CO_2放电初始反应集合

表 1 CO_2 放电初始反应集合中由 Bolsig+计算速率系数的电子碰撞反应及其参考文献

Tab. 1 The electron impact reactions with reaction rate coefficients calculated by Bolsig+ included in the initial reaction set of CO_2 discharge and the corresponding references

序号	反应	速率系数	参考文献	备注
X01	$e + CO_2 \rightarrow e + CO_2$	$f(\sigma)$	[1]	(a)
$X02_x$	$e + CO_2 \rightarrow e + CO_2v_x$	$f(\sigma)$	[1]	
$X03_i$	$e + CO_2 \rightarrow e + CO_2v_i$	$f(\sigma)$	[1]	(b)
$X04_{i,j}$	$e + CO_2v_i \rightarrow e + CO_2v_j$	$f(\sigma)$	[1]	(b), $i<j$
$X05_i$	$e + CO_2 \rightarrow e + CO_2e_i$	$f(\sigma)$	[1]	
X06	$e + CO_2 \rightarrow 2e + CO_2^+$	$f(\sigma)$	[1]	
$X07_x$	$e + CO_2v_x \rightarrow 2e + CO_2^+$	$f(\sigma)$	[1]	(c)
$X08_i$	$e + CO_2v_i \rightarrow 2e + CO_2^+$	$f(\sigma)$	[1]	(c)
$X09_i$	$e + CO_2e_i \rightarrow 2e + CO_2^+$	$f(\sigma)$	[1]	(d)
X10	$e + CO_2 \rightarrow 2e + O + CO^+$	$f(\sigma)$	[1]	
$X11_x$	$e + CO_2v_x \rightarrow 2e + O + CO^+$	$f(\sigma)$	[1]	(e)
$X12_i$	$e + CO_2v_i \rightarrow 2e + O + CO^+$	$f(\sigma)$	[1]	(e)
$X13_i$	$e + CO_2e_i \rightarrow 2e + O + CO^+$	$f(\sigma)$	[1]	(d)
X14	$e + CO_2 \rightarrow 2e + CO + O^+$	$f(\sigma)$	[1]	
$X15_x$	$e + CO_2v_x \rightarrow 2e + CO + O^+$	$f(\sigma)$	[1]	(e)
$X16_i$	$e + CO_2v_i \rightarrow 2e + CO + O^+$	$f(\sigma)$	[1]	(e)
$X17_i$	$e + CO_2e_i \rightarrow 2e + CO + O^+$	$f(\sigma)$	[1]	(d)
X18	$e + CO_2 \rightarrow e + CO + O$	$f(\sigma)$	[1]	
$X19_x$	$e + CO_2v_x \rightarrow e + CO + O$	$f(\sigma)$	[1]	(e)
$X20_i$	$e + CO_2v_i \rightarrow e + CO + O$	$f(\sigma)$	[1]	(e)
$X21_i$	$e + CO_2e_i \rightarrow e + CO + O$	$f(\sigma)$	[1]	(d)
X22	$e + CO_2 \rightarrow CO + O^-$	$f(\sigma)$	[1]	
$X23_x$	$e + CO_2v_x \rightarrow CO + O^-$	$f(\sigma)$	[1]	(e)
$X24_i$	$e + CO_2v_i \rightarrow CO + O^-$	$f(\sigma)$	[1]	(e)
$X25_i$	$e + CO_2e_i \rightarrow CO + O^-$	$f(\sigma)$	[1]	(c)
X26	$e + CO \rightarrow 2e + CO^+$	$f(\sigma)$	[2]	
X27	$e + CO \rightarrow 2e + C^+ + O$	$f(\sigma)$	[2]	
X28	$e + CO \rightarrow C + O^-$	$f(\sigma)$	[2]	
X29	$e + CO \rightarrow e + C + O$	$f(\sigma)$	[2]	

续表 1 CO_2 放电初始反应集合中由 Bolsig+计算速率系数的电子碰撞反应及其参考文献

Tab. 1 The electron impact reactions with reaction rate coefficients calculated by Bolsig+ included in the initial reaction set of CO_2 discharge and the corresponding references (continued)

序号	反应	速率系数	参考文献	备注
X30	$e + C \rightarrow 2e + C^+$	$f(\sigma)$	[3]	
X31	$e + O \rightarrow 2e + O^+$	$f(\sigma)$	[4]	
X32	$e + O_2 \rightarrow 2O + e$	$f(\sigma)$	[5]	
X33	$e + O_2 \rightarrow O + O^-$	$f(\sigma)$	[5]	
X34	$e + O_2 \rightarrow 2e + O_2^+$	$f(\sigma)$	[5]	
X35	$e + O_3 \rightarrow O_2 + O^-$	$f(\sigma)$	[6]	
X36	$e + O_3 \rightarrow O_2^- + O$	$f(\sigma)$	[6]	
X37	$e + O_3 \rightarrow O + O_2 + e$	$f(\sigma)$	[7]	
X38	$e + O_3 \rightarrow O_2^+ + O + 2e$	$f(\sigma)$	[7]	

