Thermal Radiation During Spray Combustion
Behind Reflected Shock Waves

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ABSTRACT

Tailored-interface shock tubes were used as a single compression method to study spray combustion in diesel engines. The time histories of intensities of infrared thermal radiation spectra of soot particles were obtained by using this method. The Hoeltel-Broughton equation was used to analyze the thermal radiation spectra. The results were: (i) Both the distance from the injection nozzle to maximum emissive power and total thermal emissive power increase together with the increase in the injection pressure of fuel. (ii) Total thermal emissive power is proportional to the amount of injected fuel. (iii) Thermal emissive power decreases significantly as the ignition delay of fuel increases. (iv) The observed particle temperatures were between 1800 and 2800 K.

INTRODUCTION

Several groups of researchers have studied the amount of heat loss resulting from thermal radiation generated by the liquid spray flame in diesel engines (1,2,3). When measuring the thermal radiation in diesel engines, it is important to consider various factors in addition to the conditions relating to compressed air and fuel injection; these include gas flow in the cylinder, fuel spray flame colliding with the cylinder wall, emission of the hot cylinder wall and others. The locations where the detectors are placed must also be taken into consideration. To determine the effect of the basic spray combustion variables on radiation (i.e. effect of air pressure and temperature; injection pressure, fuel volume, etc.), it is advantageous to observe spray combustion, which is simplified by eliminating the effect of the shape of the combustion chamber as well as the influence of hydrodynamic factors (e.g. swirl and squish). The experiments should then be conducted by alternating the values of the above-mentioned basic variables. For this purpose, various research groups have developed several single-compression methods (4-13). As one method, a tailored-interface shock tube was reported used to measure thermal radiation during spray combustion in the authors’ laboratory (13). Arbitrary temperature and pressure almost similar to the actual conditions of a diesel engine can be obtained by setting the initial condition using the shock tube. It is possible to observe the flame without it colliding with the wall by using a sufficiently long enough combustion chamber (i.e. tube length). It is also possible to observe the thermal radiation generated by the flame without the effect of wall radiation at room temperature. By utilizing this method, the relationship between the thermal emissive power of spray combustion and fuel injection pressure, injected fuel volume and compressed air pressure could be obtained in this study.

EXPERIMENTS

The experiments discussed here were performed in steel shock tubes having an internal diameter of 97 mm. (Fig. 1) The low pressure section was 5 or 6 m long, while the high pressure section was 5

![Fig. 1 Experimental apparatus](image)

(1) high pressure section (2) low pressure section (3) diaphragm (4) pressure gauge to measure the pressure in high pressure section (5) Hg-manometer to measure the pressure in low pressure section (6) plunger (7) piezoelectric pressure transducers to measure incident shock velocities (8) Kistler-type pressure transducer (9) observation windows (10) optical system to measure IR-spectral intensities (11) injection nozzle (12) electro-magnetic valve (13) hand pump (14) detector of valve opening

1 passed away on July 18, 1982.
or 7 m in length. Tube length was alternated based on operating cost, ignition delay and combustion duration. Incident shock velocities were calculated from the signals of three piezo-electric pressure transducers set at intervals of 500 mm. Temperature $T_0$, density $\rho_0$ and pressure $P_0$ behind the reflected shock wave were calculated as real gas using the above-mentioned incident shock velocities and three conservation laws (mass, momentum and energy). Pressure $P_0$ was varied following the arrival of the reflected shock because of the boundary layer effect and deviation from the tailored condition. Nevertheless, it was possible to obtain almost constant pressure after approximately 2 ms. The time history of temperature following the reflected shock wave was obtained from the pressure profile using the adiabatic change equation.

The low-pressure section was filled with air and heated using the above-mentioned shock tube. Pre-compressed fuel (light oil, JIS No.2) was injected into the high temperature gas behind the reflected shock wave. The amount of fuel per one injection was 37, 78, 120 mg, while the durations of fuel injection were 5.5, 6.5, 7.7 ms, respectively. The fuel injection pressures were 15 and 20 MPa. The respective pressures of shock-compressed air were 0.76 ± 0.02 and 1.45 ± 0.04 MPa, while the experiments were performed at almost similar temperature (7.57, air = 1030 - 1040 K).

