Establishment of 2-D integrated adiabatic combustion model of solid propellant used for solid propellant microthrusters

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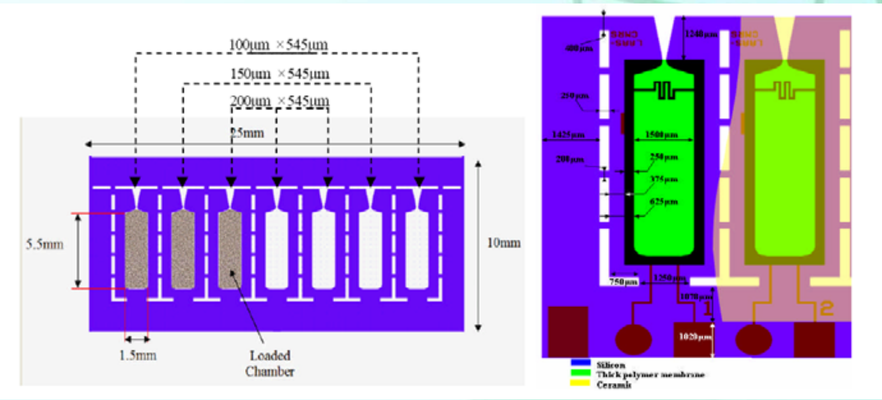
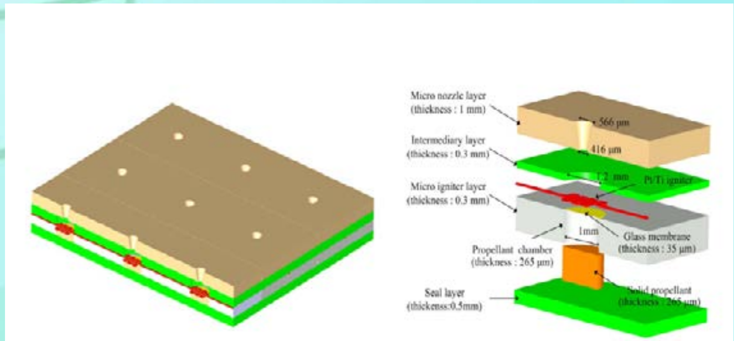
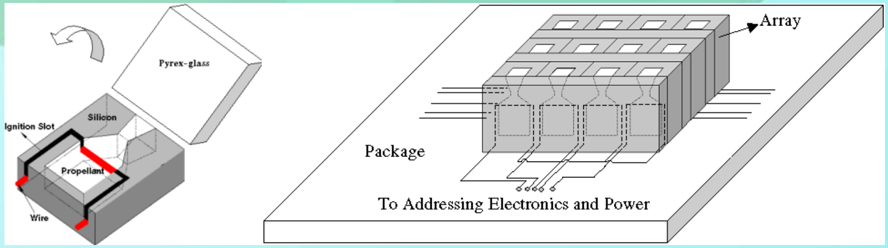
- Solid propellant microthruster(SPM)



SPM developed by LAAS-CNRS



SPM developed by KAIST



SPM developed by National University of Singapore

1. Introduction

Advantage of solid propellant microthruster:

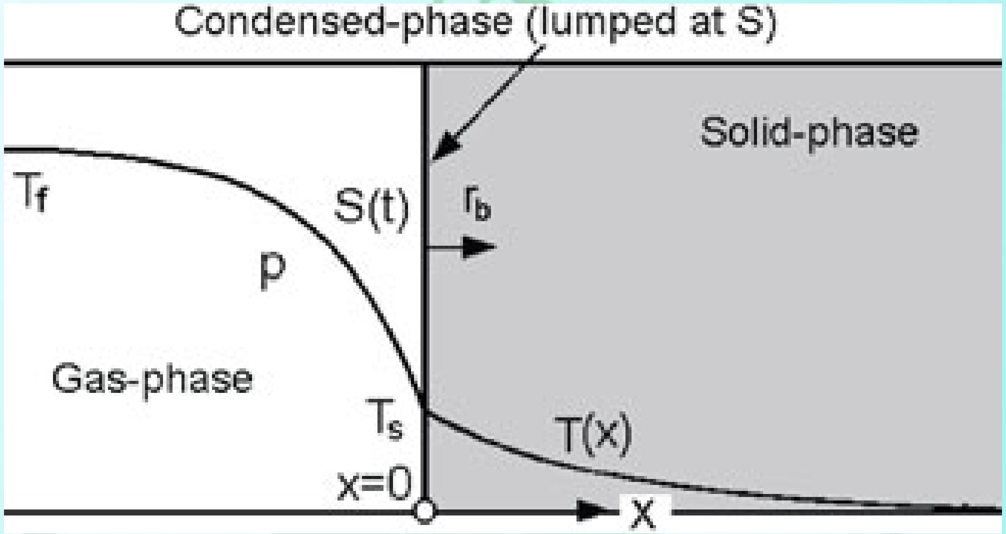
- High reliability due to its simple structure without moving parts
- No leakage of propellant
- High stability of propellant