(a) 使用相同的碰撞截面计算电子和振动激发态 CO_2 的弹性碰撞过程的速率系数。

(b) 使用 Fridman 近似对碰撞横截面进行修改。

(c) 使用与基态 CO_2 分子相同的横截面。

(d) 使用电子激发态 CO_2 分子的能量阈值对横截面进行修正。

(e) 使用振动激发态 CO_2 分子的能量阈值对横截面进行修正。

表 2 CO_2 放电初始反应集合中包含的电子-离子复合反应和电子吸附反应，以及相应的速率系数和参考文献

Tab. 2 The electron-ion recombination reactions and electron attachment reactions included in the initial reaction set of CO_2 discharge, as well as the corresponding rate coefficients and references

序号	反应	速率系数	参考文献	备注
E01	$e + O_2^+ \rightarrow O + O$	$6.0\times10^{-7} T_e^{-0.5} T_g^{-0.5}$	[8]	
E02	$e + CO_2^+ \rightarrow CO + O$	$2.0\times10^{-5} T_e^{-0.5} T_g^{-1}$	[9]	
E03	$e + CO_2^+ \rightarrow O_2 + C$	$3.94\times10^{-7} T_e^{-0.4}$	[8]	
E04	$e + O_2 + CO_2 \rightarrow O_2^- + CO_2$	$2.2\times10^{-29}(300/T_g)^{1.5}\exp(-600/T_g)$	[10]	
E05	$e + O_3 + O_2 \rightarrow O_3^- + O_2$	4.6×10^{-28}	[10]	
E06	$e + O_2^+ + CO_2 \rightarrow O_2 + CO_2$	1.0×10^{-26}	[11]	

表 3 CO_2 放电初始反应集合中包含的离子-中性反应和离子-离子反应，以及相应的速率系数和参考文献

Tab. 3 The ion-neutral reactions and ion-ion reactions included in the initial reaction set of CO_2 discharge, as well as the corresponding rate coefficients and references

序号	反应	速率系数	参考文献	备注
I01	$O^- + O \rightarrow O_2 + e$	2.3×10^{-10}	[8]	
I02	$O^- + O_2 \rightarrow e + O + O_2$	6.9×10^{-10}	[10]	
I03	$O^- + O_3 \rightarrow 2O_2 + e$	3.0×10^{-10}	[12]	
I04	$O^- + O_3 \rightarrow O_3^- + O$	8.0×10^{-10}	[9]	
I05	$O^- + C \rightarrow CO + e$	5.0×10^{-10}	[11]	
I06	$O^- + CO_2 \rightarrow O + CO_2 + e$	4.0×10^{-12}	[13]	
I07	$O^- + CO \rightarrow CO_2 + e$	5.5×10^{-10}	[14]	
I08	$O^- + O_2^+ \rightarrow O_2 + O$	$2.6\times10^{-8}(300/T_g)^{0.44}$	[8]	
I09	$O^- + O_2^+ \rightarrow 3O$	$4.2\times10^{-7}(300/T_g)^{0.44}$	[8]	
I10$_x$	$O^- + CO_2^+ \rightarrow O + CO_2$	1.0×10^{-7}	[15]	
I11$_i$	$O^- + CO_2 + O_2 \rightarrow CO_3^- + O_2$	3.1×10^{-28}	[16]	
I12	$O^- + CO_2 + CO \rightarrow CO_3^- + CO$	1.5×10^{-28}	[16]	
I13	$O^- + CO_2 + CO_2 \rightarrow CO_3^- + CO_2$	9.0×10^{-29}	[10]	
I14	$O_2^- + O \rightarrow O_2 + O^-$	3.3×10^{-10}	[8]	
I15	$O_2^- + O \rightarrow O_3 + e$	3.3×10^{-10}	[9]	
I16$_x$	$O_2^- + O_3 \rightarrow O_3^- + O_2$	4.0×10^{-10}	[9]	
I17$_i$	$O_2^- + CO_2^+ \rightarrow CO + O_2 + O$	6.0×10^{-7}	[14]	
I18	$O_2^- + CO_2 + O_2 \rightarrow CO_4^- + O_2$	4.7×10^{-27}	[10]	
I19$_x$	$O_2^- + CO_2 + CO_2 \rightarrow CO_4^- + CO_2$	1.0×10^{-29}	[10]	
I20$_i$	$O_3^- + O \rightarrow O_2^- + O_2$	2.5×10^{-10}	[9]	
I21	$O_3^- + CO_2 \rightarrow CO_3^- + O_2$	5.5×10^{-10}	[9]	
I22	$O^+ + CO_2 \rightarrow O_2^+ + CO$	9.4×10^{-10}	[9]	
I23	$O^+ + CO_2 \rightarrow O + CO_2^+$	4.5×10^{-10}	[9]	(a)
I24$_i$	$O^+ + CO_2e_i \rightarrow O + CO_2^+$	$4.5\times10^{-10}(E_{Ii}^2/E_{Ei}^2)$	[9]	(b), i = 1, 2
I25	$O_2^+ + C \rightarrow CO^+ + O$	5.2×10^{-11}	[9]	
I26	$O_2^+ + C \rightarrow C^+ + O_2$	5.2×10^{-11}	[9]	
I27	$O_2^+ + O_2^- \rightarrow 2O_2$	$2.0\times10^{-7}(300/T_g)^{0.5}$	[8]	
I28	$O_2^+ + O_2^- \rightarrow O_2 + 2O$	4.2×10^{-7}	[8]	
I29	$O_2^+ + CO_4^- \rightarrow CO_2 + 2O_2$	3.0×10^{-7}	[9]	
I30	$C^+ + CO_2 \rightarrow CO + + CO$	1.1×10^{-9}	[9]	(a)
I31$_i$	$C^+ + CO_2e_i \rightarrow CO^+ + CO$	$1.1\times10^{-9}(E_{Ii}^2/E_{Ei}^2)$	[9]	(b), i = 1, 2