Infrared emissions were observed through sapphire windows set at intervals of 32 or 56 mm from a location 18 mm off the end wall of the shock tube. (Fig. 2) The monochromatic emissive powers $E(\lambda, t, L)$ were measured using IR-detectors (PbSe, PbS, Ge, pin-Si), and the filters used in this study were 0.63, 0.90, 1.10, 1.45, 2.50, 3.56, 3.92 and 4.20 μm. All of these emissions were observed simultaneously. (Fig. 3) The pressure profile of the reflected shock wave, injection.

Figs. 4(a)-4(d) One example of measured signals
air condition:
$P_0 = 1.09$ MPa; $P_{r, air} = 1.49$ MPa.
$T_0 = 934$ K; $T_{r, air} = 1013$ K.
fuel condition:
$P_{inj} = 15.0$ MPa; $M_{fuel} = 37$ mg; $t_g = 5.5$ ms.
observation window: No.4 (136 mm off the injection nozzle)

4(a) Emission intensities at 3.56, 4.2, 3.92 μm and height of injection nozzle lift.
4(b) Emission intensities at 0.9 and 1.1 μm, height of injection nozzle lift and emission intensity at 1.45 μm.
4(c) Shock compressed air pressure and height of injection nozzle lift.
4(d) Emission intensity at 2.5 μm and light extinction of He-Ne laser at 0.6328 μm.
The emission of evaporated fuel through a 3.56 μm filter, emission of water-gas through a 2.5 μm filter and that of carbon dioxide through filters of 2.5 and 4.20 μm were observed in addition to the thermal radiation of soot particles. At low air pressure and at the end of combustion, the emission of such molecules was significantly stronger than that of soot particles. Therefore, the monochromatic emissive powers of soot particles were usually obtained at the wave lengths of 0.63, 0.90, 1.10, 1.45, 3.92 μm because the levels of radiation of soot particles were generally higher for these wave lengths in comparison to those of water-gas and carbon dioxide. Based on the best fit of the Hottel-Broughton equation, particle temperature and optical thickness kcl were thus calculated.

The tailored condition was calculated as that of ideal gas (13), but the set of the mixture composition produced and pressure ratio P_F/P_R varied slightly from the tailored condition in the case of real gas. Therefore, the mixture ratio and pressure ratio set was subjected to minor modification in the experiment.

RESULTS

The experiments described here were performed under the conditions illustrated in Table 1. One example of the observed infrared emissions is shown in Figs. 4(a), 4(b), 4(c) and 4(d). The signals were obtained at window No. 4 (136 mm from the nozzle) under the condition of A-I. Figure 4(a) shows the time histories of the emission intensities at 3.56, 4.2, 3.92 μm as well as that of the height of injection nozzle lift (from top to bottom in the same figure). Figure 4(b) shows the time histories relating to the emission intensities at 0.9 and 1.45 μm, height of injection nozzle lift and emission intensity at 1.45 μm. Figure 4(c) presents the time histories of air pressure and height of injection nozzle lift. The time histories of emission intensity at 2.5 μm and light extinction of He-Ne laser at 0.6328 μm are illustrated in Figs. 4(d) and 4(g). From the laser-ab sorption signal, it is possible to determine the start of fuel injection, which was detected as the noise-signal and arrival (t_{spr}) of fuel spray at window No. 4 as well as ignition (t_{ign}) of fuel spray, i.e., t_{spr} = 3.6 ms, t_{ign-t_{spr}} = 1.2 ms. Furthermore, it is possible to determine that the extinction of the He-Ne laser as a result of the relatively small fuel spray is mainly caused by the soot particles produced during spray combustion. Each of Figures 5(a)-5(g) shows the relation of monochromatic emissive powers E(λ, τ, L) with wave length. The relations are calculated based on the emission signals shown in Figures 4(a), 4(b), 4(c) and 4(d). Figs. 5(a)-5(g) show the variance between these relations according to the combustion sequences. The relations of these detector signals with monochromatic emissive powers E(λ, τ, L) were obtained using the black body furnace. At wave lengths 2.5 and 4.2 μm, relatively strong emissions of carbon dioxide and water-gas were observed (14). Therefore, these emission intensities were omitted in the calculation. The emission of carbon dioxide was weak at 1.4 μm when compared with the emission of soot particles (14). The 3.92 μm filter used in this work had a side band of 4.2 μm. The influence of this side band intensity to the 3.92 μm signal was about 10%. Therefore, 10% of the intensity at 4.2 μm was subtracted from the intensity at 3.92 μm. As seen in Figures 5(a)-5(g), the deviation of the intensities at 2.5 and 4.2 μm from the grey body intensity was larger at the beginning of combustion and end of combustion. Furthermore, deviation increased with decreasing air pressure: i.e. at low air pressure, pre-mixed combustion occurs instead of diesel combustion because the ignition delay is long. Consequently, the production of soot particles was also small. As for other wave lengths, the intensity distribution was similar to grey body radiation. On the basis of these intensity distributions, it is possible to calculate the apparent particle temperature T_p, value of kcl and apparently emissive power E(τ, L) using the Hottel-Broughton equation. The time histories of these values taken

