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Short communication

Experiments of a premixed flame inside a refractory tube

Rapepun Kansuntisukmogkol[a], Hiroyuki Ozoe[b,*], S.W. Churchill[c]

[a] *Interdisciplinary Graduate School of Engineering Science, Kyushu University, Kysushu, Japan*
[b] *Institute of Advanced Material Study, Kyushu University, Kyushu, Japan*
[c] *Department of Chemical Engineering, University of Pennyslvania, Philadelphia, PA, USA*

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Abstract

Experiments were carried out for a premixed flame inside an adiabatic refractory tube. The temperature of the tube wall was found to play a critical role in stabilizing a flame inside the refractory tube without any flameholder. Preheating of the wall and good thermal insulation on its outer surface are pre-requisites for this behavior. The flame may be stabilized at both upstream and downstream locations for the same external conditions depending on the initial conditions. Dependence of the flame location on the mass flow rate of the fuel; the mass flow rate of the air and the tube length was studied experimentally. The results are in agreement with prior numerical predictions.

Keywords: Pre-mixed flames; Experimental analysis; Multiple flame locations; Thermal stabilizations

1. Introduction

The efficient combustion of fuels is becoming more important due to the shortage of clean fuels and greater interest in the quality of the environment. Studies of thermally stabilized combustion have been carried out extensively in academia and in industry for sometime despite the limited current use of this process. Hardesty and Weinberg [1] showed the potential of radiative and convective feedback loops to stabilize flames of very lean air–methane mixtures and showed that the use of a part of the sensible energy of the burned gases to preheat the air–fuel mixture extended the lower limits of flammability. Cellier and Galant [2] carried out experiments on the stable laminar combustion of gaseous mixtures with a low energy content by means of convective and radiative feedback loops. Min and Shin [3] are among those who have studied laminar premixed flames stabilized inside a honeycomb ceramic experimentally and theoretically. They found two types of stable flames inside the honeycomb ceramic: one nearly one-dimensional and the other very two-dimensional. Yong et al. [4] continued this work and discovered many interesting aspects of the behavior of flames inside such a structure. They found two mass flow rates for one given flame position and equivalence ratio, that is, an upper and a lower solution. Furthermore, two flame positions, which they referred to as upstream and downstream solutions, were found for a single flow rate and equivalence ratio. The effect of side-wall heating and heat losses on the behavior were also investigated.

Howland and Simmonds [5] investigated the limit of stability for the combustion of methane and air as well as town gas and air in an insulated and uninsulated ceramic tube. They observed oscillations with intense acoustical effects and concluded that the mixture was heated and ignited by radiation and convection from the hot wall. Bath [6] studied the stability limits of propane–air flames inside a well-insulated alumina tube, 25.4 mm in diameter and 609.6 mm in length. Acoustical oscillation were not observed and in retrospect it is concluded that the stabilization and acoustic oscillation observed by Howland and Simmonds [5] were primarily due to a step increase in the diameter of their tube with consequent back mixing. Chen and Churchill [7,8] experimentally and numerically investigated the combustion of a premixed propane and air inside a refractory tube and with a diameter of 9.52 or 4.76 mm and no flameholder and determined the limits of blowoff and flashback. Their numerical predictions, which were carried out after completion of the experimental work, suggested the possible existence of multiple steady states. Bernstein and Churchill [9] verified experimentally the prediction of multiple location for thermally stabilized

*Corresponding author. Fax: +81-92-583-7838; e-mail: ozoe@cm.kyushu-u.ac.jp

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flames inside a refractory tube. Subsequent paper by Churchill and co-workers [10–12] also found the upstream and downstream flame locations for ethane and droplets of hexane. These locations were essentially independent of the type of fuel (with the exception of methane). The behavior of combustion inside a refractory tube without a flameholder is unique and radially different from that of conventional combustion. For instance, the flame is invisible, quiet, non-oscillatory and rock stable whereas the conventional combustion responds rapidly to even minor perturbations and may thereby become unstable. Perhaps the most important characteristics of thermally stabilized combustion are the minimal formation of pollutants and the feasibility of burning extreme quantities of fuel-lean mixtures. These characteristics are a consequence of thermal stabilization by conduction, convention and/or radiation and thereby the avoidance of backmixing, which is the primary mechanism of stabilization for conventional processes of combustion.

