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Numerical Simulation of Flame Spreading over Polyethylene Insulated NiCr wire for Prediction of the Limiting Oxygen Concentrations in Microgravity

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1. Introduction

The study of flame spreading over insulated electric wire in microgravity environment is an important topic regarding human space exploration. As the latter is becoming a major goal for multiple space agencies around the world, the study of fire safety in the space environment is mandatory, and electric wires are the most likely candidates for fire starts in a manned space vehicle. Studying the extinction phenomena is necessary considering the closed space that is a manned vehicle, where astronauts have limited space and time to react in case of a fire and must avoid any gas poisoning or critical equipment damage.

The Limiting Oxygen Concentration or LOC is the index chosen to evaluate fire safety, also known as quenching limit. Below this concentration, fire cannot spread, and fire safety is ensured. But this limit varies depending on the external flow velocity of the air in the spacecraft, the material and shape of the electric wire and insulation, etc.

Furthermore, microgravity environment allows for different flame spread phenomena, as natural convection is no longer affecting the fire. Takahashi et al. [1] measured the LOC for a flame spread over an insulated wire in normal gravity and microgravity environments. The results hinted at a lower LOC for microgravity environment, which means that wires are more flammable in a spacecraft, compared to on the ground. It is important to note that currently, electric wires brought aboard spacecraft are being selected based on tests performed on the ground, but for fire safety purposes, these tests should be performed in a microgravity environment, or partial gravity environment in the case of a mission on another celestial body.

In this study, the LOC was numerically calculated for a flame spreading over a polyethylene-coated Nickel-Chrome wire with respect of the ambient air flow velocity. The Damkohler number and Radiation number were calculated to compare the numerical results with the expected extinction phenomena with respect of flow velocity.

This study is the first reported case of numerical calculation for flame spread extinction phenomena over insulated electric wires.

2. Numerical analysis

The schematic diagram shown in Fig. 1 describes the model considered in this study. The electric wire is composed of a metallic core (here Nickel-Chrome alloy) and of a polymer insulation (here Polyethylene PE). The core has a diameter of 0.5 mm and the coating thickness is 0.15 mm. The gas field surrounding the wire is treated as an axially symmetric cylindrical two-dimensional coordinate system (x, r), over a domain of mm (along x and r respectively). Solid phase (wire core and insulation) is treated as a one-dimensional coordinate system (x), ignoring the radial distribution. The flame spread was assumed as unidirectional along the positive x-axis, with the wire placed horizontally on the x-axis. For simplicity of calculation, only ethylene was considered as the evaporating gas.

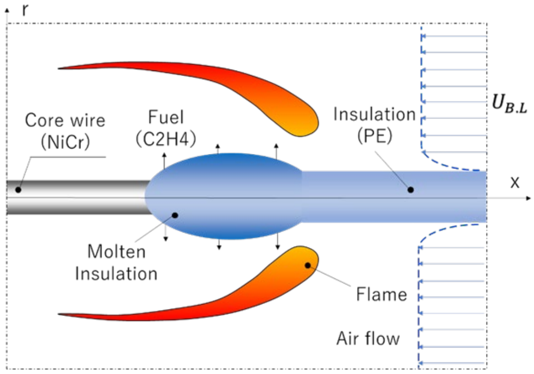

Fig. 1 The schematic of calculation model

3. Results and discussion

Fig 2-1 shows the spread and extinction cases for multiple opposite external air flow velocity (5, 10, 20, 60, 100, 150, 200, 250, 350, 500) obtained with the calculation method used in this study. Fig. 2-2 shows the median value between flame spread and extinction, as well as the experimental results obtained by Takahashi et al. [1]. In absolute value, the difference ranges between 0.918% and 0.165% oxygen concentration, and the trends match for high flow velocity, which confirms the correct behavior of the calculation method for the blow-off extinction phenomenon. For lower velocities, the LOC reaches a minimum value of 13.125% before increasing slightly for very low flow velocities. These results are different from the parabolic shape found by Olson et al. [2] for flat samples, where the LOC would increase as external flow velocity decreases for values below $50\ mm.s^{-1}$.

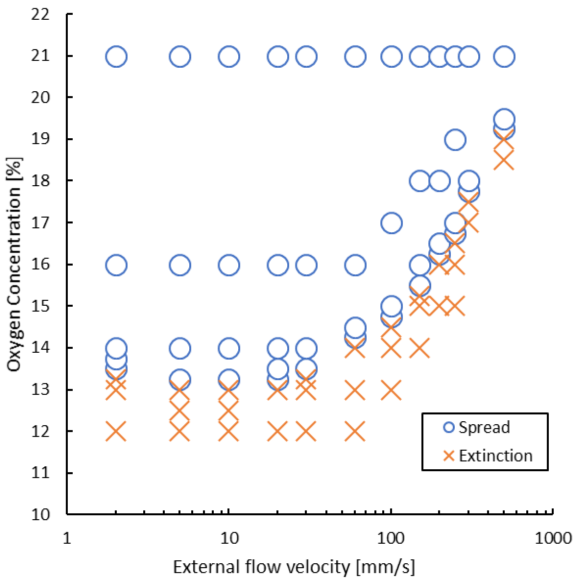

Fig. 2.1 Flame pread and extinction cases for various external flow velocity conditions