Table 1: Experimental conditions.

(i) Experiment on effect of compressed air conditions.

<table>
<thead>
<tr>
<th>Name of condition</th>
<th>L</th>
<th>H</th>
</tr>
</thead>
<tbody>
<tr>
<td>P_{5r, air}(MPa)</td>
<td>0.75 ± 0.02</td>
<td>1.45 ± 0.04</td>
</tr>
<tr>
<td>T_{5r, air}(K)</td>
<td>1031 ± 50</td>
<td>1041 ± 30</td>
</tr>
</tbody>
</table>

| P_{inj} (MPa) | 14.8 |
| N_{fuel} (mg) | 37.0 |
| t_d (ms)      | 5.5 |

(ii) Experiment on effect of fuel pressure and fuel injection volume.

<table>
<thead>
<tr>
<th>Name of condition</th>
<th>A-I</th>
<th>B-I</th>
<th>B-II</th>
<th>B-III</th>
</tr>
</thead>
<tbody>
<tr>
<td>P_{inj} (MPa)</td>
<td>15.0</td>
<td>20.0</td>
<td>20.0</td>
<td>20.0</td>
</tr>
<tr>
<td>N_{fuel} (mg)</td>
<td>37</td>
<td>37</td>
<td>78</td>
<td>120</td>
</tr>
<tr>
<td>t_d (ms)</td>
<td>5.5</td>
<td>5.5</td>
<td>6.5</td>
<td>7.7</td>
</tr>
</tbody>
</table>

| P_{5r, air} (MPa) | 1.45 ± 0.04 |
| T_{5r, air} (K)   | 1041 ± 30   |

Figs. 5(a)-5(g) Relationship between monochromatic emissive powers and wave lengths obtained from Figs. 4(a)-4(d)
Figs. 6(a)-6(c) Time histories of apparent particle temperature (a) value of kcl (b) and apparent grey body emissive power (c) at various observation windows (condition H).

These values were obtained under the condition in Figs. 4(a)-4(d).

from observation windows No.1-6 are shown in Figures 6(a), 6(b) and 6(c) under the condition of \( P_{\text{inj}} = 15 \text{ MPa}, M_{\text{fuel}} = 37 \text{ mg}, P_{\text{sr,air}} = 1.49 \text{ MPa}, T_{\text{sr,air}} = 1013 \text{ K} \). The observed temperatures were in most cases between 1800 and 2800 K at every window. (Fig. 6(a) Figures 7, 8(a) 8(b) 8(c) show the grey body emissive powers \( E(t,L) \) under different conditions.

Fig. 7 Time histories of apparent grey body emissive power at various windows (condition L)

Air condition:
\[ P_{\text{sr,air}} = 0.77 \text{ MPa}, T_{\text{sr,air}} = 1031 \text{ K} \]

Fuel condition:
\[ P_{\text{inj}} = 15 \text{ MPa}, M_{\text{fuel}} = 37 \text{ mg}, t_d = 5.5 \text{ ms} \]

From these time histories, the following results can be obtained:

1. When the pressure of compressed air \( P_{\text{sr,air}} \) was varied: \( P_{\text{sr,air}} = 0.76 \text{ MPa} \) (condition L); \( P_{\text{sr,air}} = 1.45 \text{ MPa} \) (condition H); while \( T_{\text{sr,air}} = 1030-1040 \text{ K} \), \( P_{\text{inj}} = 14.8 \text{ MPa} \), \( M_{\text{fuel}} = 37 \text{ mg} \), \( t_d = 5.5 \text{ ms} \) for both conditions.

