CHARACTERISTICS OF DIFFUSION FLAMES WITH ACCELERATED MOTION

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The aim of this work is to present an experiment to study the characteristics of a laminar diffusion flame under acceleration. A Bunsen burner (nozzle diameter 8 mm), using liquefied petroleum gas as its fuel, was ignited under acceleration. The temperature field and the diffusion flame angle of inclination were visualised with the assistance of the visual display technology incorporated in MATLABTM. Results show that the 2-D temperature field under different accelerations matched the variation in average temperatures, they both experience three variations at different time and velocity stages. The greater acceleration has a faster change in average temperature with time, due to the accumulation of combustion heat, the smaller acceleration has a higher average temperature at the same speed. No matter what acceleration was used, in time, the flame angle of inclination increased, but the growth rate decreased until an angle of 90°. This could be explained by analysis of the force distribution within the flame. It is also found that, initially, the growth rate of angle with velocity under the greater acceleration was always smaller than that at lower accelerations, and it was also different in flames with uniform velocity fire conditions.

Key words: accelerated moving fire, diffusion flame, temperature field, flame characteristics

Introduction

The characteristics of a flame are important in that they reflect the combustion process therein. Many studies have been reported to describe the temperature field and characteristics of a static flame [1-5]. It is found that three colour thermometry with a charge coupled device (CCD) optical measurement system is a useful, and universal method of measuring the characteristics of a flame [2-4]. This study used a modified three-colour thermometric method for measuring the 2-D temperature field and characteristics of a diffusion flame moving in accelerated motion. The flame temperature field depends on mixing the air as an oxidizer, the flow of air, burner dimensions, and the type of flame (premixed, partially premixed, or diffusion). All of these factors will affect the flame temperature and characteristics. The flame shape is the most intuitive of its features and there are many researchers who have investigated this issue [6-9]. Oh and Dongsoon [10] carried out an experimental study on the effects of varying the fuel and oxidizer composition on flame characteristics in a non-pre-mixed oxy-methane flame in a laboratory-scale furnace with a slot-type burner. The flame stabilisation, flame slope, flame length, and furnace temperature were investigated. The results showed that flame slope was affected by global equivalence ratio and the mass flow rate between the fuel and the oxidizer.

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However, in most of the previously outlined researchs, the characteristics of the flame were measured and studied in static fires. Limited studies have been reported to describe the influence of fire movement on flame characteristics. It is universally acknowledged that motor vehicles caused the fire, because of its motion characteristics formed moving fire. Moving fires, due to the relative lateral movement between fire and surrounding air flow, will increase flow turbulence, strengthen the heat, and mass transfer between the air and fuel, affect the flame shape, and make the fire process more complex. All of these highlight the combustion characteristics and heat transfer mechanisms of moving fires. Wind speed and the topography have important effects on fires (e.g., the influence of wind speed change on fire spread in inclined tunnels). The cross air flow is the one of the most important factor affecting flame characteristics [11-13]. Chen et al. [14] studied the effects of wind on a compartment fire with crossventilation, the ambient wind would enhance fire severity by increasing the compartment fire temperature and reducing the time to flashover. For flame tilt Pipkin and Sliepcevich [15] observed buoyant diffusion flames of natural gas in wind tunnel experiments to determine the extent of bending in the wind. The experimental results were correlated through use of a simple physical model of flame structure. Hu [16] carried out tests on ethanol and heptane square pool fires with side lengths of 10 cm, 15 cm, 20 cm, and 25 cm under a wind speed of up to 2.5 m/s and proposed a new dimensionless global parameter, equating the wind speed by a characteristic uprising velocity of the flame supported by the buoyancy strength of the pool fire.

At the scene of the fire, the wind speed might be not uniform but may be accelerated or decelerated, the burning car may be not just static, but undergoing accelerated or decelerated motion, all of these change the flame characteristics, and make them more complicated. The goal of the present research is to study (experimentally) the effect of acceleration on laminar diffusion fire behaviour. The influence of time, velocity, and acceleration on the characteristics of diffused flames was investigated. The measurement principles and test process are presented in the following sections.

