the increase of k_u . It is important to note that at near blowout conditions, the flame is slightly displaced towards the downstream. For the combustor with $k_u=1$ W/m/K and $k_b=1$ W/m/K, the flame is located at 32.2 mm from the inlet when U is increased to 0.32 m/s (the blowout limit is 0.33 m/s). There is possibility that the elevation of the inner wall temperature has no effect on the flame stability at this near blowout condition.

Fig. 12 (a) Inner wall temperature with different values of k_b at $x=29.5$ mm for $U=0.30$ m/s and $\phi=1.0$ (b) Blowout limits with different values of k_b for $\phi=1.0$.

Meanwhile, the combustion efficiency with respect to the wall thermal conductivity is presented in Fig. 13. The combustion efficiency for the combustor with wall thermal conductivity k_b of 1000 W/m/K is not shown in the graph as it has the same tendency as the combustor with $k_b=100$ W/m/K. It can be seen from the figure that there is an inverse

relationship between the wall thermal conductivity k_u and the efficiency. Jianlong et al. (2012) stated that the combustion efficiency for a micro combustor depends on the inlet velocity, heat losses and flame temperature. Thus, this variation of combustion efficiency is mainly due to the transverse heat loss to the ambient air with the use of higher wall thermal conductivity. Nevertheless, the efficiency change is relatively small.

Fig. 13 Combustion efficiency with different values of k_u and k_b for $U=0.20$ m/s and $\phi=0.90$

4. Conclusions

The numerical simulation of combustion of propane-air mixture in meso-scale tube combustors with concentric rings has been successfully demonstrated. The function of the concentric rings is to stabilize the flame at a fixed location. With the use of these rings, it is possible to vary the wall thermal conductivity in the two different regions.

In this type of combustor, the wall and gas temperature distribution in the unburned gas region is tremendously affected by the value of wall thermal conductivity. However, the use of a high value of k_u or k_b in which for this case $k=1000$ W/m/K produces no observable effect on both the wall and gas temperature profile. It is demonstrated that the flame temperature is independent to the wall thermal conductivity. On the other hand, the inlet velocity and the equivalence ratio have a significant impact on the flame temperature, which in turn affects the wall and gas temperature distribution.

It is a well-known fact that the utilization of low wall thermal conductivity values leads to the high temperature gradients that eventually contributes to hot spot related problems. Thus, by establishing the two separate regions of wall thermal conductivity, the problems related to the high thermal stress could be minimized without compromising the combustor efficiency.

Lastly, the blowout limits greatly depend on the wall thermal conductivity. The blowout limits are significantly affected by the inner wall temperature particularly in the area just before the ring position. The increased inner wall temperature at such a position conceivably increases the local burning velocity at the flame attachment region. The use of higher wall thermal conductivity in the unburned gas region brings down the value of the inner wall temperature in the area just before the ring position. As a result, the blowout limits are also reduced. It is also demonstrated that the combustion efficiency is influenced by the variation of the wall thermal conductivity k_u . The use of a combustor with a low value of k_u can improve the combustion efficiency. However, other critical factors such as the outer wall temperature and the blowout limits should also be considered before selecting the appropriate wall thermal conductivity.

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