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Effect of Flow Direction on the Extinction Limit for Flame Spread over Wire Insulation in Microgravity

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Experiments to determine the Limiting Oxygen Concentration (LOC) of a flame spread over electric wire insulation were carried out in microgravity provided by parabolic flights. The difference between the LOC in opposed and concurrent flows was evidenced. Polyethylene insulated Copper (Cu) wires and polyethylene insulated Nickel-Chrome (NiCr) wires with inner core diameter of 0.50 mm and insulation thickness of 0.30 mm were examined with external flow velocities ranging from 50mm/s to 200mm/s. The results for the Copper wires show that with increasing external flow velocity, the LOC monotonically decreased for the concurrent flow conditions and the LOC first decreased and then increased ("U" trend) for the opposed flow conditions. Similar trends were found in the experiments with NiCr wires. Also, in terms of the minimum LOC value, the minimum LOC was comparable for both wire types in both flow conditions. However, for the concurrent flow, the minimum LOC was about 1-2% lower (in oxygen concentration) than for opposed flow for both wire types. A heat balance model for the electric wire with flame propagation was established to estimate the LOC under opposed and concurrent flow conditions in microgravity. In this model, it was suggested that the LOC can be estimated using the normalized radiative heat loss from the sample surface. Result of the calculation qualitatively matched the LOC profile extracted from the experiments.

Nomenclature

c	=	Specific heat, $J(kgK)^{-1}$
L_f	=	Flame length, m
L_g	=	Length scale in gas phase, m
Q_{gs}	=	Heat conduction from flame to insulation, W
Q_{rad}	=	Radiation loss from insulation, W
Q_{req}	=	Required energy to heat up insulation until pyrolysis temperature, W
r	=	Radius, m
R_{rad}	=	Normalized radiative heat loss
T	=	Temperature, K
V	=	Velocity, m/s
Y	=	Mass fraction
α	=	Thermal diffusivity, m^2s^{-1}
ε_s	=	Emissivity

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η = Normalized flame spread rate
λ = Thermal conductivity, $W(mK)^{-1}$
ν = Stoichiometric ratio
ρ = Density, kgm^{-3}
σ = Stefan-Boltzmann coefficient, 5.67×10^{-8} $Wm^{-2}K^{-4}$

Subscript
c = Core wire
f = Flame
g = Gas
$O2$ = Oxygen
p = Pyrolysis
s = Solid (Insulation of wire)
∞ = Ambient condition

I. Introduction

In a spacecraft, ignition of electrical wires can often be the starting point for a fire, and subsequent flame spread over the wire insulation can result in a catastrophic situation. However, work on flame spread over wires in microgravity is very limited despite it having a high potential of causing fires even though much research on flame spread over flat solid samples in microgravity exist.[1,2] Greenberg et al. first conducted experiments on flame spread over wires in a space shuttle. However, details of the mechanisms driving the flame spread over the wires could not be assessed due to the limited number of experiments.[3] Subsequently, the authors of the present work have extensively studied wire insulation combustion in microgravity[4-15] and made an effort to identify the most flammable conditions in microgravity. Takahashi et al. conducted experiments to get the most flammable condition using Nickel-Chrome and copper core wires insulated with polyethylene under opposed air flow conditions.[15] Other related research findings are introduced in the recent review paper by Fujita.[16] While most of the studies investigated opposed flow conditions, Kumar et al. pointed out that the minimum condition of flammability of a flat sheet material in microgravity appeared in concurrent flow condition according to their numerical calaculation.[17] Also, authors[18] ran tests of flammability in reduced gravity condition over polyethylene insulated Nickel-chrome wire, and also pointed out that extinction limit of concurrent flow condition was much lower than that of opposed flow condition. However, the reason for such flammability difference between each flow directions is not clarified yet for wire insulation combustion.

The present paper investigates the effect of flow direction, i.e. opposed and concurrent flow, on flammability boundary of a flame spreading over a polyethylene insulated copper wire in reduced gravity (μg). In this paper, we used the Limiting Oxygen Concentration (LOC) to indicate flammability boundary. It also compares results to data obtained with NiCr core in order to evaluate the influence of core material. Also, a heat balance model of electric wire with flame propagation is introduced to estimate the LOC difference between opposed and concurrent flow conditions in μg.

II. Experimental apparatus and procedure

Figure 1 shows the experimental setup for the parabolic flight tests. It consisted of two experimental rigs.