Experiments

Test system and method

The host high-speed camera (Kodak Motion Corder Analyser, SR series) was used to store flame image data, fig. 1. The burner and high-speed camera were put on a sliding plate so that the camera could record the fire throughout. A Bunsen burner (8 mm diameter fuel nozzle) was fixed on a bracket. Propane, the main component of liquefied petroleum gas, was used as the fuel in this experiment. To form a stable diffusion flame, the fuel flow rate was 0.1 g/s, this gave a laminar flow at a Reynolds number of approximately 1055. The slid-



Figure 1. Test system for measuring the temperature field of a diffusion flame with accelerated motion in a moving fire (constant acceleration)

ing plate on the rail was fixed to a sliding trolley that was driven by a non-elastic rope. The other end of the rope was passed through the pulley and the pulley block, before the experiment, an electronic balance was used to measure the total mass, *m*. By adjusting the system parameters of the high-speed camera and host (as well as the distance from the camera to the flame), the observer can display clear images of the fire over the whole process, from a static, to an accelerated moving-state. In these tests, acceleration was adjusted by changing the masses used. First, it was necessary to determine the shooting distance on the slide and to set the frame rate and shutter speed (in these tests, the frame rate was set to 500 fps). According to the number of images obtained, and the distance moved by the trolley, the velocity and acceleration of the moving fire can be determined (accelerations of 2.5 m/s^2 , 3.6 m/s^2 , 5.4 m/s^2 , and 6.5 m/s^2 were found).

The original image sequence of a diffusion flame in a moving fire

Figure 2 shows an image sequence obtained from a uniformly-accelerated moving diffusion flame undergoing rectilinear motion (acceleration 3.6 m/s^2 , velocity range 0.036-0.9 m/s). The 25-image sequence in fig. 2 was formed from the original image sequence by selecting one in four of the images. The time interval between two adjacent images was 0.01 s. The image sequence provides the original outer flame image data for the measurement of the flame temperature field using digital image processing technology.

<i>v</i> = 0.036 ms ⁻¹	$v = 0.072 \text{ ms}^{-1}$	$v = 0.108 \text{ ms}^{-1}$	$v = 0.144 \text{ ms}^{-1}$	$v = 0.180 \text{ ms}^{-1}$
	٨			
v = 0.216 ms ⁻¹	v = 0.252 ms ⁻¹	v = 0.288 ms ⁻¹	v = 0.324 ms ⁻¹	v = 0.360 ms ⁻¹
v = 0.396 ms ⁻¹	<i>v</i> = 0.432 ms ⁻¹	<i>v</i> = 0.468 ms ⁻¹	$v = 0.504 \text{ ms}^{-1}$	<i>v</i> = 0.540 ms ⁻¹
1	1	1	1	1
v = 0.576 ms ⁻¹	v = 0.612 ms ⁻¹	v = 0.648 ms ⁻¹	v = 0.684 ms ⁻¹	v = 0.720 ms ⁻¹
1	1	1	1	1
<i>v</i> = 0.756 ms ⁻¹	v = 0.792 ms ⁻¹	v = 0.828 ms ⁻¹	<i>v</i> = 0.864 ms ⁻¹	<i>v</i> = 0.900 ms ⁻¹
1	1	1	1	1

Figure 2. Flame images corresponding to 25 velocities at an acceleration of 3.6 m/s² (for color image see journal web site)

Three-colour thermometry

Theory and principles

According to combustion radiation theory, flame brightness varies with temperature. Thus, for measurement of flame temperature, the brightness of the flame must be recorded. Then, using the three primary-colour photoelectric channels, the optical signals contained in the pixel brightness data can be transformed into electrical signals. Moreover, the brightness thereof can be input into a computer using an image acquisition card. Using the grey body, assumption the wavelength is independent of the emissivity and the emissivity can be simplified as a function of temperature [17]:

$$\frac{\partial \varepsilon[\lambda, T(i, j)]}{\partial \lambda} = 0 \tag{1}$$

$$\varepsilon[\lambda_{\rm R}, T(i,j)] = \varepsilon[\lambda_{\rm G}, T(i,j)] = \varepsilon[\lambda_{\rm B}, T(i,j)]$$
(2)

where, $\varepsilon[\lambda_R, T(i, j)]$, $\varepsilon[\lambda_G, T(i, j)]$, and $\varepsilon[\lambda_B, T(i, j)]$ are the emissivity of the adjacent narrow wave-bands in the R, G, and B channels over the band used in the measurement, respectively. The equation for three-colour thermometry of the flame image can be derived [18]:

$$T(i,j) = \frac{c\left(\frac{2}{\lambda_{\rm G}} - \frac{1}{\lambda_{\rm R}} - \frac{1}{\lambda_{\rm B}}\right)}{\ln\frac{R(i,j)B(i,j)}{G^2(i,j)} + \ln\frac{K_2^2}{K_1K_3} + 5\ln\frac{\lambda_{\rm R}\lambda_{\rm B}}{\lambda_{\rm G}^2}}$$
(3)

where T(i, j) is the temperature corresponding to an arbitrary pixel, c – the second radiation constant ($c = 1.438 \cdot 10^{-2}$ mK), λ_R – the wave-length of the red channel ($\lambda_R = 700.1 \cdot 10^{-9}$ m), λ_G – the wave-length of the green channel ($\lambda_G = 546.1 \cdot 10^{-9}$ m), and λ_B – the wave-length of the blue channel ($\lambda_B = 435.8 \cdot 10^{-9}$ m), and K_1, K_2 , and K_3 – the constants of proportionality. By calibrating the system using the K_2^2/K_1K_3 values from tests and pre-processing a series of images from the original flame images, the flame temperature, T(i, j), is calculable using the grey level signals of the three components R(i, j), G(i, j), and B(i, j) at an arbitrary point (*i*, *j*). After all the pixel temperatures in the flame image have been computed, the 2-D temperature field of the diffusion flame in the moving fire is available. Three-colour thermometry is an extension of two-colour thermometry. Two-colour thermometry merely uses two of the RGB components (RG, RB, or GB) and neglects one of them. The information in the original flame image is thereby not fully used. In contrast, three-colour thermometry yields a more accurate measurement result since it uses all image data relating to the three primary colours.

Temperature calibration for three-colour thermometry

The thermometric theory leading to eq. (3) is based on the assumption that the combustion flame is a grey body. In fact, a flame does not radiate with grey features all the time. Therefore, the grey body assumption that $\varepsilon[\lambda_R, T(i, j)] = \varepsilon[\lambda_G, T(i, j)] = \varepsilon[\lambda_B, T(i, j)]$ is only true when the values of λ_R , λ_G , and λ_B are close enough. However, due to the limitations resulting from the nature of the colour CCD, the wave-lengths of the colour images can only be centered on 700, 546.1, and 435.8 nm. This is certain to cause errors that can not be ignored. The error can be reduced using the values of $T_{cn} = 2$, $T_{cn} = 2$, and $T_{cn} = 2$ calculated by eq. (3).

The error can be reduced using the values of T_{GB/R^2} , T_{BR/G^2} , and T_{RG/B^2} calculated by eq. (3). According to the monochromatic wave-lengths of the different combinations used [19], three temperature solutions also can be calculated using eq. (3), and these were denoted as T_{GB/R^2} , T_{BR/G^2} , and T_{RG/B^2} . By summing their expressions, it was found that these temperature solutions are not independent, that is to say, they obey the following relationship:

$$\frac{1}{T_{\text{GB/R}^2}} \left(\frac{2}{\lambda_{\text{R}}} - \frac{1}{\lambda_{\text{G}}} - \frac{1}{\lambda_{\text{B}}}\right) + \frac{1}{T_{\text{BR/G}^2}} \left(\frac{2}{\lambda_{\text{G}}} - \frac{1}{\lambda_{\text{B}}} - \frac{1}{\lambda_{\text{R}}}\right) + \frac{1}{T_{\text{RG/B}^2}} \left(\frac{2}{\lambda_{\text{B}}} - \frac{1}{\lambda_{\text{R}}} - \frac{1}{\lambda_{\text{G}}}\right) = 0 \quad (4)$$

Equation (4) provides the necessary condition for reducing the error by using the known information. Based on the present theoretical analysis and experimental studies, we propose a method of three-colour thermometric correction. The method modifies the three-colour thermometry process by applying a numerical correction which was deduced:

Let $T_{\text{GB/R2}} = T_1$, $T_{\text{BR/G2}} = T_2$, $T_{\text{RG/B2}} = T_3$, $2/\lambda_{\text{R}} - 1/\lambda_{\text{G}} = \mu_1$, $2/\lambda_{\text{G}} - 1/\lambda_{\text{B}} = 1/\lambda_{\text{R}} = \mu_2$, and $2/\lambda_{\text{B}} - 1/\lambda_{\text{R}} = \mu_3$. Therefore:

$$\mu_1 + \mu_2 + \mu_3 = 0 \tag{5}$$

Suppose that the true temperature of the tested flame is T. The deviations of the three related temperature solutions are therefore $\delta_1 = T_1 - T$, $\delta_2 = T_2 - T$, and $\delta_3 = T_3 - T$. Thus, eq. (4) can be written:

$$\frac{\mu_1}{T+\delta_1} + \frac{\mu_2}{T+\delta_2} + \frac{\mu_3}{T+\delta_3} = 0$$
(6)

By expanding eq. (6) using a Taylor series:

$$\mu_{1}\left[\frac{1}{T} - \frac{\delta_{1}}{T^{2}} + \frac{\delta_{1}^{2}}{T^{3}} + R_{3}(\delta_{1})\right] + \mu_{2}\left[\frac{1}{T} - \frac{\delta_{2}}{T^{2}} + \frac{\delta_{2}^{2}}{T^{3}} + R_{3}(\delta_{2})\right] + \mu_{3}\left[\frac{1}{T} - \frac{\delta_{3}}{T^{2}} + \frac{\delta_{3}^{2}}{T^{3}} + R_{3}(\delta_{3})\right] = 0 \quad (7)$$

Neglecting terms in the expansion which are higher than third order $[R_3(\delta_n)]$, according to eq. (5) and the definitions of δ_1 , δ_2 , and δ_3 , eq. (7) can be rewritten:

$$T = \frac{\mu_1 T_1^2 + \mu_2 T_2^2 + \mu_3 T_3^2}{3(\mu_1 T_1 + \mu_2 T_2 + \mu_3 T_3)}$$
(8)

Using this expression, a flame temperature that was much closer to the true value was calculated.



Figure 3. Tested points are marked in (a) and (b) which compare the temperatures of the tested points calculated using T (from the modified thermometry formula) with the experimental temperature T_m (for color image see journal web site)

To verify the modified three-colour thermometric expression in eq. (8), we measured the temperature of a laminar flame in a static combustion fire. As shown in fig. 3(a), nine

tested points are marked on the medial axis of the outer flame, with heights, z, of 0.0, 10, 20, 30, 40, 50, 60, 70, and 80 mm, the z height of 0.0 mm represents the lower end of the wick. Expressions for T were used calculate the temperatures at the nine test points. The T_m refers to the temperatures measured using a pyrometer. Comparison of the temperatures calculated using the modified three-colour method, T, with the experimentally measured temperature, T_m , is shown in fig. 3(b). It is observed that the two curves are in good agreement. The maximum absolute error in the modified method is 45.5 K. That is, the maximum relative error in the modified three-colour thermometric method is 3.9%. The slopes were different between thermocouple experiments and the three color temperature measuring methods owning to the error caused by two main reasons. The first one is that the three color temperature measuring method had ignored those truncations error which are greater than the fourth order in Taylor expansion, the second reason is that there are undoubtedly some measuring errors in the thermocouple and image position. While the agreement between the measurement using modified three-colour thermometry and experiments was good. Therefore, the temperature calculated using the modified three-colour thermometry, T, is a valid measure of the experimentally measured conditions.

Flame region segmentation

In this research, the images obtained by the high-speed camera are colour flame images in RGB colour space. As the Euclidean distance between any two points in RGB space is not linearly proportional to colour distance, the red, green, and yellow components are extensively correlated. Thus, in the event of a fluctuation in the brightness of any one component, those of the other two components will also vary accordingly. Therefore, RGB colour space fails to meet the independence and uniformity conditions required for colour image segmentation and so the flame image can not be directly segmented in RGB space. After repeated attempts at the data processing of flame images, this study identified a colour space that has the independence and uniformity requirements necessary for colour image segmentation. This is the HSV colour space. Parameter H represents the colour information (hue), S refers to its saturation, and V (value) is the brightness of the colour.

