

Horizontal flame spread along paper sheet with a backing board

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1 INTRODUCTION

Flame spread along combustible surface is affected the flow condition. Under normal gravity condition, flame spread without forced convection depends on the propagation orientation, upward or downward for vertical propagation, and upper side or lower side for horizontal propagation, etc.

The flame spread along ceiling^[1,2] is a case of lower side propagation where hot pyrolysis zone locates on cold air layer. The heat transfer from the hot pyrolysis zone is carried out through conduction. Considering the lower heat transfer rate of conduction comparing convection, the heat and mass transfer rates from the hot pyrolysis zone is smaller in the conduction dominant case than in the convection conduction dominant case^[1,2,3]. If the heat and mass transfer rates are smaller than a critical limit, no flame propagation occurs.

For the case of horizontal flame spread along paper sheet with a backing board^[4,5], lower side propagation occurs during ignition when the combustible is externally heated. The minimum separation between the combustible and backing board surfaces exists for the horizontal flame spread. If the separation is smaller than this minimum separation, no flame propagation occurs with a finite heating. Once the separation is larger than this minimum separation, flame propagation occurs.

As the paper is heated externally, the thermal boundary layer grows near the paper surface. As the thermal layer grows, the temperature gradient in the horizontal direction also grows and lateral convection layer will form in this temperature boundary layer. Once, this lateral convection layer formed, the heat and mass transfer rates increases and flame propagation may occur.

In this study, a numerical simulation of two dimensional flow field heated from upper side is carried out to investigated the governing mechanisms of the ignition of horizontal flame spread along paper sheet with a backing board.

2 Numerical Model

Two dimensional space with constant temperature walls is considered as the model of this study. The external heating is simulated with locally high temperature region on the upper wall. The observed minimum separation, d_s between paper and backing surfaces is between 2 mm and 5mm for filter paper experiments^[4,5]. This separation is consistent with the results of flame spread experiments^[6]. Assuming the temperature of pyrolysis zone, T_p is 700 K^[6] and the environmental temperature, T_e is 300 K, the temperature difference, $T_p - T_e$ is 400 K. The temperature gradient, $(T_p - T_e)/d_s$ is from 2.0×10^5 K/m to 8.0×10^4 K/m. Assuming thermal conductivity of air at 400 K, k is 3.3×10^{-2} W/(m K), the heat flux for this temperature gradient is 5.0×10^3 W/m² to 2.0×10^4 W/m². Grashof number, Gr_l for the characteristic length, l is from 100 to 1600. This low Grashof number indicates that the natural convection in this two dimensional space does not occur for uniform heating. In this study, local heating is considered to understand the temperature and flow field in this two dimensional space. In the horizontal flame spread experiment, flammable gas is emitted downward from the heated area. This downward gas flow forms a counter flow field in this two dimensional space. In this study, the flammable gas emission is not considered for the early stage of heating process where the pyrolysis is slow. With these condition, a model of two dimensional space of height, l and width, w is considered. The flow field is two dimensional. The fluid is a perfect gas with a constant volumetric thermal expansion coefficient, β and the density change in the inertial term of the moment equation is small. With Boussinesq assumption, the governing equations are simplified.

A two-dimensional flow field in the x-y plane of width $10l$ contained between two planes at $y = 0$ and $y = l$ is considered. The fluid originally uniform temperature T_0 is heated from top wall between $x = 4l$ and $x = 6l$ at the temperature T_1 .