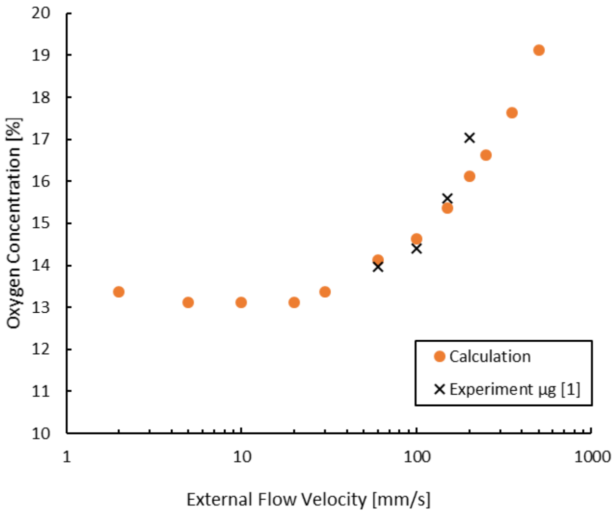

Fig. 2.1 Limiting oxygen concentration for various external flow velocity conditions, experimental and numerical results

Further investigation on the data obtained numerically show a good match with expected behavior for extinction phenomena at low and high velocities. Dimensionless numbers such as the Damkohler number and the Radiation number have been used to verify these behaviors, as well as plotting of different scalar fields such as temperature, mass fraction of combustion products, reaction rate, as well as vector field for flow velocity. Additionally, flame temperature was compared to the adiabatic flame temperature. These results allowed for a better understanding of the phenomena, as most of those parameters are impossible to monitor in experiments.

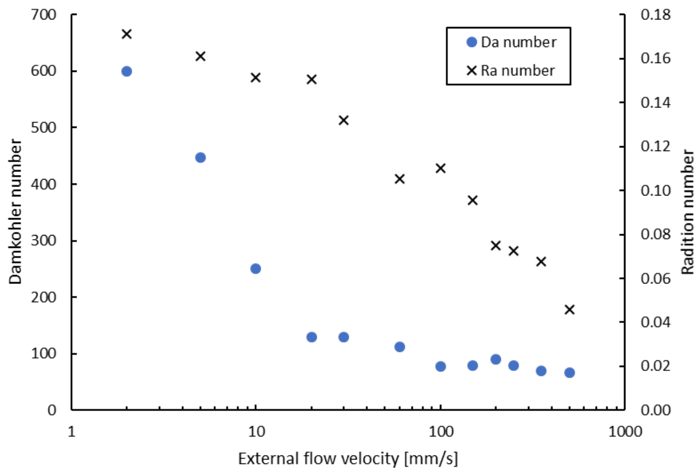

Fig. 3 Damkohler and Radiation number for various external flow velocity conditions

As Fig. 3 shows, the Damkohler number, calculated as the ratio of local residence time over characteristic chemical reaction time, decreases with increasing flow velocity. This highlights the blow-off extinction phenomena for high flow velocities. The Radiation number, calculated with the energy balance in a defined zone in the insulation, increases with decreasing flow velocity. This behavior matches the expected result for the radiation extinction or quenching extinction, but as mentioned previously, this extinction does not impact the LOC as expected from the results by Olson. Fig. 4 shows the ratio between the flame spread velocity and external flow velocity. As it can be seen, this ratio increases as the external flow velocity decreases, up to a point where the value is above one for very low flow velocity. This means that the movement of the flame is sustaining the flame in oxygen, in addition to the external flow, which increases its flammability. The quenching extinction is still observable as deduced from the radiation number increasing with decreasing external flow velocity, but not to the same extent as for a flat sample. Additional research on this phenomenon are to be expected for fire safety purpose as the numerical results would suggest a higher flammability for electric wires for low external flow velocities than previously expected.

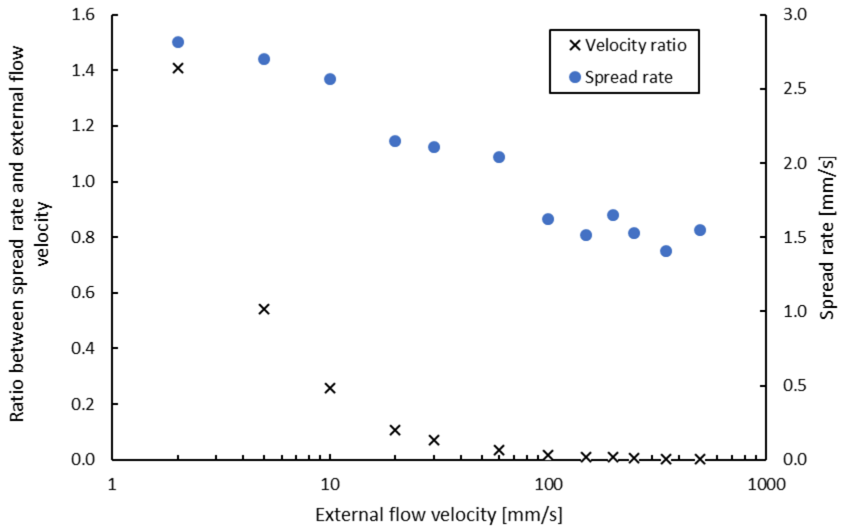

Fig. 4 Spread rate and ratio of spread rate over external flow velocity for various external flow velocity conditions

4. Conclusion

The Limiting Oxygen Concentration (LOC) of a flame spread over a polyethylene-insulated wire with respect of external air flow velocity was obtained by numerical calculation. In addition, the Damkohler number and Radiation number have been obtained, which are considered to indicate the extinction phenomena of flame spread over the wire insulation from the obtained numerical analysis and discussed. The difference between numerical results and theoretical results has been determined, concluding that the flammability of insulated wires in microgravity is higher than expected.

Acknowledgment

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References

[1] S. Takahashi, H. Ito, Y. Nakamura, and O. Fujita: Combust. Flame, vol. 160, no. 9 (2013), pp. 1900

[2] S. L. Olson: Combust. Sci. Technol., vol. 76, no. 4-6 (1991), pp. 233