To extract image data from the flame region in HSV colour space, it was necessary to calculate the optimum threshold of the flame image. In this study, the optimum thresholds of each flame image are calculated using a new iterative threshold segmentation algorithm. Using the optimum thresholds so obtained, the flame region was then divided into combustion and non-combustion regions. In turn, useful image data were obtained. The image segmentation results show that this iterative segmentation algorithm has a significant effect. For example, the *S* component in HSV space is extracted using the following steps in the iterative segmentation algorithm:

(1) Select an estimated value for the initial threshold $T^0 = \{T^k | k = 0\}$:

$$T^0 = \frac{S_{\min} + S_{\max}}{2} \tag{9}$$

where S_{\min} and S_{\max} refer to the minimum and maximum values of the S component of the flame image in HSV space, respectively. The image is divided into two regions using threshold T^{k} , namely, R_{1} and R_{2} . The two regions are calculated using:

$$R_{1} = \{S(x, y) \mid S(x, y) \ge T^{k}\}$$
(10)

$$R_2 = \{S(x, y) \mid 0 < S(x, y) < T^k\}$$
(11)

where S(x, y) represents the S component image.

(2) Calculate the mean saturations S_1 of R_1 and S_2 of R_2 using:

$$S_{1} = \frac{\sum_{f(i,j) < T^{k}} S(i,j) N(i,j)}{\sum_{f(i,j) < T^{k}} N(i,j)}$$
(12)

$$S_{2} = \frac{\sum_{f(i,j)>T^{k}} S(i,j)N(i,j)}{\sum_{f(i,j)>T^{k}} N(i,j)}$$
(13)

where S(i, j) refers to the saturation of point (i, j) and N(i, j) is the weight coefficient of the point. Generally, N(i, j) = 1 or N(i, j) = 0. (3) Select a new threshold T^{k+1}

$$T^{k+1} = \frac{S_1 + S_2}{2} \tag{14}$$

(4) If $T^{k+1} = T^k$, the extraction is ended. Otherwise, $k \leftarrow k+1$, and we repeat the procedure from step 2.

Figure 4(a) shows the flame temperature field constructed using the original image data (i. e. data from a moving fire that has not been segmented using the iterative algorithm). It can be seen that the construction effect is unsatisfactory. For example, consider the edge of the flame. As the image data in the non-combustion region were also incorporated into the modified three-colour thermometry model, the temperatures of the narrow bands on the outer edges of the flame region are higher than those in the centre of the flame region. At the same time, the temperatures of the narrow bands on the inner edges of the flame region are much lower than the ambient temperature (this can be verified by comparing the values displayed in



Figure 4. Comparison of flame temperature fields constructed using image data extracted from the segmented flame region and the original data; (a) the 2-D temperature field constructed using the original flame region, (b) the temperature field constructed using the moving fire region extracted by the iterative algorithm (for colour image see journal web site)

the thermometric scale). These two observations are inconsistent with the actual situation. In contrast, fig. 4(b) describes the temperature field constructed using the modified three-colour thermometry model, after the moving fire regions had been extracted using the iterative algorithm. As can be seen from the thermometric scale, the temperatures on the edges of the flame region lie within the range 850-900 K, while those of the bright red, high-temperature regions are between 1200 K and 1350 K. These measurement results are close to actual conditions, *i. e.* the reconstruction achieved an ideal effect.

Results and discussions

Influence of acceleration on flame temperature

The processing system used for the flame temperature field involved compiling image processing code in MATLABTM. In section *Three-colour thermometry*, the results from the modified three-color thermometry measurement of a static flame were compared with those using a micro-thermometer, and a satisfactory result was obtained. That is, the temperature calculated using modified three-colour thermometry was valid. Here, the same method was used to measure a moving fire under constant acceleration. The average temperature of the 2-D outer flame was extracted: figs. 5(a) and (b) show the average flame temperature variation with time and velocity under different accelerations, respectively.