续表 3 CO_2 放电初始反应集合中包含的离子-中性反应和离子-离子反应，以及相应的速率系数和参考文献

Tab. 3 The ion-neutral reactions and ion-ion reactions included in the initial reaction set of CO_2 discharge, as well as the corresponding rate coefficients and references (continued)

序号	反应	速率系数	参考文献	备注
I32	$CO^+ + CO_2 \rightarrow CO_2^+ + CO$	1.0×10^{-9}	[17]	(a)
I33$_i$	$CO^+ + CO_2e_i \rightarrow CO_2^+ + CO$	$1.1\times10^{-9}(E_{Ii}^2/E_{Ei}^2)$	[17]	(b), $i = 1, 2$
I34	$CO_2^+ + O \rightarrow O_2^+ + CO$	1.64×10^{-10}	[10]	
I35	$CO_2^+ + O \rightarrow CO_2 + O^+$	9.62×10^{-11}	[9]	
I36	$CO_2^+ + O_2 \rightarrow O_2^+ + CO_2$	6.4×10^{-11}	[10]	
I37	$CO_3^- + CO \rightarrow 2CO_2 + e$	5.0×10^{-13}	[18]	
I38	$CO_3^- + CO_2^+ \rightarrow 2CO_2 + O$	5.0×10^{-7}	[18]	
I39	$CO_3^- + O \rightarrow CO_2 + O_2^-$	8.0×10^{-11}	[18]	
I40	$CO_3^- + O_2^+ \rightarrow CO_2 + O_2 + O$	3.0×10^{-7}	[9]	
I41	$CO_4^- + CO_2^+ \rightarrow 2CO_2 + O_2$	5.0×10^{-7}	[9]	
I42	$CO_4^- + O \rightarrow O_3^- + CO_2$	1.4×10^{-10}	[9]	
I43	$CO_4^- + O \rightarrow CO_3^- + O_2$	1.1×10^{-10}	[9]	
I44	$CO_4^- + O \rightarrow CO_2 + O_2 + O^-$	1.4×10^{-11}	[9]	

(a) 电子激发态 CO_2 分子除外。

(b) 使用电子激发态 CO_2 分子的能量阈值对横截面进行修正。

表 4 CO_2 放电初始反应集合中包含的中性粒子反应，以及相应的速率系数和参考文献

Tab. 4 The neutral reactions included in the initial reaction set of CO_2 discharge, as well as the corresponding rate coefficients and references

序号	反应	速率系数	参考文献	备注
N01	$O_2 + C \rightarrow O + CO$	3.0×10^{-11}	[8]	
N02	$CO_2 + O \rightarrow CO + O_2$	$2.8\times10^{-11}\exp(-26500/T_g)$	[8]	(a)
N03	$CO_2v + O \rightarrow CO + O_2$	$k_R(E_v, T_g)$	[8]	(b)
N04	$CO_2 + C \rightarrow 2CO$	1.0×10^{-15}	[8]	
N05	$O + O_2 + CO_2 \rightarrow O_3 + CO_2$	$1.7\times10^{-30}T_g^{-1.2}$	[13]	
N06	$O + O + CO_2 \rightarrow O_2 + CO_2$	$3.81\times10^{-30}T_g^{-1}\exp(-529/T_g)$	[13]	
N07	$CO_2 + CO_2 \rightarrow CO + O + CO_2$	$3.91\times10^{-10}T_g^{-1}\exp(-49430/T_g)$	[19]	(a)
N08	$CO_2v + CO_2 \rightarrow CO + O + CO_2$	$k_R(E_v, T_g)$	[19]	(b)