Disadvantage of solid propellant microthruster:

- One shot use, which can be mitigated by forming an array

1. Introduction

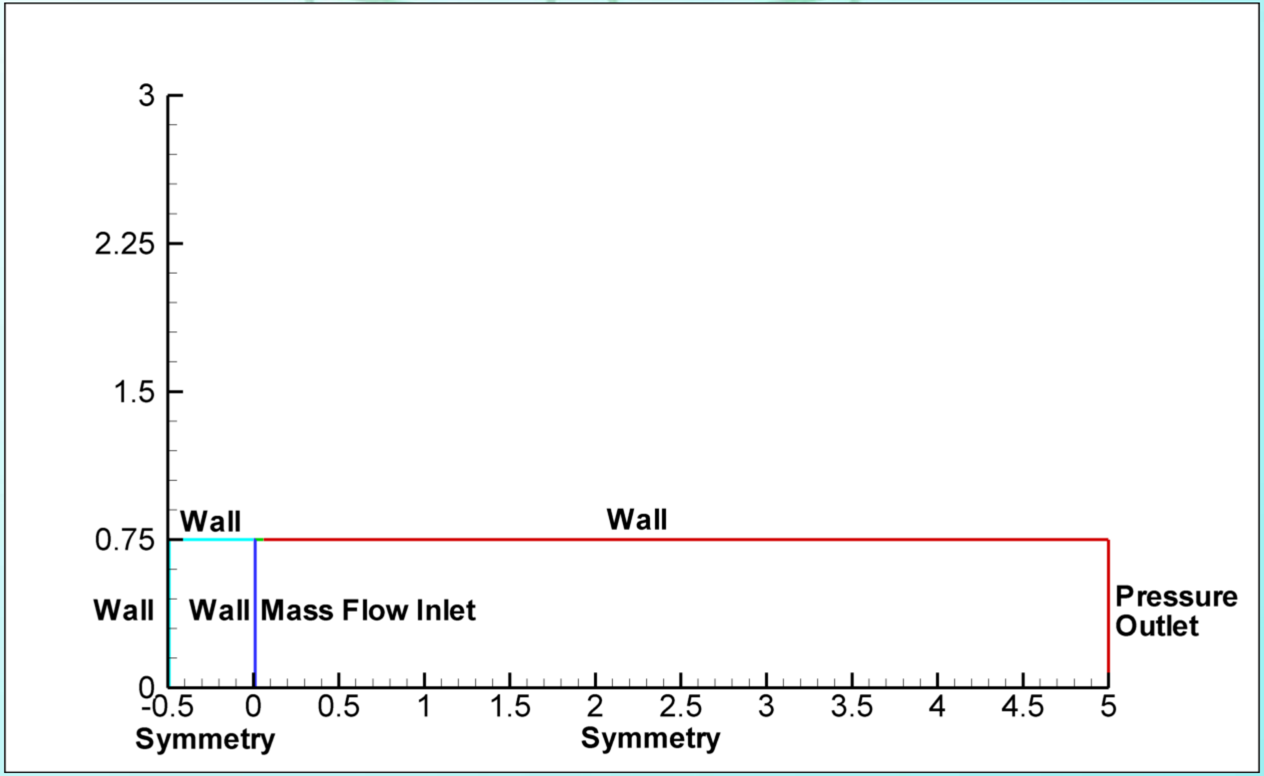
- Combustion model of solid propellant



- 1-dimensional models containing both gas phase and condensed phase have been proposed
- No implementation in 2-dimensional or 3-dimensional cases