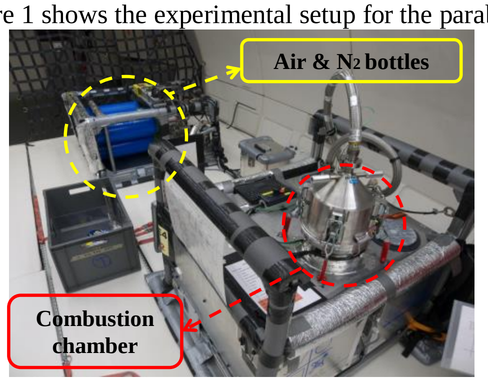

Figure 1. Photo of the experimental setup

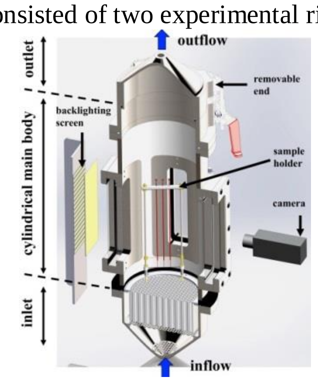

Figure 2. Schematic cut of the experimental setup

The first one was dedicated to the storage of air and nitrogen bottles, which were mixed together using two Bronkhost mass flow controllers to obtained the desired oxidizer concentration and flow velocity. Oxygen concentration in the oxidizer flow could be adjusted from 0 to 21 % and the flow velocity could be set anywhere between 50 and 200 mm/s. The second rig hosted the combustion chamber. Experiments were conducted inside the combustion chamber under μg condition, as shown in Fig. 2. In the combustion chamber, the oxidizer flow entered from the bottom and evacuated at the top. This setup was further described in a paper by Citerne et al[19]. Two cameras were set to capture detailed live information. One camera captured direct flame emission and the other one imaged the flame before a backlighting screen to evaluate the burning rate of molten insulation as well as flame absorption.

The pressure inside the chamber was always set to 1 atmosphere using RCV(Rapid Control Valve) control valve.

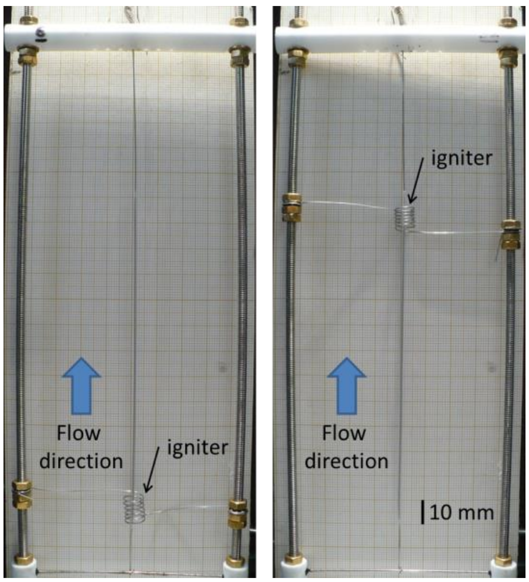

Figure 3. Picture of samples ready for upward propagation (left) and downward propagation (right) using 6 times wrapped igniter

Table 1. Sample wire specification

Inner core material	Nickel-chrome (NiCr)	Cupper (Cu)
Insulation material	Low density polyethylene	
Core diameter [mm]	0.5	
Insulation thickness [mm]	0.3	

Figure 3 shows pictures of the sample holders. Every sample holder had a wire coated with polyethylene over 130 mm. The position of the igniter could vary, in order to enable both opposed and concurrent flow propagation. Table 1 shows the specifications of wire. In this research, two types of core wire: Nickel-chrome (NiCr) and Cupper (Cu) wire insulated by Low density polyethylene were used. Core diameter was 0.5 mm, and insulation thickness was 0.3 mm. For the ignition procedure, a 0.5 mm diameter Kanthal wire was wrapped around the leading edge of every insulation coating, and about 94 W were delivered by a power supply along the 8 s long ignition sequence. The shape of igniter was coil, which diameter was as same as M8 screw and winding number was 6 times. We started the ignition sequence before the starting of μg. So ignition occurred in the μg.