(a) 振动激发态 CO_2 分子除外。

(b) 由于涉及振动激发态的反应活化能的变化，速率系数有所改变。

表 5 CO_2 放电初始反应集合中包含的振动能量交换反应，以及相应的速率系数和参考文献

Tab. 5 The vibrational energy exchange reactions included in the initial reaction set of CO_2 discharges, as well as the corresponding rate coefficients and references

序号	反应	速率系数	参考文献	备注
V01	$CO_2v_a + M \rightarrow CO_2 + M$	$7.14\times10^{-8}\exp(-177T_g^{-1/3}+451T_g^{-2/3})$	[20]	(a)
V02	$CO_2v_b + M \rightarrow CO_2 + M$	$1.071\times10^{-9}\exp(-137T_g^{-1/3})$	[20]	(b)
V03	$CO_2v_b + M \rightarrow CO_2v_a + M$	$1.438\times10^{-7}\exp(-177T_g^{-1/3}+451T_g^{-2/3})$	[20]	(a)
V04	$CO_2v_c + M \rightarrow CO_2v_a + M$	$1.071\times10^{-9}\exp(-137T_g^{-1/3})$	[20]	(b)
V05	$CO_2v_c + M \rightarrow CO_2v_b + M$	$2.897\times10^{-7}\exp(-177T_g^{-1/3}+451T_g^{-2/3})$	[20]	(a)
V06	$CO_2v_d + M \rightarrow CO_2v_b + M$	$1.528\times10^{-5}\exp(-272T_g^{-1/3}+437T_g^{-2/3})$	[20]	(b)
V07$_i$	$CO_2v_d + M \rightarrow CO_2v_c + M$	$4.321\times10^{-7}\exp(-177T_g^{-1/3}+451T_g^{-2/3})$	[20]	(a)
V08	$CO_2v_d + M \rightarrow CO_2v_1 + M$	$1.775\times10^{-11}\exp(-108T_g^{-1/3}+165T_g^{-2/3})$	[20]	(c)
V09	$CO_2v_{1a} + M \rightarrow CO_2v_c + M$	$8.57\times10^{-1}\exp(-404T_g^{-1/3}+1096T_g^{-2/3})$	[20]	(d)
V10	$CO_2v_{1a} + M \rightarrow CO_2v_d + M$	$1.431\times10^{-5}\exp(-252T_g^{-1/3}+685T_g^{-2/3})$	[20]	(d)
V11	$CO_2v_{1a} + M \rightarrow CO_2v_1 + M$	$7.14\times10^{-8}\exp(-177T_g^{-1/3}+451T_g^{-2/3})$	[20]	(a)
V12	$CO_2v_{1b} + M \rightarrow CO_2v_c + M$	$3.218\times10^{-9}\exp(-137T_g^{-1/3})$	[20]	(b)
V13	$CO_2v_{1b} + M \rightarrow CO_2v_d + M$	$6.447\times10^{-7}\exp(-177T_g^{-1/3}+451T_g^{-2/3})$	[20]	(a)
V14	$CO_2v_{1b} + M \rightarrow CO_2v_{1a} + M$	$6.447\times10^{-7}\exp(-177T_g^{-1/3}+451T_g^{-2/3})$	[20]	(a)
V15	$CO_2v_{1b} + M \rightarrow CO_2v_1 + M$	$1.071\times10^{-9}\exp(-137T_g^{-1/3})$	[20]	(b)
V16	$CO_2v_{1c} + M \rightarrow CO_2v_{1a} + M$	$1.071\times10^{-9}\exp(-137T_g^{-1/3})$	[20]	(b)
V17	$CO_2v_{1c} + M \rightarrow CO_2v_{1b} + M$	$2.897\times10^{-7}\exp(-177T_g^{-1/3}+451T_g^{-2/3})$	[20]	(a)
V18	$CO_2v_s + M \rightarrow CO_2v_a + M$	$1.071\times10^{-9}\exp(-137T_g^{-1/3})$	[20]	(b)
V19	$CO_2v_s + M \rightarrow CO_2v_b + M$	$2.897\times10^{-7}\exp(-177T_g^{-1/3}+451T_g^{-2/3})$	[20]	(a)
V20	$CO_2v_1 + M \rightarrow CO_2v_a + M$	$4.25\times10^{-1}\exp(-407T_g^{-1/3}-824T_g^{-2/3})$	[20]	(d)
V21	$CO_2v_1 + M \rightarrow CO_2v_b + M$	$8.568\times10^{-1}\exp(-404T_g^{-1/3}-1096T_g^{-2/3})$	[20]	(d)
V22	$CO_2v_1 + M \rightarrow CO_2v_c + M$	$1.43\times10^{-5}\exp(-252T_g^{-1/3}-685T_g^{-2/3})$	[20]	(d)
V23	$CO_2v_1 + M \rightarrow CO_2v_s + M$	$1.43\times10^{-5}\exp(-252T_g^{-1/3}-685T_g^{-2/3})$	[20]	(d)
V24	$CO_2v_1 + M \rightarrow CO_2v_{1a} + M$	$8.568\times10^{-1}\exp(-406T_g^{-1/3}-829T_g^{-2/3})$	[20]	(d)
V25	$CO_2v_2 + M \rightarrow CO_2v_{1b} + M$	$1.725\times10^{-1}\exp(-404T_g^{-1/3}-1098T_g^{-2/3})$	[20]	(d)
V26	$CO_2v_2 + M \rightarrow CO_2v_{1c} + M$	$2.882\times10^{-5}\exp(-253T_g^{-1/3}-683T_g^{-2/3})$	[20]	(d)
V27$_i$	$CO_2v_i + M \rightarrow CO_2v_{i-1} + M$	$f(k(\mathrm{VT}_{v_1-v_a}), k(\mathrm{VT}_{v_1-v_b}))$	[20]	(e) i=1 ,…, 8
V28	$CO_2v_b + CO_2 \rightarrow CO_2v_a + CO_2v_a$	$2.157\times10^{-9}\exp(-88T_g^{-1/3}-233T_g^{-2/3})$	[20]	
V29	$CO_2v_c + CO_2 \rightarrow CO_2v_a + CO_2v_b$	$5.305\times10^{-9}\exp(-88T_g^{-1/3}-233T_g^{-2/3})$	[20]	
V30	$CO_2v_d + CO_2 \rightarrow CO_2v_a + CO_2v_c$	$6.48\times10^{-9}\exp(-88T_g^{-1/3}-233T_g^{-2/3})$	[20]	
V31	$CO_2v_d + CO_2 \rightarrow CO_2v_b + CO_2v_b$	$2.384\times10^{-9}\exp(-89T_g^{-1/3}-234T_g^{-2/3})$	[20]	
V32	$CO_2v_{1a} + CO_2 \rightarrow CO_2v_1 + CO_2v_a$	$1.071\times10^{-9}\exp(-88T_g^{-1/3}-230T_g^{-2/3})$	[20]	