2. Models and method

- 2.1 Geometric model and boundary types



2. Models and method

- 2.2 Reaction mechanism
- Condensed phase reactions:

$$\text{propellant} \rightarrow 0.4821\,NO_2 + 0.2960\,CH_2O + 0.1500\,(CHO)_2 + 0.0419\,CO + 0.03\,C \quad (1)$$

$$NO_2 + 0.56\,CH_2O + 0.16\,(CHO)_2 \rightarrow NO + 0.38\,CO + 0.5\,CO_2 + 0.5\,H_2O + 0.03\,C \quad (2)$$

- Gas phase reactions:

$$NO_2 + 0.56\,CH_2O + 0.16\,(CHO)_2 \rightarrow NO + 0.38\,CO + 0.5\,CO_2 + 0.5\,H_2O + 0.03\,C \quad (3)$$

$$2\,CH_2O \rightarrow CO + 0.5\,C_2H_4 + H_2O \quad (4)$$

$$2\,(CHO)_2 \rightarrow 4\,CO + 2\,H_2 \quad (5)$$

$$NO + 0.16\,CO + 0.12\,C_2H_4 + 0.12\,H_2 \rightarrow 0.5\,N_2 + 0.4\,CO_2 + 0.36\,H_2O \quad (6)$$

$$C + NO \rightarrow CO + 0.5\,N_2 \quad (7)$$

2. Models and method

- 2.3 Controlling equations of condensed phase
- Species transport equation: $\rho_c \frac{\partial Y_i}{\partial t} + \rho_c r_b \frac{\partial Y_i}{\partial x} = \dot{w}_i$
- Energy equation: $\rho_c C_c \frac{\partial T}{\partial t} + \rho_c r_b C_c \frac{\partial T}{\partial x} = \lambda_c \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) + \dot{q}_c$
- Reactant's mass source of Reaction (1): $\dot{w}_1 = -\rho_c B_c \exp\left(-E_c / R_u T\right)$
- Reaction rate of Reaction (2): $\dot{w}_2 = \rho_g B_{NO_2} p^{0.39} \exp\left(-E_{NO_2} / R_u T\right) \frac{Y_{NO_2}}{M_{NO_2}}$
- Energy source: $\dot{q}_c = \sum_{j=1}^{2} w_j Q_j$

2. Models and method

- 2.4 Controlling equations of gas phase
- Universal Navier-Stokes equation:

$$\partial\left(\rho\Phi\right)/\partial t + div(\rho\vec{U}\Phi) = div(\Gamma\, grad\Phi) + S$$

- Ideal gas: $p = \rho RT$
- Reaction rate of Reaction (3): $\dot{w}_3 = \rho_g A_{NO_2} p^{0.39} \exp\left(-E_{NO_2}/R_u T\right)\frac{Y_{NO_2}}{M_{NO_2}}$
- Reaction rate of Reaction (4): $\dot{w}_4 = \rho_g^2 A_{CH_2O} \exp\left(-E_{CH_2O}/R_u T\right)\frac{Y_{CH_2O}^2}{M_{CH_2O}^2}$
- Reaction rate of Reaction (5): $\dot{w}_5 = \rho_g^2 A_{(CHO)_2} \exp\left(-E_{(CHO)_2}/R_u T\right)\frac{Y_{(CHO)_2}^2}{M_{(CHO)_2}^2}$

2. Models and method

- Reaction rate of Reaction (6):

$$\dot{w}_6 = \rho_g^2 A_{NO} \exp\left(-E_{NO}/R_u T\right)\frac{Y_{NO}^2}{M_{NO}^2}$$

- Reaction rate of Reaction (7):

$$\dot{w}_7 = \rho_g A_{CARB} p\bar{M} \exp\left(-E_{CARB}/R_u T\right)\frac{Y_{CARB}Y_{NO}}{M_{CARB}M_{NO}}$$