The μg condition was obtained from parabolic flights on board of the Novespace A310 airplane. Every parabola enabled μg conditions of about 20 s duration with a g-jitter +/- 10^{-2} g_0. The parabolic flight had a g-jitter[20,21] of 10^{-2} g_0 (0.5~1 Hz), and consequently, a mild flow of around 30 mm/s was expected.[21] Therefore the data obtained with all external flow are expected to have insignificant errors, because all the flow velocities were higher than 30 mm/s. However, when we discuss the trend of LOC vs. external flow velocity such as Fig.4, each plot should have error bar of ±30mm in terms of air flow velocity, which is actually not shown to avoid complication.

III. Result of the extinction limit

In this study, when a flame is sustained during the whole μg period of each parabola, it is considered as a "propagation" scenario. When the flame is not sustained during the whole period of μg, it is considered an "extinction" scenario. Near the LOC condition, propagation flame was too dim to capture the visible camera. So we judged the propagation and extinction using the movement of molten insulation in the flame using backlighting camera. Then, the LOC is assumed to exist between the maximum extinction case and minimum propagation case. In the past research[18], there was the comparison between normal gravity and microgravity in terms of LOC using NiCr wire.

Figure 4 and Figure 5 show the extinction limits of spreading flames over NiCr wire and Cu wire in μg under different flow velocity conditions, set by the mass flow controllers. This was single run experiment. One plot shows one experiment. An open circle corresponds to flame propagation conditions in μg, and a cross shows flame extinction conditions in μg. Positive velocities means opposed flow velocity condition, and negative velocities means concurrent flow velocity condition.

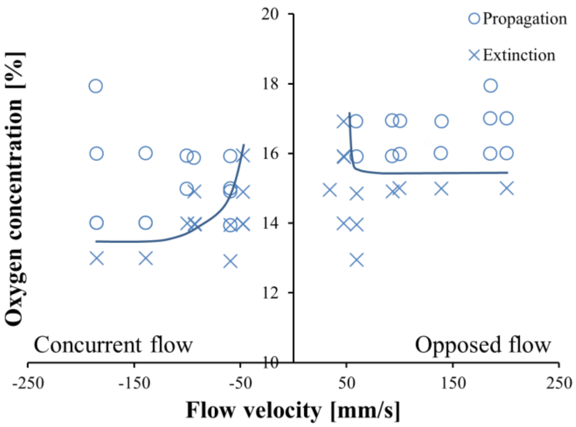

Figure 4. The LOC of NiCr wire in μg[18]

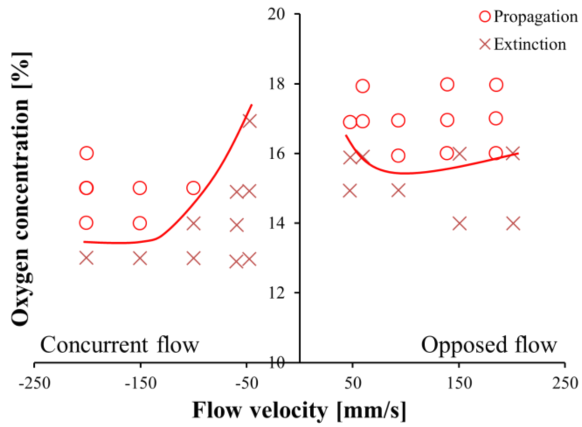

Figure 5. The LOC of Cu wire in μg

Previous results[18] established using NiCr wires in μg showed that under opposed flow, the LOC value first decreases with increasing external flow velocity, and then becomes constant. In μg concurrent flow case, the tendency of LOC is similar to the trend in opposed flow. The minimum LOC for concurrent flow is about 2 % lower in oxygen concentration than that for opposed flow.

With respect to the core wire material, the trend of LOC of Cu wire in both opposed and concurrent flow case are similar to that of NiCr wire, and the minimum LOC of Cu wire is close to that of NiCr wire in both opposed and concurrent flow case. Past results[22] show that the minimum LOC of NiCr wire is lower than that of Cu wire in both opposed and concurrent flow case because the heat loss passed through the core wire is much larger for Cu core wire than for NiCr core wire[22]. However, in this experiment, the difference of the minimum LOC between NiCr wire and Cu wire is quite small. This is because the thickness of the insulation is different. In this experiment, the insulation of the wire is two times thicker compared to the past research one (insulation thickness was 0.15 mm). These fact implies that thicker insulation suppress the effect of thermal conductivity of core material. However, we need more discussion about the effect of core material under different insulation thickness.