续表 5 CO_2 放电初始反应集合中包含的振动能量交换反应，以及相应的速率系数和参考文献

Tab. 5 The vibrational energy exchange reactions included in the initial reaction set of CO_2 discharges, as well as the corresponding rate coefficients and references (continued)

序号	反应	速率系数	参考文献	备注
V33	$CO_2v_{1b} + CO_2 \rightarrow CO_2v_a + CO_2v_d$	$9.667\times10^{-9}\exp(-88T_g^{-1/3}-233T_g^{-2/3})$	[20]	
V34	$CO_2v_{1c} + CO_2 \rightarrow CO_2v_a + CO_2v_d$	$2.378\times10^{-8}\exp(-88T_g^{-1/3}-233T_g^{-2/3})$	[20]	
V35	$CO_2v_s + CO_2 \rightarrow CO_2v_a + CO_2v_b$	$5.305\times10^{-9}\exp(-88T_g^{-1/3}-233T_g^{-2/3})$	[20]	
V36	$CO_2v_1 + CO_2 \rightarrow CO_2v_a + CO_2v_b$	$1.06\times10^{-5}\exp(-242T_g^{-1/3}-633T_g^{-2/3})$	[20]	
V37	$CO_2v_2 + CO_2 \rightarrow CO_2v_a + CO_2v_{1b}$	$4.299\times10^{-5}\exp(-241T_g^{-1/3}-635T_g^{-2/3})$	[20]	
V38	$CO_2v_2 + CO_2 \rightarrow CO_2v_{1a} + CO_2v_b$	$4.299\times10^{-5}\exp(-241T_g^{-1/3}-637T_g^{-2/3})$	[20]	
V39$_i$	$CO_2v_i + CO_2 \rightarrow CO_2v_{i-1} + CO_2v_a$	$2.03\times10^{-5}\exp(-242T_g^{-1/3}-633T_g^{-2/3})$	[20]	i=1, …, 8
V40$_i$	$CO_2v_i + CO_2 \rightarrow CO_2v_{i-1} + CO_2v_b$	$2.03\times10^{-5}\exp(-242T_g^{-1/3}-633T_g^{-2/3})$	[20]	i=1, …, 8
V41	$CO_2v_c + CO_2v_a \rightarrow CO_2v_b + CO_2v_b$	$5.305\times10^{-9}\exp(-88T_g^{-1/3}-233T_g^{-2/3})$	[20]	
V42	$CO_2v_d + CO_2v_a \rightarrow CO_2v_b + CO_2v_c$	$1.442\times10^{-8}\exp(-88T_g^{-1/3}-233T_g^{-2/3})$	[20]	
V43	$CO_2v_d + CO_2v_b \rightarrow CO_2v_c + CO_2v_c$	$2.628\times10^{-8}\exp(-88T_g^{-1/3}-233T_g^{-2/3})$	[20]	
V44	$CO_2v_{1a} + CO_2v_a \rightarrow CO_2v_1 + CO_2v_b$	$2.157\times10^{-9}\exp(-88T_g^{-1/3}-233T_g^{-2/3})$	[20]	
V45	$CO_2v_{1a} + CO_2v_b \rightarrow CO_2v_1 + CO_2v_c$	$4.344\times10^{-9}\exp(-88T_g^{-1/3}-233T_g^{-2/3})$	[20]	
V46	$CO_2v_{1a} + CO_2v_c \rightarrow CO_2v_1 + CO_2v_d$	$6.48\times10^{-9}\exp(-88T_g^{-1/3}-233T_g^{-2/3})$	[20]	
V47	$CO_2v_{1b} + CO_2v_a \rightarrow CO_2v_b + CO_2v_d$	$9.667\times10^{-9}\exp(-88T_g^{-1/3}-233T_g^{-2/3})$	[20]	