Figure 9 shows the relationship between grey body emissive power \( E(t,L) \) and the distance from the injection nozzle under condition L and H in Table 1(i). The maximum emissive power \( \text{E}_{\max} \) under condition H (\( P_{\text{sr,air}} = 1.45 \text{ MPa} \)) was approximately 50 times greater than that under condition L (\( P_{\text{sr,air}} = 0.76 \text{ MPa} \)). Distance \( l_{\max} \) from the nozzle to max. emissive power \( \text{E}_{\max} \) under the condition L was 2 times longer than that under condition H; i.e. \( \text{E}_{\max} = 3.0 \text{ KJ/m}^2 \), \( l_{\max} > 90 \text{ mm} \) under condition H and \( \text{E}_{\max} = 0.06 \text{ KJ/m}^2 \), \( l_{\max} = 180 \text{ mm} \) under condition L. The fuel spray flames were observed to be between 80 and 260 mm under condition H. This decrease in emissive power was not the result of the decrease in air pressure, but due to the increase of ignition delay time; i.e. ignition delay under condition L was longer than that under condition H. Therefore, the atomization of fuel was greater during ignition delay. Therefore, the dependence of monochromatic emissive power on wave length under condition L was similar to that of the premixed mixture; i.e. emissions of water-gas and carbon dioxide were substantially greater than those of soot particles.

2. When the injection pressure was altered: \( P_{\text{inj}} = 15 \text{ MPa} \) (condition A-I); \( P_{\text{inj}} = 20 \text{ MPa} \) (condition B-I); \( P_{\text{inj}} = 1040 \text{ K} \), \( M_{\text{fuel}} = 37 \text{ mg} \) and duration of fuel injection was 5.5 ms for both conditions.

Figure 10 shows the relation between grey body emissive power \( E(t,L) \), \( E(t,L)_d \) and injection pressure under conditions A-I and B-I in Table 1(ii). Distance \( l_{\max} \) under condition B-I \( P_{\text{inj}} = 20 \text{ MPa} \) was longer than that under condition A-I. Emissive power at each window under condition B-I was greater than that under condition A-I. Emissive power \( E(t,L)_d \) which was integrated along the center line of the fuel spray, was also greater than that under condition A-I; i.e. \( \text{E}_{\max} = 5.6 \)
Figs. 8(a)-8(c) Time histories of apparent grey body emissive power at various windows

air condition:

\( P_{5r,air} = 1.45 \text{ MPa}, \ T_{5r,air} = 1041 \text{ K} \)

fuel condition:

(a) \( P_{\text{inj}} = 20 \text{ MPa}, \ M_{\text{fuel}} = 37 \text{ mg}, \ t_d = 5.5 \text{ ms} \).

(b) \( P_{\text{inj}} = 20 \text{ MPa}, \ M_{\text{fuel}} = 78 \text{ mg}, \ t_d = 6.5 \text{ ms} \).

(c) \( P_{\text{inj}} = 20 \text{ MPa}, \ M_{\text{fuel}} = 120 \text{ mg}, \ t_d = 7.7 \text{ ms} \).

\( \text{kJ/m}^2, \ l_{\text{max}} = 180 \text{ mm}, \ E_{\text{sum}} = 68 \) (arbitrary unit) in condition B-I (\( P_{\text{inj}} = 20 \text{ MPa} \)) and \( E_{\text{max}} = 3.0\) \( \text{kJ/m}^2 \). \( l_{\text{max}} = 90 \text{ mm}, \ E_{\text{sum}} = 53 \) under condition A-I. The flames under condition A-I were observed to be between 20 and 200 mm, while flames under condition B-I were seen to be between 50 and 220 mm.

Fig. 9 Relationship between grey body emissive power and distance from injection nozzle under different air pressure

air condition:

\( P_{5r,air} = 0.76 \) and 1.45 MPa.

\( T_{5r,air} = 1030-1040 \text{ K} \) under both air pressures.

fuel condition:

\( P_{\text{inj}} = 15 \text{ MPa}, \ M_{\text{fuel}} = 37 \text{ mg}, \ t_d = 5.5 \text{ ms} \).

Fig. 10 Relationship between grey body emissive power and distance from injection nozzle under different injection pressure

fuel condition:

\( P_{\text{inj}} = 15 \) and 20 MPa, \( M_{\text{fuel}} = 37 \text{ mg}, \ t_d = 5.5 \text{ mg} \) for both injection pressures.

air condition:

\( P_{5r,air} = 1.45 \text{ MPa}, \ T_{5r,air} = 1040 \text{ K} \).