Based on the reference quantities of the reference length l , reference velocity ν/l , reference temperature difference $T_1 - T_0$, the following dimensionless variables are constructed^[7].

$$X = x/l, Y = y/l, T = t/(l^2/\nu),$$

$$U = u/(\nu/l), V = v/(\nu/l), \theta = (T - T_0)/(T_1 - T_0). \quad (1)$$

The governing equations in dimensional form^[7] are

$$U = \partial \Phi / \partial Y \quad (2)$$

$$V = - \partial \Phi / \partial X \quad (3)$$

$$\Omega = - (\partial^2 / \partial X^2 + \partial^2 / \partial Y^2) \Phi \quad (4)$$

$$\partial \Omega / \partial T + \partial (U \Omega) / \partial X + \partial (V \Omega) / \partial Y = Gr \partial \theta / \partial X + (\partial^2 / \partial X^2 + \partial^2 / \partial Y^2) \Omega \quad (5)$$

$$\partial \theta / \partial T + \partial (U \theta) / \partial X + \partial (V \theta) / \partial Y = Pr^{-1} (\partial^2 / \partial X^2 + \partial^2 / \partial Y^2) \theta \quad (6)$$

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where $Gr = g l^3 (T_1 - T_0) / T_0 \nu^2$ is the Grashof number and $Pr = \nu / \alpha$ is the Prandtl number.

Flow field is computed with square meshes of size 300×30 in this study.

3 RESULTS

Dimensionless temperature θ , horizontal velocity U , and vertical velocity V at $T = 1.9$ of $Gr = 100$ and 300 are shown as monochrome map in figure 1. Heated and positive velocity areas are shown as white color in this figure.

Horizontal velocity U indicates that the heated air flows outward in the upper part and the cold air flows inward in the lower part. Vertical velocity V indicates that the heated air flows upward below the heated area. Stagnation point is seen the middle of the heated area. The velocity gradient of horizontal velocity U and vertical velocity V are larger in $Gr = 300$ than that in $Gr = 100$.

The flow direction at the boundary of heated area is outward, the heat is convected to the outer unburned area from the burned area for flame spread condition.