V48	$CO_2v_{1b} + CO_2v_b \rightarrow CO_2v_c + CO_2v_d$	$4.332\times10^{-8}\exp(-88T_g^{-1/3}-233T_g^{-2/3})$	[20]	
V49	$CO_2v_{1b} + CO_2v_c \rightarrow CO_2v_d + CO_2v_d$	$5.848\times10^{-8}\exp(-88T_g^{-1/3}-233T_g^{-2/3})$	[20]	
V50	$CO_2v_{1c} + CO_2v_a \rightarrow CO_2v_b + CO_2v_d$	$5.292\times10^{-8}\exp(-88T_g^{-1/3}-233T_g^{-2/3})$	[20]	
V51	$CO_2v_{1c} + CO_2v_b \rightarrow CO_2v_b + CO_2v_d$	$1.066\times10^{-7}\exp(-88T_g^{-1/3}-233T_g^{-2/3})$	[20]	
V52	$CO_2v_{1c} + CO_2v_c \rightarrow CO_2v_d + CO_2v_d$	$1.438\times10^{-7}\exp(-88T_g^{-1/3}-233T_g^{-2/3})$	[20]	
V53	$CO_2v_{1c} + CO_2v_{1a} \rightarrow CO_2v_{1b} + CO_2v_{1b}$	$5.308\times10^{-9}\exp(-88T_g^{-1/3}-233T_g^{-2/3})$	[20]	
V54	$CO_2v_{1b} + CO_2v_1 \rightarrow CO_2v_{1a} + CO_2v_{1a}$	$2.157\times10^{-9}\exp(-88T_g^{-1/3}-233T_g^{-2/3})$	[20]	
V55	$CO_2v_{1c} + CO_2v_1 \rightarrow CO_2v_{1a} + CO_2v_{1b}$	$5.305\times10^{-9}\exp(-88T_g^{-1/3}-233T_g^{-2/3})$	[20]	
V56$_{i,j}$	$CO_2v_i + CO_2v_j \rightarrow CO_2v_{i+1} + CO_2v_{j-1}$	$1.453\times10^{-11}\exp(-22.1T_g^{-1/3}-40.3T_g^{-2/3})$	[20]	i=1, …, 6 j=3, …, 8 $j \geqslant i$+2
V57	$CO_2v_1 + CO_2v_1 \rightarrow CO_2 + CO_2v_2$	$1.453\times10^{-11}\exp(-22.1T_g^{-1/3}-40.3T_g^{-2/3})$	[20]	
V58	$CO_2v_1 + CO_2v_2 \rightarrow CO_2 + CO_2v_3$	$2.927\times10^{-11}\exp(-21.4T_g^{-1/3}-53T_g^{-2/3})$	[20]	
V59	$CO_2v_1 + CO_2v_3 \rightarrow CO_2 + CO_2v_4$	$4.825\times10^{-11}\exp(-20.1T_g^{-1/3}-65T_g^{-2/3})$	[20]	
V60	$CO_2v_1 + CO_2v_4 \rightarrow CO_2 + CO_2v_5$	$7.199\times10^{-11}\exp(-1.84T_g^{-1/3}-76T_g^{-2/3})$	[20]	
V61	$CO_2v_2 + CO_2v_2 \rightarrow CO_2v_1 + CO_2v_4$	$1.453\times10^{-11}\exp(-22.1T_g^{-1/3}-40.3T_g^{-2/3})$	[20]	
V62	$CO_2v_2 + CO_2v_3 \rightarrow CO_2v_1 + CO_2v_5$	$2.927\times10^{-11}\exp(-21.4T_g^{-1/3}-53T_g^{-2/3})$	[20]	
V63	$CO_2v_2 + CO_2v_4 \rightarrow CO_2v_1 + CO_2v_6$	$4.825\times10^{-11}\exp(-20.1T_g^{-1/3}-65T_g^{-2/3})$	[20]	