- Energy source:

$$\dot{q}_c = \sum_{j=3}^{7} w_j Q_j$$

2. Models and method

- 2.5 Boundary conditions
- Left wall: $Y_{propellant} = 1, \quad Y_i = 0$
- Condensed phase side of propellant's burning surface:

$$Y_{propellant} = 0, \quad T = 300K, \quad T_{s,c} = T_{s,g}$$

- Gas phase side of propellant's burning surface:

$$\dot{m}Y_{s,g} = \dot{m}Y_{s,c} + \rho_g D_{i,g} \frac{\partial Y_{i,g}}{\partial x} \rightarrow Y_{s,g} = \frac{Y_{s,c} + \rho_g D_{i,g} Y_{i,g} / (\dot{m}dx)}{\left[1 + \rho_g D_{i,g} / (\dot{m}dx)\right]}$$

$$\lambda_g \left(\frac{\partial T}{\partial x}\right)_g = \lambda_c \left(\frac{\partial T}{\partial x}\right)_c + \rho_c r_b C_s \left(T_s - T_{ref}\right) \rightarrow T_{s,g} = \frac{\lambda_c T_c / dx_c + \lambda_g T_g / dx_g - \rho_c r_b C_c T_{ref}}{\lambda_c / dx_c + \lambda_g / dx_g - \rho_c r_b C_c}$$

2. Models and method

- Burning rate at the propellant's burning surface:

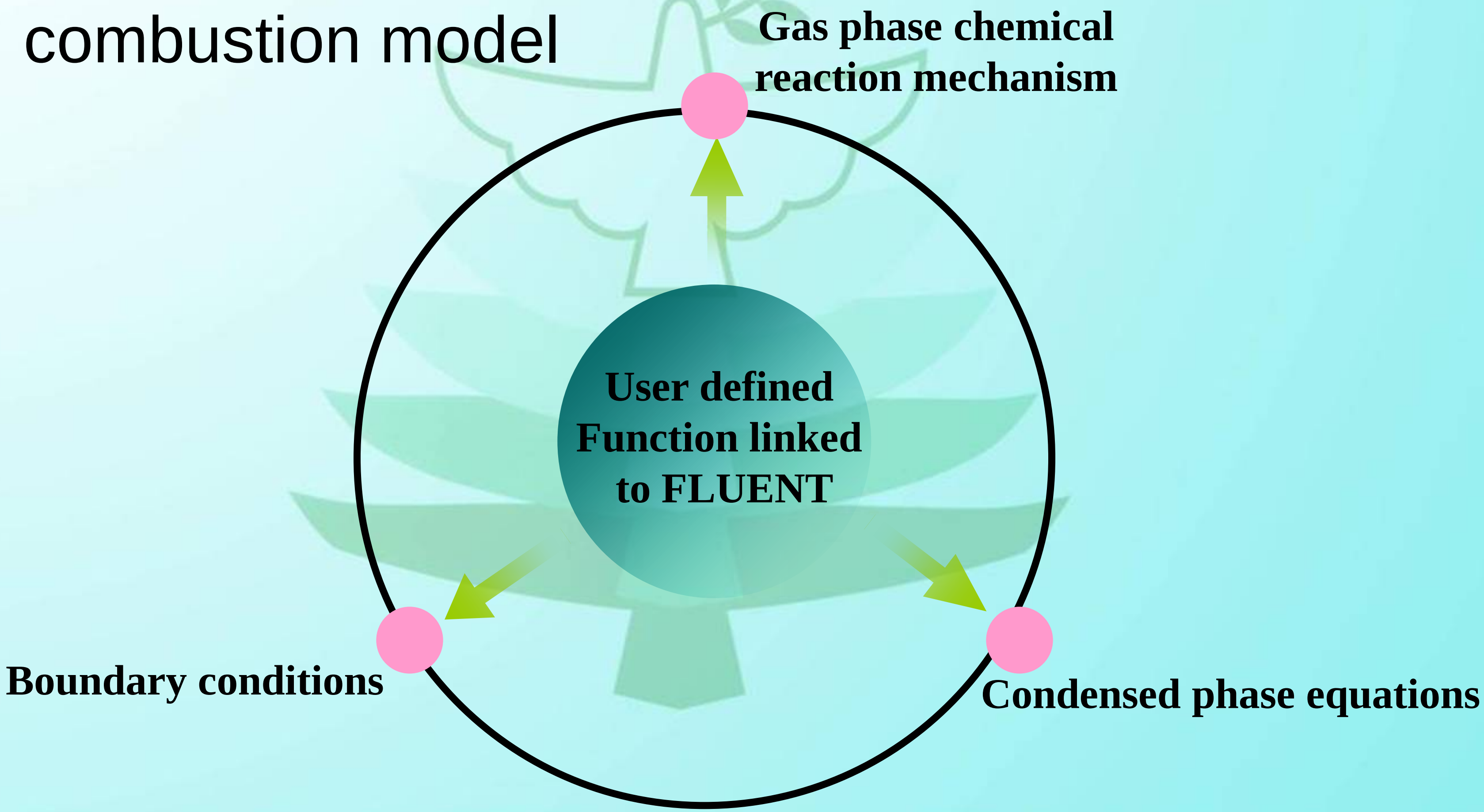
$$\left.\begin{aligned}
&\lambda_c\left(\frac{dT}{dx}\right)_s A_s = \rho_c r_b A_s\left[C_c\left(T_s - T_i\right) - Q_c\right]\\
&Q_c = Q_1 + Q_2\left(Y_{NO_2,0} - Y_{NO_2,s}\right)\\
&\rho_p r_b\left(Y_{NO_2,0} - Y_{NO_2,s}\right)A_s\\
&= B_{NO_2}\int \rho_g Y_{NO_2}\exp\left(-E_{NO_2}/RT\right)dv
\end{aligned}\right\}\rightarrow r_b = \frac{\lambda_c\left(\frac{dT}{dx}\right)_s A_s + B_{NO_2}Q_2\int \rho_g Y_{NO_2}\exp\left(-E_{NO_2}/RT\right)dv}{\rho_c\left[C_c\left(T_s - T_i\right) - Q_1\right]A_s}$$