The primary objective of the present work is to study stable combustion and to determine if there are any multiple locations for the flame. The second objective is to test the theoretically predicted transient characteristics. The third objective is to characterize quantitatively the effects of the mass flow rates of fuel and air, the tube length and the initial conditions on the flame locations.

2. Experimental apparatus

The experimental apparatus consisted of a fuel-supply system, an air-supply system, a mixer for the fuel and air, a combustion chamber and instrumentation for measuring wall temperatures. A schematic diagram of the experimental apparatus is shown in Fig. 1. An alumina tube ($3Al_2O_3 \cdot 2SiO_2$) 200 mm long 13 mm × 9 mm in OD × ID, filled with ceramic balls of 3 mm diameter and wire netting premixes the fuel and air well and protects against flash-back. The combustion chamber is an alumina tube 250 mm in length and 13 mm × 9 mm in OD × ID. It is well insulated on the outer surface to minimize radial heat losses by kao-wool 1600 VFS, 250 mm long, 63 mm × 13 mm in OD × ID, which is further surrounded by five layers of kao-wool blanket 8 LBS, 250 mm in length, giving a total insulation of 125 mm in thickness. Fig. 2 is a photograph of the combustion chamber. Nine R-type platinum 13% rhodium/platinum thermocuples with a ceramic protection tubes were employed for the temperature measurements. They were placed along the ceramic tube wall at 25, 50, 75, 100, 125, 150, 175, 200 and 225 mm from the inlet. Compensating extension wire (copper) was employed to connect the thermocouples to the hybrid recorder YOKOGAWA HR2300 (3760). The wall-temperature profile determined from the thermocouples was fed to this recorder and stored in a personal computer via a GP-IB interface. The hybrid recorder was arranged so that the measured temperatures could be sent to a computer monitor or a chart recorder or both on demand. The digitized temperature data were used for precise values and locating the flame front,

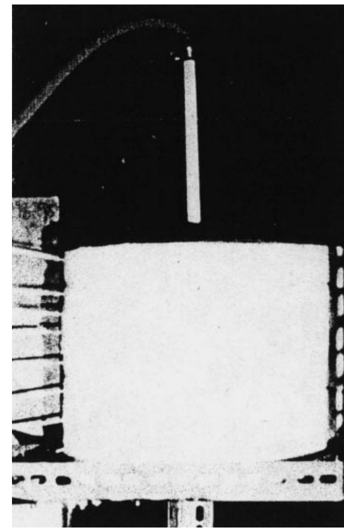

Fig. 2. Photograph of the combustion chamber with nine R-type thermocouples.

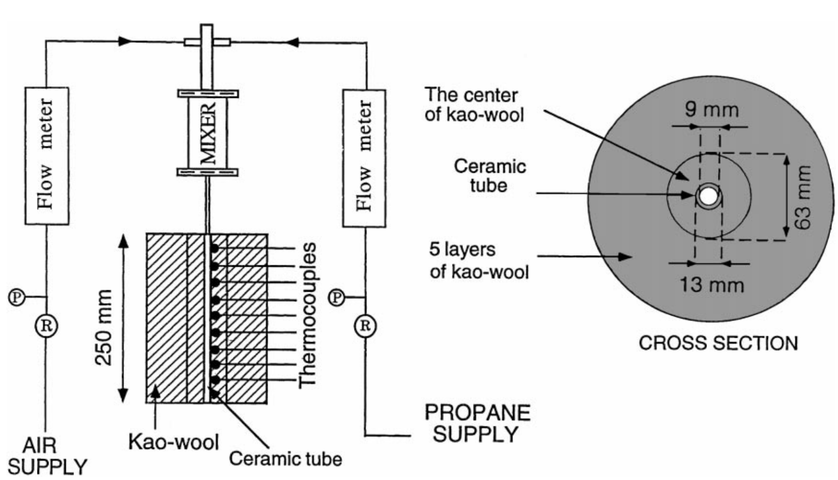

Fig. 1. Schematic diagram of the experimental apparatus.

whereas the chart recorder was used to see the general trend of the wall-temperature profile with time.

3. Experimental procedures

The experimental steps were: first the preheating of the combustion chamber; second the establishment of a stationary flame inside the ceramic tube; third the observation of the transients; and fourth the study of the influence of several parameters.