IV. Discussion

According to research by Olson[2], two types of the extinction phenomena exist, namely quenching extinction in the low flow region, and blow-off extinction in the high flow region. In this research, a physical model is proposed to predict the LOC in low flow region (quenching extinction) of spreading flame over electrical wire. As a base of discussion, the concept of scale analysis carried out by Takahashi et al. is adapted for the case of electrical wire[23]. In this model, NiCr wire was considered to ignore the core wire effect.

A. Model of spreading flame over electric wire in opposed flow case

Figure 6 shows the schematics of a flame spread over the wire in opposed flow case. The opposing flow velocity V_g is due to forced-flow. With respect to the flame, the oxidizer, assumed to be a mixture of oxygen and nitrogen, approaches with a velocity V_g and the flame spread rate is given as V_f.

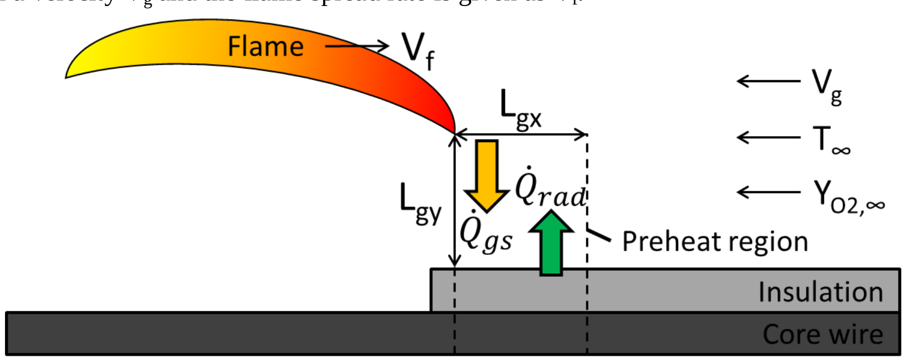

Figure 6. Schematic of propagating flame in opposed flow (Not to scale)

This physical model has the assumptions in the following list:

1. Core and insulation are thermally thin for radial direction.
2. Shape of insulation does not change in preheat zone.
3. Heat conduction through core wire is ignored.

In opposed flow case, the length of preheat zone L_g and height of leading edge of flame were assumed as the following equation.

$$L_g = L_{gx} = L_{gy} = \frac{\alpha_g}{V_g} \tag{1}$$

In the preheat zone, two types of heat transfer were considered; heat conduction from flame to wire (Q_{gs}), and radiation loss from wire (Q_{rad}). In this model, we assume that there was the minimum flame spread rate to keep the flame propagation. And some energy was needed to keep the minimum flame spread rate from flame. So, an energy balance for the solid phase in preheat zone can be express as follows,

$$Q_{gs} = Q_{rad} + Q_{req} \tag{2}$$

It means that extinction happens when the heat generated by the flame is lost through radiations from insulation and there is not enough energy available to keep the minimum flame spread rate. Using some algebraic manipulations, the equation can be made non-dimensional into the following form:

$$1 = R_{rad.wire} + \eta_{wire} \tag{3}$$

It means that extinction happen when the ratio of radiative energy loss to heat input from flame exceeds critical value. Energies are expressed as follows,

$$\dot{Q}_{gs\_opp} = \frac{2\pi\,\lambda_g(T_f\text{-}T_p)}{\ln\left(1+\frac{L_g}{r_s}\right)} L_g \tag{4}$$

$$\dot{Q}_{rad\_opp} = 2\pi r_s \epsilon_s \sigma\left(T_p^4\text{-}T_\infty^4\right) L_g \tag{5}$$

$$Q_{req\_opp} = V_f \pi\left\{r_c^2 \rho_c c_c + \left(r_s^2\text{-}r_c^2\right)\rho_s c_s\right\}\left(T_p\text{-}T_\infty\right) \tag{6}$$

Hence, the energy balance equation from Eq.(2), when substituted into Eq. (4), produce:

$$R_{rad.wire_{opp}} = \frac{Q_{rad_{opp}}}{Q_{gs_{opp}}} = \frac{r_s \epsilon_s \sigma(T_p^4\text{-}T_\infty^4)}{\lambda_g(T_f\text{-}T_p)/\ln(1+L_g/r_s)} \tag{7}$$

$$\eta_{wire\_opp} = \frac{Q_{req\_opp}}{Q_{gs\_opp}} = \frac{V_f\{r_c^2\rho_c c_c + (r_s^2\text{-}r_c^2)\rho_s c_s\}(T_p\text{-}T_\infty)}{2\lambda_g(T_f\text{-}T_p)L_g/\ln(1+L_g/r_s)} \tag{8}$$