续表 5 CO_2 放电初始反应集合中包含的振动能量交换反应，以及相应的速率系数和参考文献

Tab. 5 The vibrational energy exchange reactions included in the initial reaction set of CO_2 discharges, as well as the corresponding rate coefficients and references (continued)

序号	反应	速率系数	参考文献	备注
V64	$CO_2v_2 + CO_2v_5 \rightarrow CO_2v_1 + CO_2v_7$	$7.199\times10^{-11}\exp(-1.84T_g^{-1/3}-76T_g^{-2/3})$	[20]	
V65	$CO_2v_3 + CO_2v_3 \rightarrow CO_2v_2 + CO_2v_4$	$1.453\times10^{-11}\exp(-22.1T_g^{-1/3}-40.3T_g^{-2/3})$	[20]	
V66	$CO_2v_3 + CO_2v_4 \rightarrow CO_2v_2 + CO_2v_5$	$2.927\times10^{-11}\exp(-21.4T_g^{-1/3}-53T_g^{-2/3})$	[20]	
V67	$CO_2v_3 + CO_2v_5 \rightarrow CO_2v_2 + CO_2v_6$	$4.825\times10^{-11}\exp(-20.1T_g^{-1/3}-65T_g^{-2/3})$	[20]	
V68	$CO_2v_3 + CO_2v_6 \rightarrow CO_2v_2 + CO_2v_7$	$7.199\times10^{-11}\exp(-1.84T_g^{-1/3}-76T_g^{-2/3})$	[20]	
V69	$CO_2v_4 + CO_2v_4 \rightarrow CO_2v_3 + CO_2v_5$	$1.453\times10^{-11}\exp(-22.1T_g^{-1/3}-40.3T_g^{-2/3})$	[20]	
V70	$CO_2v_4 + CO_2v_5 \rightarrow CO_2v_3 + CO_2v_6$	$2.927\times10^{-11}\exp(-21.4T_g^{-1/3}-53T_g^{-2/3})$	[20]	
V71	$CO_2v_4 + CO_2v_6 \rightarrow CO_2v_3 + CO_2v_7$	$4.825\times10^{-11}\exp(-20.1T_g^{-1/3}-65T_g^{-2/3})$	[20]	
V72	$CO_2v_4 + CO_2v_7 \rightarrow CO_2v_3 + CO_2v_5$	$7.199\times10^{-11}\exp(-1.84T_g^{-1/3}-76T_g^{-2/3})$	[20]	
V73	$CO_2v_5 + CO_2v_5 \rightarrow CO_2v_4 + CO_2v_8$	$1.453\times10^{-11}\exp(-22.1T_g^{-1/3}-40.3T_g^{-2/3})$	[20]	
V74	$CO_2v_5 + CO_2v_6 \rightarrow CO_2v_4 + CO_2v_6$	$2.927\times10^{-11}\exp(-21.4T_g^{-1/3}-53T_g^{-2/3})$	[20]	
V75	$CO_2v_5 + CO_2v_7 \rightarrow CO_2v_4 + CO_2v_7$	$4.825\times10^{-11}\exp(-20.1T_g^{-1/3}-65T_g^{-2/3})$	[20]	
V76	$CO_2v_6 + CO_2v_6 \rightarrow CO_2v_5 + CO_2v_8$	$1.453\times10^{-11}\exp(-22.1T_g^{-1/3}-40.3T_g^{-2/3})$	[20]	
V77	$CO_2v_6 + CO_2v_7 \rightarrow CO_2v_5 + CO_2v_8$	$2.927\times10^{-11}\exp(-21.4T_g^{-1/3}-53T_g^{-2/3})$	[20]	
V78	$CO_2v_7 + CO_2v_7 \rightarrow CO_2v_6 + CO_2v_8$	$1.453\times10^{-11}\exp(-22.1T_g^{-1/3}-40.3T_g^{-2/3})$	[20]	