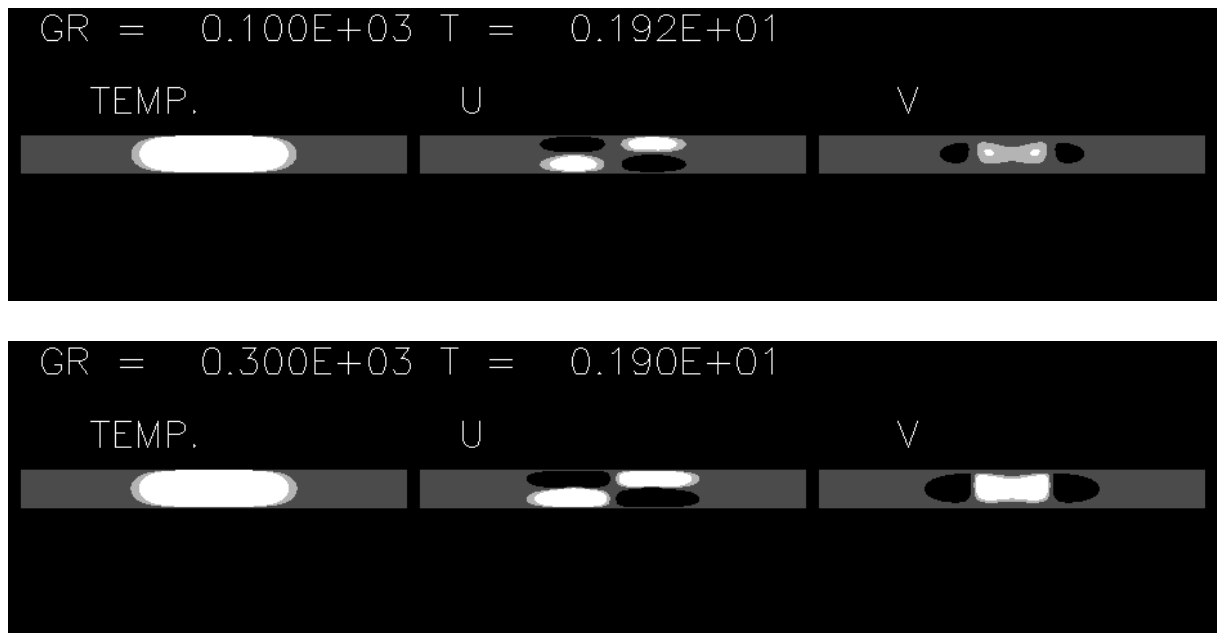


Figure 1 Dimensionless temperature, horizontal velocity, and vertical velocity

The distributions of dimensionless horizontal velocity U at $X = 6$ of $Gr = 250, 500, 1000, 2000$ after $T = 1.5$ are shown with Y in figure 2. The sign of the dimensionless horizontal velocity is negative for $Y < 0.545$ and positive for $Y > 0.545$. The fluid is moving to the heated area in the lower part and exiting from heated area in the upper part. The absolute value of the dimensionless horizontal velocity increases with the Grashof number Gr . The absolute value of dimensionless horizontal velocity U of $Gr = 250$ is smaller than 1.0 , which indicates that the flow velocity is smaller than the characteristic thermal wave velocity ν/l .

The distributions of dimensionless temperature θ at $X = 6$ of $Gr = 250, 500, 1000, 2000$ after $T = 1.5$ are shown with Y in figure 3.