To determine the critical value of $R_{rad,wire\_opp}$, we give the following equation based on Eq.(3):

$$R_{rad,opp} = 1\text{-}\eta_{wire,opp} = 1\text{-}\frac{Q_{req,opp}}{Q_{gs,opp}} = 1\text{-}\frac{Q_{req,opp}(V_f)}{Q_{rad,opp}(V_g)+Q_{req,opp}(V_f)} \tag{9}$$

From this equation, $R_{rad,opp}$ can be derived from a steady flame spread rate in a given flow velocity near a extinction limit. In this research, we define that extinction happens in opposed flow case when $R_{rad,wire\_opp}$ becomes 0.168 from the calculation result of using flame spread rate of V_g = 60 mm/s, which is lowest flow velocity in this experiment. This flame spread rate was experimental data.

B. Model of spreading flame over electric wire in concurrent flow case

Figure 7 shows the schematics of spreading flame over the wire in concurrent air flow. The concurrent flow velocity V_g is due to forced-flow. With respect to the flame, the oxidizer, assumed to be a mixture of oxygen and nitrogen, approaches with a velocity V_g and the flame spreads with a velocity V_f.

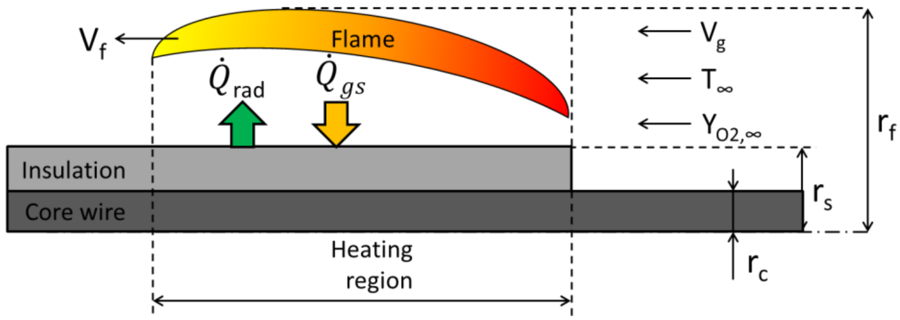

Figure 7. Schematic of propagating flame in concurrent flow (Not to scale)

This physical model has the assumptions in the following list;

1. Core and insulation are thermally thin for radial direction
2. Shape of insulation does not change in preheat zone
3. Steady flame spread is achieved[24]

In this research, the preheat zone in concurrent flow is defined as the flame length, L_f. Flame height, r_f, is given by the equation below according to the research by Bhattachargee et al. based on stoichiometric ratio of fuel and oxydizer[25].

$$r_f \sim \sqrt{\frac{\nu V_f \pi \left(r_s^2 - r_c^2\right)\rho_s}{\pi V_g \rho_g Y_{O2,\infty}} + r_s^2} \tag{10}$$

In the same manner as opposed flow case, each of the energies are expressed as follows,

$$\dot{Q}_{gs\_conc} = \frac{2\pi \lambda_g \left(T_f - T_p\right)}{\ln(r_f/r_s)} L_f \tag{11}$$

$$\dot{Q}_{rad\_conc} = 2\pi r_s \epsilon_s \sigma \left(T_p^4 - T_\infty^4\right) L_f \tag{12}$$

$$\dot{Q}_{req\_conc} = V_f \pi \left\{r_c^2 \rho_c c_c + \left(r_s^2 - r_c^2\right)\rho_s c_s\right\}\left(T_p - T_\infty\right) \tag{13}$$

Hence the energy balance equation leads to:

$$R_{rad.wire_{opp}} = \frac{r_s \epsilon_s \sigma \left(T_p^4 - T_\infty^4\right)}{\lambda_g \left(T_f - T_p\right)/\ln(r_f/r_s)} \tag{14}$$

$$\eta_{wire} = \frac{V_f \left\{r_c^2 \rho_c c_c + \left(r_s^2 - r_c^2\right)\rho_s c_s\right\}\left(T_p - T_\infty\right)}{2\lambda_g \left(T_f - T_p\right)/\ln(r_f/r_s)} \tag{15}$$

In concurrent flow case, the flame heats up the unburned sample widely. It means that the ratio of Q_{req} to heat input from flame to the sample becomes small because unburned sample is efficiently heated up by combustion gas. So, in this research, we defined that extinction happen in concurrent flow case when $R_{rad,wire\_conc}$ is 1.