3.1. Preheating

A flame cannot be stabilized inside a ceramic tube without preheating it. This preheating also minimizes the length of the unsteady state period. Fig. 3 shows a flame inside the refractory tube during the preheating process. For an upstream location of the flame, the preheating was considered to be completed when two-thirds of the tube length was heated above 100 K. One-third of the tube length needed to be preheated above 100 K for downstream locations.

3.2. Seeking a steady-state

After preheating, the flowrates of air and propane were increased slowly to the prechosen values. The flame inside the refractory tube was relatively invisible while the tube wall glowed with bright orange colour as shown in Fig. 4. This is an evidence of the attainment of stable combustion. For the downstream flame, a light-orange tail was observed at the exit of the tube as shown in Fig. 5. This tail was not observed for the upstream flame location and is presumed to be associated with conditions outside the tube. Careful adjustment was required to control the propagation of the flame. With an increase of the air flowrate or a decrease of the fuel flowrate, both upstream and downstream flames start to move downstream to the exit. Likewise, both flames shift to the inlet when the flowrate of the air is decreased or that of fuel is increased. Both the temperature readings from the computer and the reflection of the flame on the TV-screen were monitored continuously. If the temperatures began to fall rapidly or the flame reflection starts to disappear, the flame was soon extinguished. A stationary-state was presumed to have been achieved when all of the measured temperatures changed less than 10°C over a span of 20 min. The location of the flame front was arbitrarily defined as the position of the maximum gradient in the wall temperature.

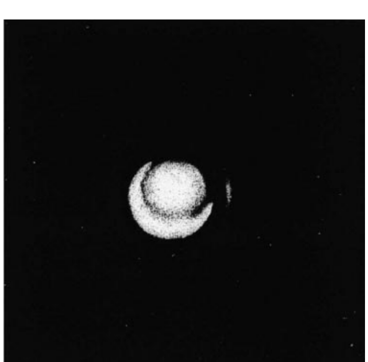

Fig. 3. Flame inside the refractory tube during the preheating time.

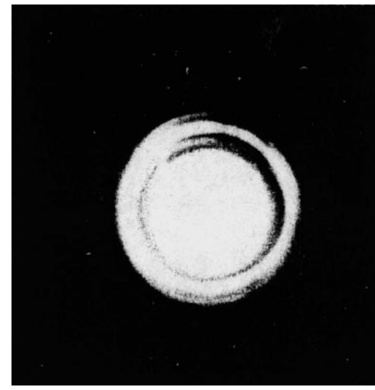

Fig. 4. Steady-state flame inside a refractory tube.

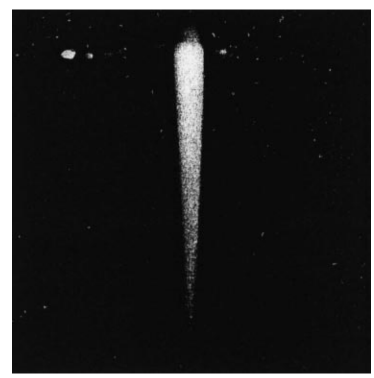

Fig. 5. A light orange-tail at the exit of the tube for a downsteam flame.

3.3. Transient responses

Once a stable flame location was found, the flowrate of air and/or fuel was changed to shift the flame to a new location. Rapid changes in the flowrates were avoided to prevent blowoff or flashback of the flame. Usually only the flowrate of the air was changed in the interests of simplicity. After the flame moved to a new pseudo-stable location near another expected steady-state location. The flowrate of the air was adjusted back to its former value and the further propagation of flame front, if any, was observed.

3.4. Parametric effects

The various parameters such as the mass flowrate of the mixture, the mass flowrate of the air, and the tube length were changed to determine their effects on both the upstream and downstream location of the flame.

4. Results and discussion

The present apparatus differs from those of Chen and Churchill [7] in that only a central combustion tube was employed, whereas they used six guard heaters. The radial heat losses of the present experimental apparatus are, therefore, greater than that of the prior ones. The maximum temperature attained in the present apparatus was about 1500 K, whereas that of the prior reports was about 1800 K. However, the general behavior was expected to be unchanged. The present apparatus is similar to that used by Brown et al. [13] to study incineration. Their maximum tube-wall temperature ranged from 1300 K to 1600 K.