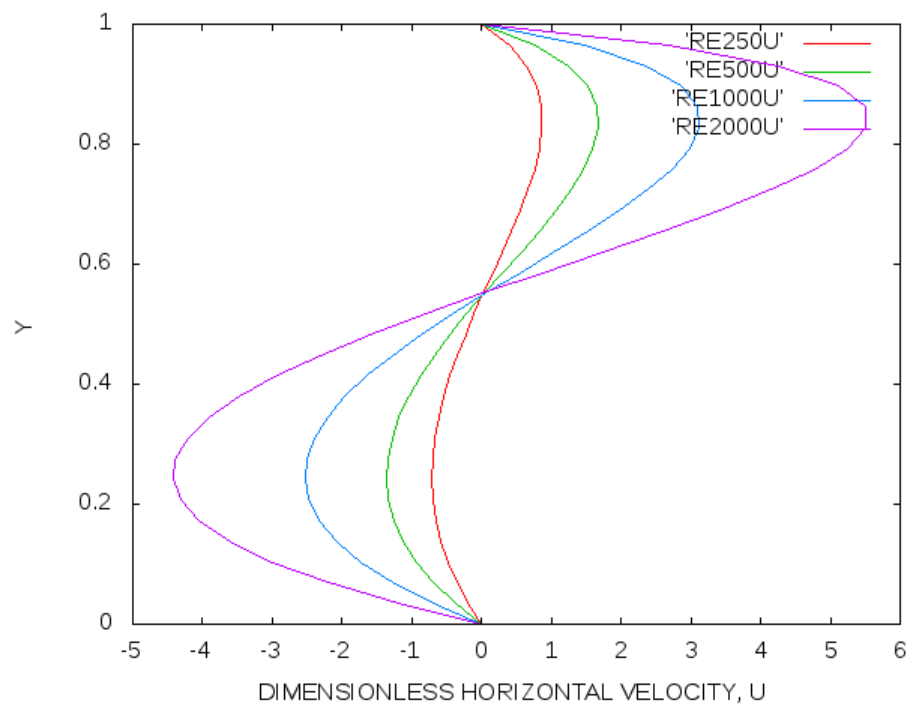


Figure 2 Distributions of dimensionless horizontal velocity

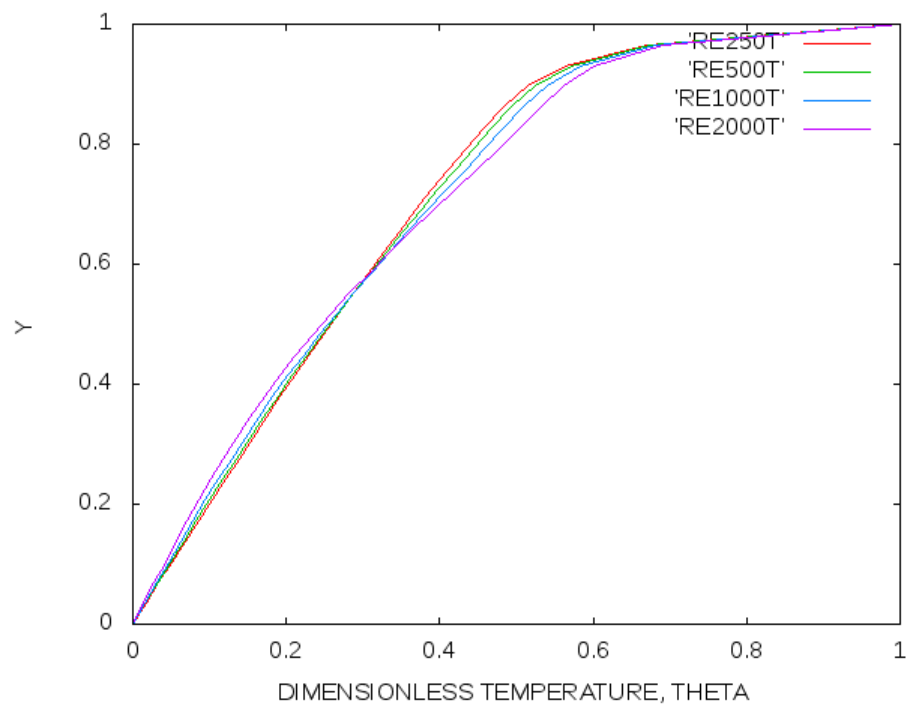


Figure 3 Distributions of dimensionless temperature

4 DISCUSSION

The natural convection of uniform heating from below the field occurs for $Gr > 1708$. The natural convection of non uniform heating from above the field also occurs for $Gr = 250, 300, 500, 1000, 2000$. For the case of horizontal flame spread along paper sheet with a backing board, the estimated Grashof number, Ga_1 is from 100 to 1600. With this small value of Grashof number, convection flow is seen near the boundary of heating area.

The induced horizontal velocity near the boundary of heating area is less than unity for $Gr = 250$. For this small Grashof number, the formed temperature distribution is governed by thermal diffusion. The heat and mass transfer is mainly controlled by diffusion process.

The vertical temperature gradient in the lower part increases with Grashof number and a steep distribution is seen at $Gr = 2000$. The vertical temperature distribution is almost identical for $250 < Gr < 1000$. This result indicates that the heat transfer is enhanced by the natural convection for $Gr > 2000$. It seems that the flow induced thermal diffusion field which supports the flame spread along paper sheet is formed for $Gr > 2000$ in the lower part. The steady flame spread along paper sheet seems difficult for $Gr < 2000$ which is close to the estimated Grashof number, Ga_1 .

References

- [1]OHTANI H, HIRANO T, AKITA K.(1981).Experimental study of bottom surface combustion of polymethylmethacrylate. Eighteenth Symposium(International) on Combustion:591.
- [2] CLARK RSF.(1984).Radiative Ignition of Thermoplastic and Char-forming Materials. Fire and Materials 8-4:196.
- [3]ZHOU L.(1992).Solid Fuel Flame Spread and Mass Burning in Turbulent Flow. NIST-GCR-92-602.
- [4]SUUCHI T, TAYAMA T, NISHIKI S, KADOWAKI S.(2008).Flame Spread over Cellulosic Paper in a Narrow Space. Forty-Sixth Symposium(Japanese) on Combustion:160.
- [5]TOKUDA M, ITO A, TORIKAI H.(2010).Circular Flame Spread along a Thin Combustible Solid using a Center Point Ignition Source. Forty-Eighth Symposium(Japanese) on Combustion:322.
- [6]GAO L, HIRANO T.(2008). Mechanisms of Flame Spread over a Filter Paper Permeated with an Adhesive. Univ. Bull. Chiba Inst. Sci. 1:159.
- [7]Torrance KE,Rockett JA.(1969).Numerical study of natural convection in an enclosure with localized heating from below creeping flow to the onset of laminar instability.J. Fluid Mech. 36(1):33.