Figure 5. Variation in average temperature with time and velocity under different accelerations

As shown in fig. 5(a) and (b), the average temperature of the moving fire under different accelerations presented certain similarities, that is, they both experienced three variations at different time and velocity stages. (1) In the first stage, from 0 to 0.05 seconds, and at a velocity of 0-0.2 m/s, the fire began to move, the velocity was small, and the average temperatures varied slightly during this stage. (2) On maintaining the increase in fire velocity, the temperature accelerated growth stage began and in this stage, the average temperatures fluctuated. (3) When the velocity increased beyond a threshold, the growth rate of average temperatures of the flame region began to slow down until reaching its highest temperature. This arose because, at the beginning of the fire motion, the relative motion between the flame front and the surrounding air is small, and there is no apparent interference to the flame front caused by the air flow. The combustion merely relies on the free diffusion of fuel molecules in a mild chemical reaction. With increasing velocity under constant acceleration, disturbance of the air surrounding the flame is seen. Here, more air makes contacts, and reacts, with the fuel, intensifying the chemical reaction and combustion. This triggers an increase in the temperature of the flame, however, further increasing the velocity intensifies the interference

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from the surrounding air, resulting in more heat being released from the flame. As a result, the combustion reaction is diminished and rate of change of temperature decreased. The process previously outlined was consistent with the physical principles of a moving fire.

In the meantime, differences between each curve may be seen in fig. 5. According to fig. 5(a) the greater acceleration causes faster variation in the average temperature with time, and ultimately achieves the highest average temperature earlier. Due to measuring range, the cases of $a = 2.5 \text{ m/s}^2$ and $a = 3.6 \text{ m/s}^2$ did not reach the highest temperature, but they nevertheless heated more slowly. This was because the greater the acceleration, the fire moved with greater speed at the same time, then accelerated combustion, thus triggering a higher temperature in the flame. Figure 5(b) also shows that the average temperature always increases as the velocity increases while at the same speed, the smaller acceleration had a higher average temperature. Flame temperature changed depending on the flame combustion generation, $Q_{\text{generation}}$, and dissipation, $Q_{\text{dissipation}}$, of heat. According to the energy conservation equation:

$$mc_p \Delta T = \int_{0}^{t} (Q_{\text{generation}} - Q_{\text{dissipation}}) \,\mathrm{d}t \tag{15}$$

where *m* is the flame quality, c_p – the specific heat capacity, *t* – the time, and ΔT – the flame temperature difference. According to eq. (15), at smaller acceleration longer time is needed to increase fire speed to a certain value. At the same fire speed the flame combustion generation and dissipation heat will be the same. Under such conditions, at smaller acceleration longer time will be needed, to accumulate more heat and thus to reach higher average temperature.

Influence of acceleration on flame inclinational angle

The flame, when moving, will bend, here, the flame angle of inclination, α , is defined as that made by the flame area image centroid O and the flame root middle point O', the angle between the line and the vertical direction lies in the flame angle of inclination. In the flame root, mid-point O' is the mid-point segment between the flame root A and B point (fig. 6). MATLABTM was used to extract the edge of the flame image, and identify and mark, the flame centroid and flame root mid-point. The E-Ruler electronic measuring angle tool was then used to measure the flame angle in conjunction with the eqs. (16) and (17).

$$x_{c} = \frac{\sum_{y=y_{c}}^{y_{c}} \sum_{x=x_{c}}^{x_{c}} xg(x,y)}{\sum_{y=y_{c}}^{y_{c}} \sum_{x=x_{c}}^{x_{c}} g(x,y)}$$
(16)
$$y_{c} = \frac{\sum_{y=y_{c}}^{y_{c}} \sum_{x=x_{c}}^{x_{c}} yg(x,y)}{\sum_{y=y_{c}}^{y_{c}} \sum_{x=x_{c}}^{x_{c}} g(x,y)}$$
(17)



where x, y are the flame picture arbitrary coordinates, g(x, y) – a two-valued function, x_c, y_c – the flame centroid co-ordinates, when (x, y)

Figure 6. Schematic of the flame angle of inclination

lies within the characteristic region, g(x, y) = 1, otherwise, (x, y) is in the background, and g(x, y) = 0.