(3) When the amount of injected fuel \( M_{\text{fuel}} \) was varied: \( M_{\text{fuel}} = 37, 78, 120 \text{ mg under conditions B-I, B-II, B-III, respectively; while P}_{5r,air} = 1.45 \text{ MPa}, T_{5r,air} = 1040 \text{ K for these conditions.} \)

Figure 11 shows the relationships between grey body emissive power \( E(L) = \int E(t, L) \text{d}t \) and amount of injected fuel under conditions B-I, B-II, B-III. Even if the amount of fuel was increased, location \( l_{\text{max}} \) of maximum radiation did not vary, but emissive power at each observation window in-
Fig. 11 Relationship between grey body emissive power and distance from injection nozzle under different amount of fuel condition:

- $M_{fuel} = 37, 78, 120$ mg for $t_g = 5.5, 6.5, 7.7$ ms.
- $P_{inj} = 20$ MPa at above amounts of fuel.

Air condition:

- $P_{a, air} = 1.45$ MPa, $T_{a, air} = 1041$ K.

creased. Max. emissive power $E_{max}$ also showed a tendency to increase, but values $E_{max}$ under conditions B-II and B-III showed almost similar values; i.e. $E_{max} = 3.6, 7.9, 7.9$ kJ/m² for conditions B-I, B-II, B-III, respectively. Emissive powers $E_{sum}$ increased with increased fuel injection. They were almost proportional to the amount of fuel. The flames were observed between 50 and 220, 20 and 260, 20 and 300 mm under conditions B-I, B-II, B-III, respectively.

DISCUSSION

By observing the spray combustion in the tailored-interface shock tubes, combustion could be simplified. The difference in the spray combustion in this shock tube from that in actual diesel engines was:

- (A-1) The spray does not collide against the cylinder wall.
- (A-2) The temperature and pressure remain constant during combustion.
- (A-3) The compressed air has no swirl nor swirl, but was calm behind the reflected shock wave.
- (A-4) The wall is at room temperature. Due to the above-mentioned difference, spray combustion could be simplified. In addition to these simplifications, the following differences in conditions were considered in this study: (B-1) The experiments were performed under relatively lower air pressure than that of an actual diesel engine because of the wall strength of the shock tubes. (B-2) A throttle nozzle was used. The difference of the experimental conditions (B-1) results in the following: with decreasing air-pressure, ignition delay increases. Therefore, during this ignition delay time, the sprayed fuel travels further and wider. During this time the diameter of the fuel-mist decreases and the mist density number increases. Furthermore the amount of evaporated fuel increases. As the result, ignition and combustion are similar to those created by premixed fuel: i.e. the production of soot particles decreases and emission from these particles decreases; instead of this emission, the emission of carbon dioxide and water gas increase. These phenomena become more dominant, when air-pressure decreases. By using a throttle nozzle, it is possible to obtain a spray having high-level penetration and small spray angle. By using other nozzle types, experiments for other types of spray can be conducted.

In spite of the above-mentioned simplifications, there are still numerous variables influencing thermal radiation generated from the fuel spray flames. Therefore, it was not possible to perform the experiments covering a broad range of conditions. However, the following relations could be obtained: (i) With increasing injection pressure, distance $L_{max}$ of maximum emissive power from the injection nozzle increases as does the total thermal emissive power of soot-particles. (ii) Total thermal emissive powers denotes the sum of emissive power $E_{total} = \int \left( \int E(t, L) \, dL(L) \right) \, dt$ where $S(L)$ is the surface area of flame. The form of the flame was estimated based on high-speed photographs and observation of intensities in the radial direction at each respective window. (ii) Total thermal emissive power $E_{total}$ was proportional to the amount of injected fuel. This means that the total emissive power per unit amount of injected fuel is constant. (iii) With decreasing pressure of compressed air, the total emissive power $E_{total}$ decreased remarkably because of the increase of ignition delay with the decrease of air pressure, as was mentioned in result (i) of the RESULTS. This decrease of thermal radiation of soot particles $E_{total}$ can occur under a condition where fuel atomizes rapidly and where gas-phase ignition takes place slowly.

From the results of this study, the followings regarding the combustion improvement of diesel engines, can be proposed: (i) The fuel should atomize as rapidly as possible. (ii) The ignition delay of gas phase should expand as much as possible. When both conditions can be satisfied simultaneously, the thermal radiation of particles can be reduced.