C. Estimated trend of LOC based on the proposed model

Figure 8 shows a result of trial to estimate the trend of LOC as a function of opposed and concurrent flow velocity. In this calculation, we assumed the adiabatic flame temperature. So we could change the flame temperature to Oxygen concentration.

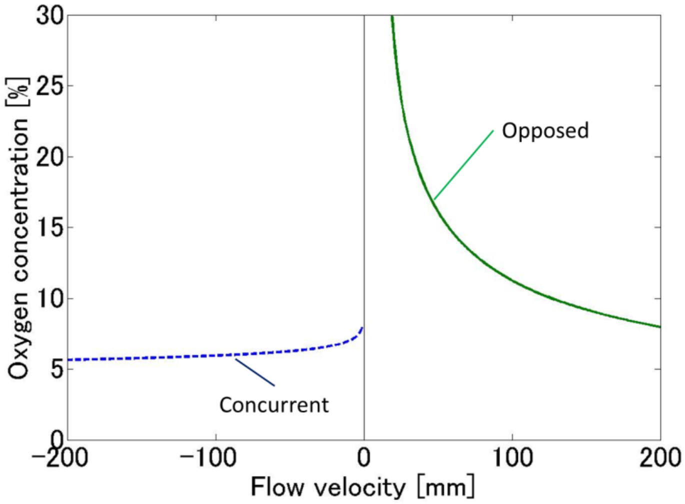

Figure 8. The calculated result of LOC

In both case, the LOC decreases with increase in the external flow velocity. Also, in low flow velocity range, the LOC of concurrent flow case is lower than that of opposed flow case. This trend qualitatively matched with the experimental data. If the blow-off extinction curve is superposed to the figure, minimum LOC both in opposed and concurrent could be given at the crossover point of two lines.

However, when the absolute value of the calculation is compared with experimental data, significant discrepancy is found. We need more deep discussion to improve the calculation.

V. Conclusion

The present work investigated the effect of flow direction on Limiting Oxygen Concentration (LOC) of a spreading flame over Cupper (Cu) and Nickel-chrome (NiCr) wire insulation in reduced gravity. The main conclusions of the present study may be summarized as follows:

(1) According to the flammability tests, LOC in concurrent flow condition was lower than that in opposed flow condition in both NiCr and Cu wire.
(2) The minimum LOC of NiCr wire was close to that of Cu wire. This is because the insulation of wire was thick, so the effect of the core material was minimized.
(3) The heat balance model of spreading flame over electrical wire was proposed to explain the LOC difference between opposed flow and concurrent flow conditions using the concept of normalized radiative heat loss value.
(4) The trend of LOC calculated from the model was qualitatively matched with experimental results.

These results provide insight into the mechanism of extinction limit of flame spread over wire insulation, especially the effect of flow direction on the extinction limit, which will be useful for establishing reliable fire safety standard for spacecraft.

Appendix

The following the value for the calculation.

r_s = 0.00055; radius of wire [m];
r_c = 0.00025; radius of core wire [m]
ρ_s = 910; density of insulation [kg/m3]
ρ_c = 8400; density of core material [kg/m3]
ρ_g = 0.3528; density of gas at 1000K [kg/m3]
ε_s = 1; insulation emissivity
σ = 5.670367E-8; Stefan-Boltzmann coefficient [W/m2K4]
T_p = 710; pyrolysis temperature [K]
T_∞ = 300; ambient temperature [K]
λ_g = 0.06763; thermal conductivity at 1000K [W/mK]

V_f = 1.3681391E-3; minimum flame spread rate of concurrent flow at 60 mm/s [m/s]
V_f = 7.17E-4; minimum flame spread rate of opposed flow at 60 mm/s [m/s]
c_c = 0.45E3; specific heat of core material [J/kg/k]
c_s = 2.32E3; specific heat of insulation material [J/kg/K]
c_p = 1142; specific heat of gas at 1000K [J/kg/K]
ν = 3.4; stoichiometric ratio
λ_{O2} = 0.07046; thermal concuctivity of Oxygen at 1000K [W/mK]
c_{p_O2} = 1089; specific heat of Oxygen at 1000K [J/kg/K]

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