Figure 7. shows the transient behaviour of flame angle of inclination, α , at different accelerations. It was found that α increased with time, but the growth rate decreased until $\alpha = 90^{\circ}$ and the greater acceleration always had the greater growth rate. For the flame to tilt, there must be some forces acting thereon. Flame angle of inclination changed depending on the angle of the resultant force. Then, the change in α may be explained by analysing the force distribution on the flame and the variations therein

As shown in fig. 8, in an accelerated moving state, the fire is acted upon by four main forces: the flame buoyancy, F_b , air drag, F_d , inertia force, F_i , and the force, F_v generated by the positive pressure of the vortex due to velocity difference, u, respectively. Buoyancy is produced by the density difference between the flame and surrounding air, and this increased with flame volume and temperature, in the vertical direction. Drag is generated by relative motion between the fire and air, and increases with the speed increases. The direction of the drag is horizontal and in the opposite direction to the fire movement. Inertial force is generated when fire accelerates under straight line motion, and increases with the acceleration, in the opposite direction to the movement of the fire: F_r is the resultant force which made the flame tilt, α is the angle of inclination of the flame, β is the angle between the resultant force and reference line, the angle between them γ is the reason why α changed because the fire accelerated.



Center line F_t F_t F_t F_t Centroid B

Figure 7. Transient behaviour of inclination α at different acceleration

Figure 8. Analysis of flame inclinational angle and flame resultant force

According to fig. 8, β may be found from:

$$\tan \beta = \frac{F_{\rm d} + F_{\rm i}}{F_{\rm b} + F_{\rm v}} \tag{18}$$

The triangular transformation of eq. (18) gives:

$$\beta = \arctan \frac{F_{\rm d} + F_{\rm i}}{F_{\rm b} + F_{\rm v}} \tag{19}$$

Differentiating eq. (19), and letting $x = (F_d + F_i)/(F_b + F_v)$ gives:

$$\frac{\partial \beta}{\partial x} = \frac{1}{1+x^2} \tag{20}$$

When the flame began to move, α decreased, the temperature increase rapidly, the main force acting on the flame was the air resistance and buoyancy. With increasing flame speed, flame inclination near the burner vortex to the rear of the positive pressure area increased, and no flame temperature peak was obvious (the effects on buoyancy were similar). At this time the main factors influencing α were the drag, and the vortex positive pressure, F_{v} . And the two forces both increased with speed so the inclination angle changed slightly.

Using eq. (19), as the forward velocity increased, the drag F_d increased, as did the resultant angle, β . From eq. (20), the growth rate of the angle of the resultant force, β , decreased with increasing x, where $x = (F_d + F_i)/(F_b + F_v)$. As the flame accelerated, the fire velocity increased with time, so that the drag F_d increased, the rate of growth of the resultant angle (β) with time decreased. This finally resulted in a decrease in the rate of growth of the angle of inclination of the flame (α) with time.

Figure 9 shows the flame inclinational angle variation with velocity for different accelerations. It was found that the trends were almost the same as seen in fig. 7, the flame angle increased with velocity, but the growth rate decreased. However, there is a turning point for the speed (0.7 m/s), before α began to vary slightly. The greater the acceleration, the smaller the value of α , which meant that the rate of change of α initially decreased with increasing acceleration. After that, the opposite was true because when the flame began to move with constant acceleration, the inertial force, which was in the opposite direction to its motion, acted on the flame to restore it to its original state,



Figure 9. Flame angle variation with moving velocity under different accelerations

and this effect increased with increasing acceleration. So in a short time after starting to move, the greater the acceleration, the more powerful the flame's ability to retain its original state.

Conclusions

This study used three-colour thermometric techniques to measure the 2-D temperature field of a diffusion flame undergoing accelerated motion in a moving fire. By combining three-colour thermometry with visual display technology, the 2-D temperature field, and flame characteristics of the diffusion flame in an accelerated moving fire, could be obtained. Key conclusions are as follow.

- The 2-D temperature field at different accelerations is found to be in agreement with the variation in average temperatures, they both experience three variations at different time and velocity stages. The greater acceleration has the faster variation of the average temperature with time, due to the accumulation of heat. The lower accelerations give a higher average temperature at the same speed.
- Regardless of the acceleration, in time, the angle of inclination of the flame increased, but the growth rate decreased until it reached 90°, and the growth rate thereof increases with increasing acceleration. An analysis of the force distribution acting on the flame could explain this behaviour.
- The trend in flame inclination with velocity is almost the same as that with time. However, there is a turning point in the speed plot such that, a short time after the start of its mo-

tion, the greater acceleration always has the smaller flame inclination at the same velocity, and v.v. thereafter. This behaviour differs from that observed in a fire under uniform wind conditions.

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