$$T_s = T_{s,g} = T_{s,c}$$

- Mass flux at the burning surface: $\dot{m} = \rho_c r_b$

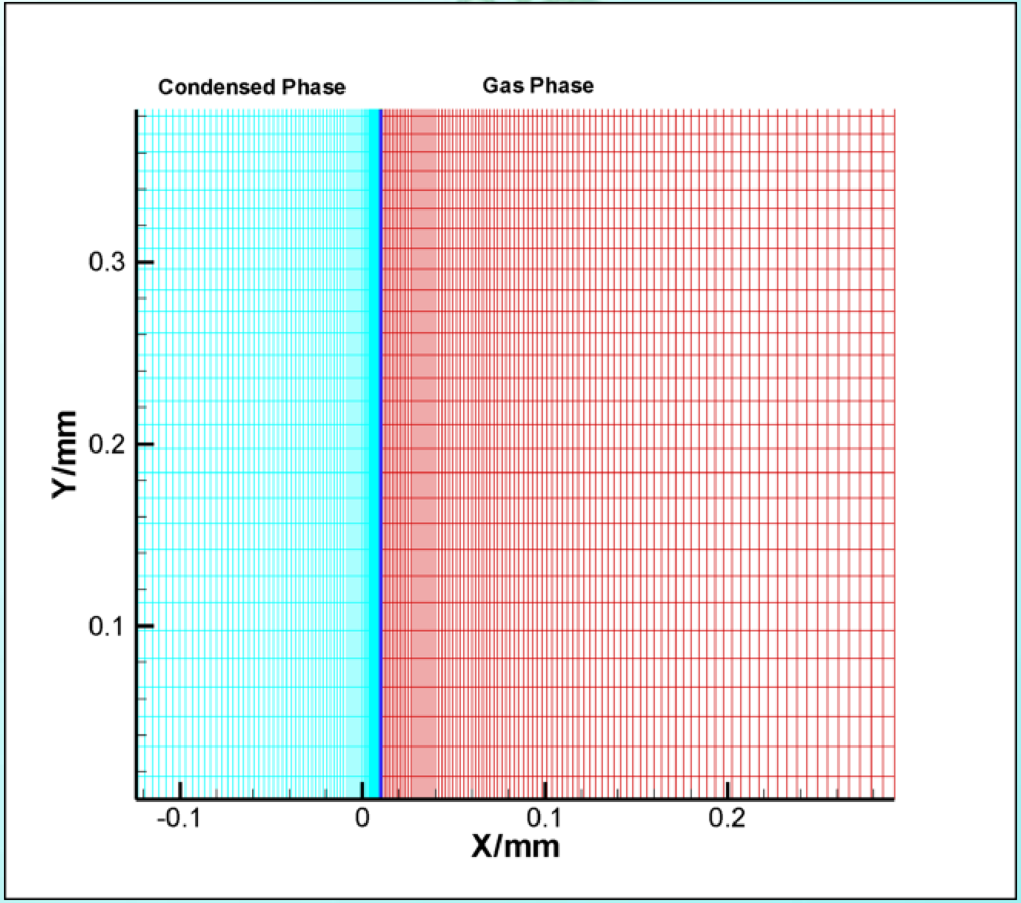
2. Models and method

- 2.6 Implementation of the 2-D integrated combustion model



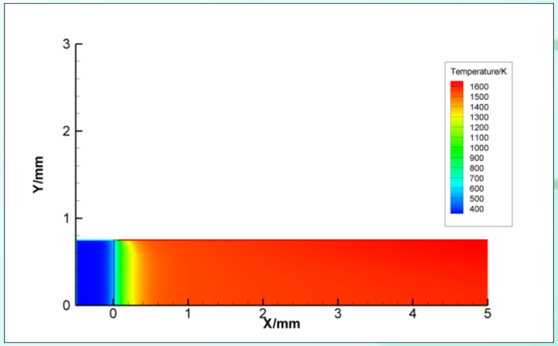
2. Models and method

- 2.7 Mesh used for calculation

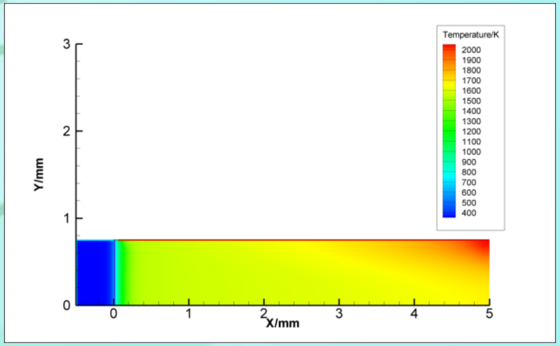


3. Results

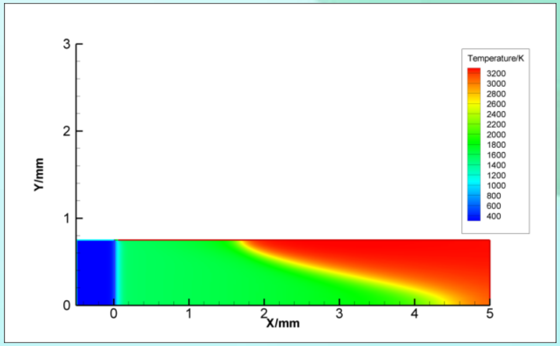
- Temperature contour for 4 sets of local pressure values



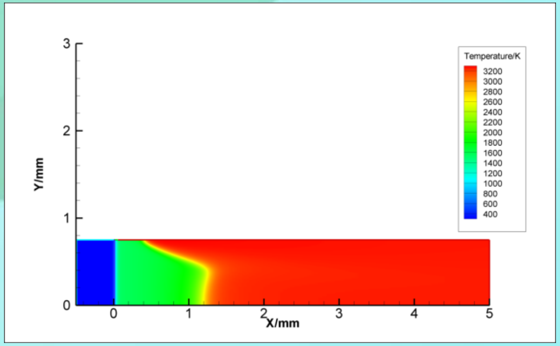
(a) 5atm



(b) 10atm



(c) 20atm



(d) 50atm

3. Results

- Calculated temperature and burning rate at various positions of burning surface

Pressure/atm	5	10	20	50
Burning surface temperature near the wall/K	604.61	623.09	642.59	670.05
Burning surface temperature near the symmetry/K	602.87	621.36	640.90	668.53
Local propellant burning rate near the wall/$mm \cdot s^{-1}$	1.682	2.776	4.570	8.785
Local propellant burning rate near the symmetry/ $mm \cdot s^{-1}$	1.622	2.684	4.431	8.564

4. Conclusion

1. **Establishment of 2-D micro scale integrated combustion model of solid propellant is realized.**
2. **The effect of fluid viscosity causes flow speed variation, which leads to flame stretch in 2-D atmosphere.**
3. **The asymmetry of flame structure in gas phase leads to asymmetry in condensed phase, which is demonstrated by temperature and burning rate at the propellant's burning surface.**
4. **In future study, more effects will be taken into consideration, including heat loss through the wall and non-flat recession of the propellant's burning surface.**

Thank you for your attention!

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