4.1. Multiple location of stationary-state flames

The dimension and physical properties utilized in this work are shown in Table 1. The basic experimental conditions were $W_{mix} = 2.5 \times 10^{-4}$ kg/s ($W_{air} = 2.36 \times 10^{-4}$ kg/s and $W_{fuel} = 0.14 \times 10^{-4}$ kg/s), $\Phi = 0.927$, $T_{external} = 20°C$ and $P_{external} = 1$ kgf/cm^2, gauge. The corresponding Reynolds number at the inlet was 1970. Experiments with the above conditions for the steady-state downstream flame location were carried out twice in order to verify reproducibility as shown in Fig. 6. Then, the steady-state upstream flame location was sought for the same conditions using the experimental procedure described in Section 2. The upstream tube-wall temperature profile is also plotted in Fig. 7, verifying the existence of a multiple steady-state. The establishment of an upstream or a downstream stationary-state is ordinarily determined by the startup procedure, but the flame can also be moved from one location to another.

Thermally stabilized combustion in a refractory tube is sustained by conduction in the tube wall and wall-to-wall radiation and thereby avoids mixing of the burned and unburned gas. The, upstream and downstream flame locations are a consequence of the heat losses at the upstream and downstream ends of the tubes, which depend critically on the wall temperature profile.

4.2. Transient combustion

The transient movement of the flame from an initial stable location to another stable position was also studied. First a steady-state flame location was attained. Then the flow rate of either air and/or fuel was changed to move the flame to another position where a second stationary-state was presumed to exist. Both upstream and downstream flames move toward the exit after an increase in the air flowrate or a decrease in the fuel flowrate. Likewise, both flames are shifted toward the inlet when the flowrate of air is decreased or that of fuel is increased. After the flame had moved to the new location as expected, the flowrates of both air and fuel were returned to their original settings. A new stationary-state was considered to have been attained if a change of temperature of less than 10°C was observed over a period of 20 min.

In the experimental work, the downstream flame location of $W_{mix} = 2.56 \times 10^{-4}$ kg/s ($W_{air} = 2.42 \times 10^{-4}$ kg/s and $W_{fuel} = 0.14 \times 10^{-4}$ kg/s and $\Phi = 0.904$ was sought first. Then decreasing the air flowrate to 3.0×10^{-4} kg/s moved the flame toward the inlet and heated the upstream portion of the tube wall simultaneously. After the flame moved near the position where an upstream steady-state flame was previously found, the mass flowrate of the air was increased slowly up to 2.42×10^{-4} kg/s (the original value). The flame then shifted back near the previous upstream flame locations as shown in Fig. 8. This transient response took about 6 h. This displacement of the two upstream flame locations is in accord with the measurements of Bernstein and Churchill [9] who used such transiently varying conditions to identity as many as four closely grouped upstream locations and three very closely grouped downstream location for the same external conditions. These observed transient movements are all in accord with the prior numerical predictions [14].

4.3. The effect of the mass flowrate of the mixture on the steady-state location of the flame

The effect of the mass flowrate of a mixture was investigated experimentally with an equivalence ratio 0.927. Fig. 9 shows four experimental results for two different mass flow rates of the mixture. The square symbols are the experimental upstream and downstream wall temperature results at $W_{mix} = 2.5 \times 10^{-4}$ kg/s ($W_{air} = 2.36 \times 10^{-4}$ kg/s, $W_{fuel} = 0.14 \times 10^{-4}$ kg/s) and the equivalence ratio $\Phi = 0.927$. The circular symbols are the experimental upstream and downstream wall temperature data at $W_{mix} = 2.78 \times 10^{-4}$ kg/s ($W_{air} = 2.62 \times 10^{-4}$ kg/s, $W_{fuel} = 0.16 \times 10^{-4}$ kg/s) and the equivalence ratio $\Phi = 0.927$. As a result, both the flame locations moved into the center of the tube when the mass flowrate was increased.

This result suggests that the required feedback of energy for ignition increase when the mass flowrate of the mixture is increased. Consequently, both upstream and downstream flame locations move toward the center of the tube in order of reduce the energy losses from the tube-end openings.