CONCLUSION

By using tailored-interface shock tube, it is possible to observe the thermal radiation of spray combustion. Based on the results, the following conclusions can be drawn: (i) The distance from the injection nozzle to maximum emissive power and total thermal emissive power increase, when the injection pressure of fuel increases. (ii) The total thermal emissive power is proportional to the amount of injected fuel. (iii) The thermal radiation decreases significant-ly, when the ignition delay of fuel increases. (iv) The observed particle temperatures were between 1800 and 2800 K.

NOMENCLATURE

- $E(\lambda, t, L) = \text{monochromatic thermal emissive power at wave length } \lambda, \text{ time } t \text{ and distance } L \text{ from injection nozzle. (kW/m²·um)}$
- $E(t, L) = \int E(\lambda, t, L) \, d\lambda$, grey body emissive power at $t$ and $L$
- $E(L) = \int E(t, L) \, dt$, grey body emissive power integrated with combustion time at the distance $L$.

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\[ E_{\text{sum}} = \int E(L) \, dL \], sum of \( E(L) \) along center line of fuel injection

\[ E_{\text{total}} = \int E(L) \, dS \], sum of \( E(L) \) around whole surface area of flame.

\[ E_{\max}(l_{\max}) = \text{maximum grey body emissive power.} \]

\[ k_{\text{cl}} = \text{optical thickness obtained from Hottel-Broughton equation. (} \mu \text{m}^{-1} \text{cm}^{-1} \)

\[ l_{\max} = \text{distance from injection nozzle to maximum grey body emissive power.} \]

\[ M_{\text{fuel}} = \text{amount of injected fuel.} \]

\[ P_{1}, P_{2} = \text{pressures of driven section and of driver section.} \]

\[ P_{s}, T_{s}, P_{d} = \text{pressure, temperature and density in reflected shock wave.} \]

\[ P_{r, \text{air}}, T_{r, \text{air}} = \text{pressure and temperature of the moment when the reflected shock wave collides with contact surface and is 'tailored'.} \]

\[ P_{\text{inj}} = \text{pressure of pre-compressed fuel.} \]

\[ t_{d} = \text{duration of fuel injection.} \]

\[ t_{\text{ign}} = \text{period from fuel injection to observation of flame at each observation window.} \]

\[ t_{\text{spr}} = \text{period from fuel injection to arrival of fuel spray at each observation window.} \]

\[ T_{p} = \text{apparent particle temperature.} \]

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REFERENCES


APPENDIX A

Hottel-Broughton equation is described as follows:

\[ E(\lambda) = c_{1} \frac{\varepsilon_{\lambda}}{\lambda^{2}(\exp(c_{2}/T_{p})-1)} \]

\[ \varepsilon_{\lambda} = 1 - \exp(-k_{\text{cl}}/\lambda^{2}) \]

\[ c_{1} = 3.74 \times 10^{5} \text{ Wm}^{-1} \text{ m}^{-2} \]

\[ c_{2} = 1.44 \times 10^{10} \text{ m}^{-2} \]

APPENDIX B

Relations between \( E(\lambda, t, L) \) and signals. \( \lambda (\mu \text{m}) \):

\[ E(\lambda, t, L) \text{ (W/m}^{2}\text{cm}) \]

- 0.6328: 3.85 \times 10^{-2} \text{(V<0.250); 1.65 \times 10^{-2} (V<0.025)}
- 0.90: 5.5 \times 10^{-2} \text{(V<0.011); 4.1 \times 10^{-2} (V<0.0001)}
- 1.10: 7 \times 10^{-2} \text{(V<0.034); 8 \times 10^{-2} (V<0.004)}
- 1.45: 4 \times 10^{-2} \text{(V<0.115); 4.6 \times 10^{-2} (V<0.028)}
- 2.50: 3 \times 10^{-2} \text{(V<0.160); 2.6 \times 10^{-2} (V<0.058)}
- 3.56: 5 \times 10^{-2} \text{(V<0.250); 2.3 \times 10^{-1} (V<0.156)}
- 3.92: 1.6 \times 10^{-1} \text{(V<0.0250); 1.1 \times 10^{-1} (V<0.027)}
- 4.20: 1 \times 10^{-1} \text{(V<0.260); 8 \times 10^{-2} (V<0.080)}

\text{V (volt)}