Table 1
Dimensions and physical properties employed in this experiment

Representative properties		Value	Unit
Tube diameter	D	90×10^{-3}	m
Tube length	l	0.25	m
Pressure	P	9.807×10^4	N/m^2
Inlet temperature	T_i	293.15	K
Mass rate of flow	W_{mix}	2.5×10^{-4}	kg/s
The equivalence ratio	Φ	0.927	–
Reynolds number at inlet	Re_i	1970	–

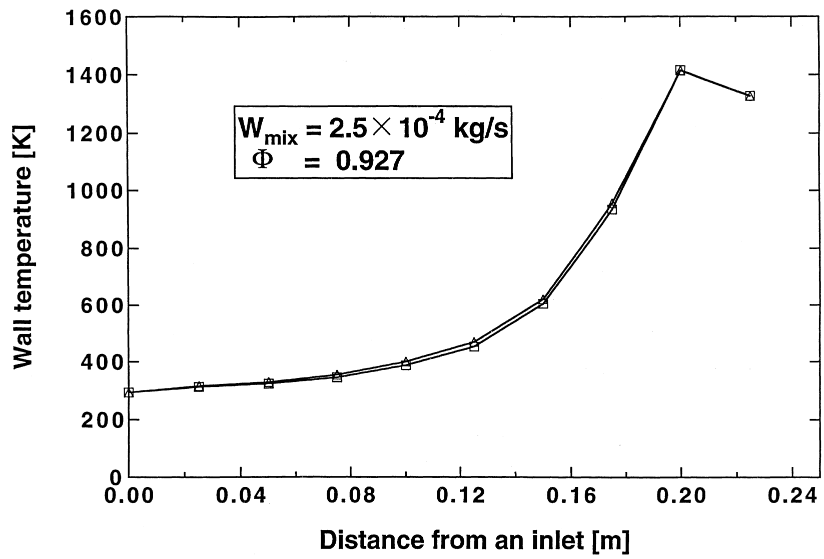

Fig. 6. Reproducibility of the experimental tube-wall temperature profiles for $W_{mix} = 2.5 \times 10^{-4}$ kg/s and $\Phi = 0.927$.

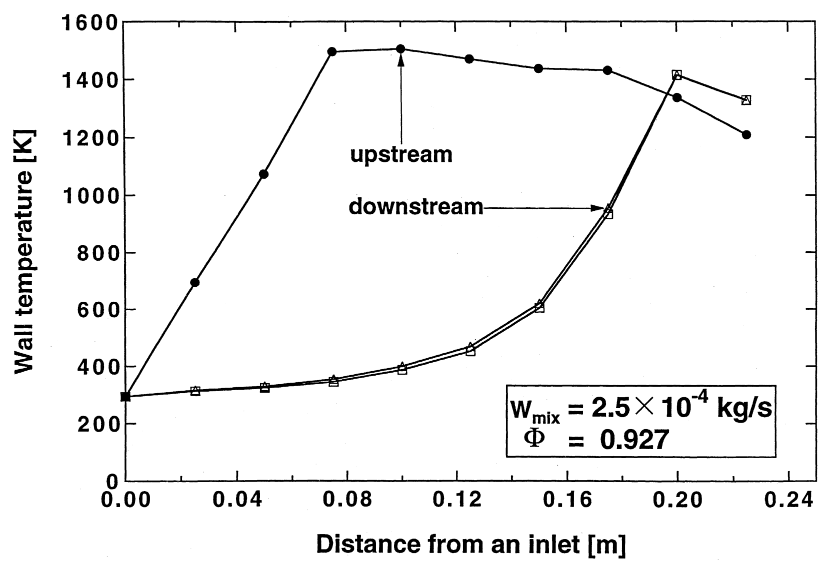

Fig. 7. Multiple stationary state tube-wall temperature profiles for $W_{mix} = 2.5 \times 10^{-4}$ kg/s and $\Phi = 0.927$.

4.4. *The effect of the mass flowrate of air on the steady-state flamefront locations*

The effect of the mass flowrate of air was next studied. The mass flowrate of air was increased from 2.36×10^{-4} kg/s to 2.42×10^{-4} kg/s while the fuel mass flowrate was kept constant at 0.14×10^{-4} kg/s, which meant that the mass flowrate of the mixture was changed from 2.5×10^{-4} kg/s to 2.56×10^{-4} kg/s and the equivalence ratio decreased from 0.927 to 0.904. As plotted in Fig. 10, the flame location moved into the center of the tube when the mass flowrate of air was increased. This result is similar to the effect of the mass flowrate of the mixture. Moreover, the decrease of the equivalence ratio also causes the movement of the flame front toward the center of the tube. An increase of the mass flowrate of air means that an increase in mass flowrate of the mixture and a decrease in the equivalence ratio occur simultaneously. Therefore, both upstream and downstream flame fronts would be expected to shift to the center of the tube. The present experimental work supports that expectation.

As the mass flowrate of air is increased, the mass flowrate of the mixture increases and the equivalence ratio decreases. Consequently, as the energy required for ignition of the cold reactants increases, the flame moves toward the center of the tube in order to decrease energy losses from the inlet and/or the exit.

These observed shifts in flame front location are in good accord with prior theoretical predictions [15]. These movements of the steady-state locations are to be constrated with the short-term transient movement of both upstream and downstream locations toward the exit with increasing flow rates of the mixture, etc.

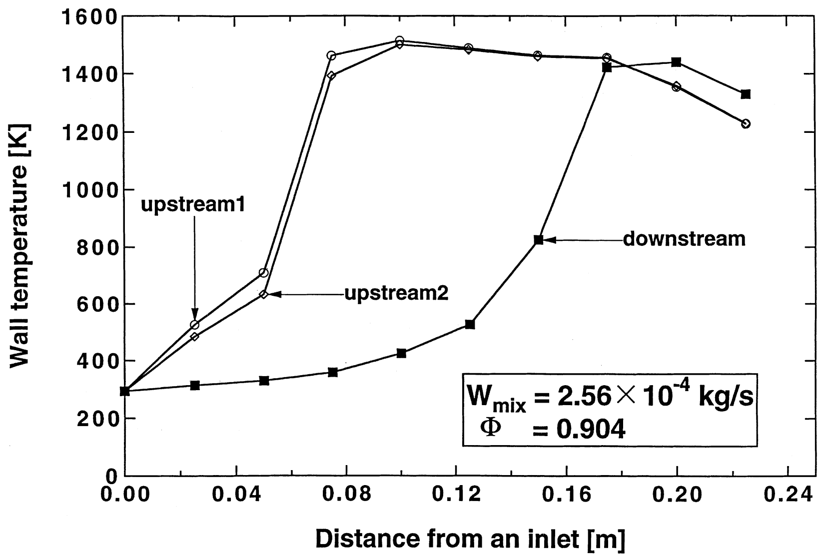

Fig. 8. The previous upstream, initial downstream and second upstream (after transient process) tube-wall temperature profiles. $W_{mix} = 2.56 \times 10^{-4}$ kg/s and $\Phi = 0.904$.

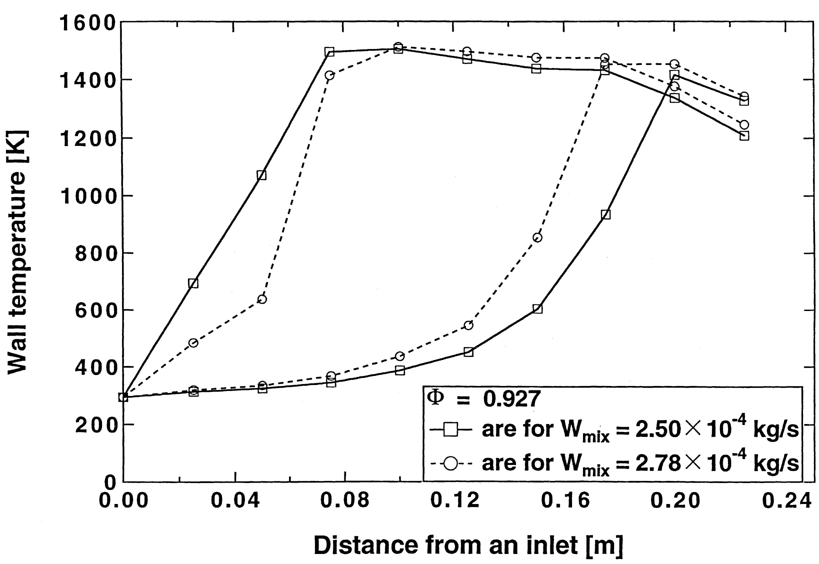

Fig. 9. The effect of the mass flowrate of the mixture on the multiple steady-state tube-wall temperature profiles.

4.5. The effect of the tube length on the steady-state flame locations

The effect of tube length was investigated numerically in a previous study [15]. Experiments were carried out for the different tube lengths to check the validity of these predictions. The tube length varied from 250 mm to 350 mm. The other common experimental conditions of $W_{mix} = 2.78 \times 10^{-4}$ kg/s ($W_{air} = 2.62 \times 10^{-4}$ kg/s, $W_{fuel} = 0.16 \times 10^{-4}$ kg/s) and equivalence ratio = 0.927 were utilized. The observed effect of the tube length on the multiple steady states is displayed in Fig. 11. The upstream and downstream flame location for $l = 0.25$ m are approximately at 0.065 m and 0.165 m from the inlet, respectively. On the other hand, those for $l = 0.35$ m are at about 0.055 m and 0.26 m, respectively. The distance from the downstream flame front to the exit for $l = 0.25$, 0.35, 0.085 m and 0.09 m, respectively. The experimental data of the downstream solution for $l = 0.25$ m was also plotted for the same exit location in Fig. 12. These experimental results reveal that as the tube length is increased, the upstream flame location changes only slightly but the downstream location moves significantly toward the exit. On the other hand, the distance of the downstream flame front from the outlet is nearly unchanged. This experimental result is in agreement with the previous numerical work of Kansuntisukmongol et al. [15]. The locations of stable flame appear to be determined by the distance to the nearest opening.

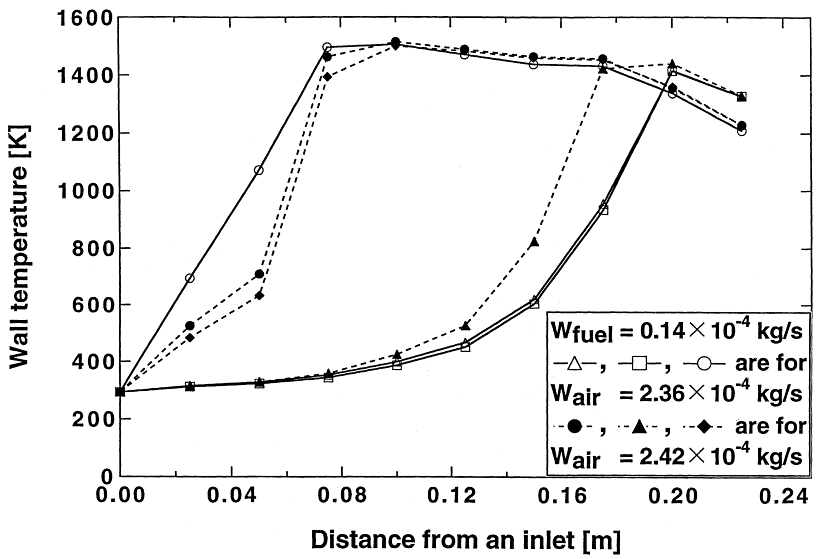

Fig. 10. The effect of the mass flowrate of air on the multiple steady-state tube-wall temperature profiles.

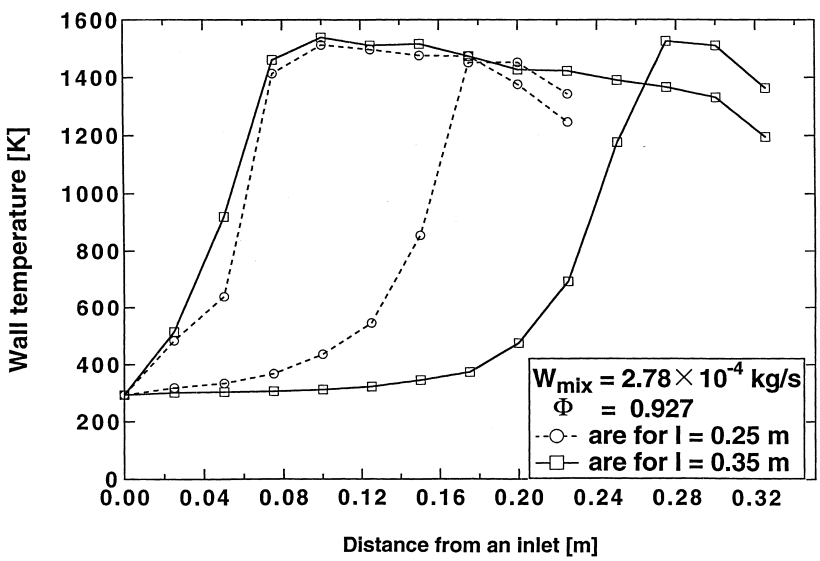

Fig. 11. The effect of the combustion tube length on the tube-wall temperature profile with multiple steady-states.

5. Conclusions

Transient and steady-state experiments on thermally stabilized combustion in an adiabatic refractory tube without a flameholder were carried out. The significant results may be summarized as follows.

1. The hot tube wall controls the stabilization of a flame inside a refractory tube without a flameholder.
2. Multiple steady-state flame locations are observed for the same external conditions with the different initial-wall-temperature profile. Flame fronts are classified into two locations, that is, upstream and downstream.
3. The effect of the mass flowrate of the mixture on the multiple steady-state flame locations was studied experimentally. As the mass flowrate of the mixture increases, both the upstream and downstream flames move toward the center of the tube in order to decrease the heat losses through the openings, and thereby increase the thermal feedback.
4. The effect of the mass flowrate of air on the multiple steady-state flame fronts was also investigated experimentally. The results are similar to those for the mass flowrate of the mixture because the increase of the mass flowrate of the air increases the mass flowrate of the mixture and decreases the equivalence ratio. Both effects result in the movement of the flame locations toward the center of the tube.
5. The effect of the tube on the multiple steady-state flame locations was studied experimentally, apparently for the

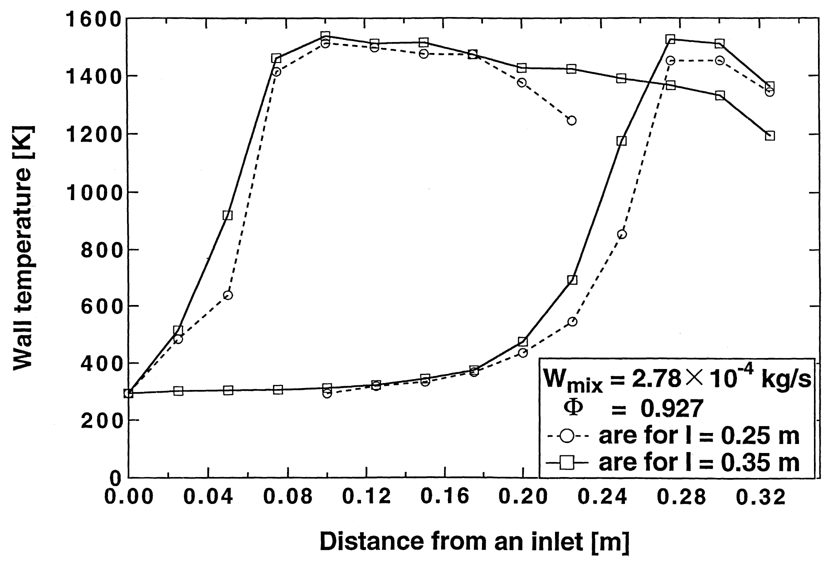

Fig. 12. The effect of combustion tube length. The downstream result for tube length $l = 0.25$ m is replotted for the same exit location.

first time. The location of a stable flame is almost constantly relative to the nearest tube and is determined by the energy losses through those openings.

6. Transient movements of the flamefronts were also studied qualitatively. These movements are very slow and their short-time direction differ from the long-time direction because of the great thermal heat capacity of the wall relative to that of the gas contained within the tube.

6. Nomenclature

D	Inner tube diameter (m)
l	Tube length (m)
P	Pressure (N/m^2)
Re	Reynolds number
T	Temperature (K)
W	Mass rate of flow (kg/s)

6.1. Greek letters

Φ	The equivalence ratio = (fuel − air ratio)/(stoichiometric fuel − air ratio)

6.2. Subscripts

air	Air
fuel	Fuel (propane)
i	Inlet
mix	Mixture

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