(a) 当 M 为 CO_2、CO 和 O_2 时，反应速率系数分别乘以 1.0、0.7 和 0.7。

(b) 当 M 为 CO_2、CO 和 O_2 时，反应速率系数分别乘以 1.0、3.1 和 3.1。

(c) 当 M 为 CO_2、CO 和 O_2 时，反应速率系数分别乘以 1.0、1.2 和 1.2。

(d) 当 M 为 CO_2、CO 和 O_2 时，反应速率系数分别乘以 1.0、0.3 和 0.4。

(e) 反应速率系数由基于 SSH 理论的缩放定律给出。

注：表中 CO_2v_x 表示对称拉伸模式和弯曲模式，CO_2v_i 和 CO_2v_j 表示非对称拉伸模式，CO_2e_i 表示电子激发态。在速率系数表达式中，T_e 是以 eV 为单位的电子温度，T_g 是以 K 为单位的气体温度。双体反应的速率系数的单位为 cm^3s^{-1}，三体反应的速率系数的单位为 cm^6s^{-1}。

参考文献

[1] GROFULOVIĆ M, ALVES L L, GUERRA V. Electron-neutral scattering cross sections for CO_2: A complete and consistent set and an assessment of dissociation[J]. Journal of Physics D: Applied Physics, 2016, 49(39): 395207.

[2] OGLOBLINA P, TEJERO-DEL-CAZ A, GUERRA V, et al. Electron impact cross sections for carbon monoxide and their importance in the electron kinetics of CO_2-CO mixtures[J]. Plasma Sources Science and Technology, 2019, 29(1): 015002.

[3] WANG Y, ZATSARINNY O, BARTSCHAT K. B-spline R-matrix-with-pseudostates calculations for electron-impact excitation and ionization of carbon[J]. Physical Review A, 2013, 87(1): 012704.

[4] ALVES L L, COCHE P, RIDENTI M A, et al. Electron scattering cross sections for the modelling of oxygen-containing plasmas[J]. The European Physical Journal D, 2016, 70: 1-9.

[5] GOUSSET G, FERREIRA C M, PINHEIRO M, et al. Electron and heavy-particle kinetics in the low pressure oxygen positive column[J]. Journal of Physics D: Applied Physics, 1991, 24(3): 290.

[6] MATEJCIK S, KIENDLER A, CICMAN P, et al. Electron attachment to molecules and clusters of atmospheric relevance: Oxygen and ozone[J]. Plasma Sources Science and Technology, 1997, 6(2): 140.

[7] ELIASSON B. Basic data for modeling of electrical discharges in gases: Oxygen[J]. Asea Brown Boveri Corporate Research Report, 1986: KLR86-11C.

[8] SUN S, WANG H, BOGAERTS A. Chemistry reduction of complex CO_2 chemical kinetics: Application to a gliding arc plasma[J]. Plasma Sources Science and Technology, 2020, 29(2): 025012.

[9] KOZáK T, BOGAERTS A. Splitting of CO_2 by vibrational excitation in non-equilibrium plasmas: A reaction kinetics model[J]. Plasma Sources Science and Technology, 2014, 23(4): 045004.

[10] BEUTHE T G, CHANG J S. Chemical kinetic modelling of non-equilibrium Ar-CO_2 thermal plasmas[J]. Japanese Journal of Applied Physics, 1997, 36(7S): 4997.

[11] WANG W, SNOECKX R, ZHANG X, et al. Modeling plasma-based CO_2 and CH_4 conversion in mixtures with N_2, O_2, and H_2O: The bigger plasma chemistry picture[J]. The Journal of Physical Chemistry C, 2018, 122(16): 8704-8723.

[12] SNOECKX R, BOGAERTS A. Plasma technology-a novel solution for CO_2 conversion?[J].

Chemical Society Reviews, 2017, 46(19): 5805-5863.
[13] PONDURI S, BECKER M, WELZEL S, et al. Fluid modelling of CO_2 dissociation in a dielectric barrier discharge[J]. Journal of Applied Physics, 2016, 119(9): 093301.
[14] AERTS R, SOMERS W, BOGAERTS A. Carbon dioxide splitting in a dielectric barrier discharge plasma: A combined experimental and computational study[J]. ChemSusChem, 2015, 8(4): 702-716.
[15] CHENG H, MA M, ZHANG Y, et al. The plasma enhanced surface reactions in a packed bed dielectric barrier discharge reactor[J]. Journal of Physics D: Applied Physics, 2020, 53(14): 144001.
[16] VERMEIREN V, BOGAERTS A. Supersonic microwave plasma: Potential and limitations for energy-efficient CO_2 conversion[J]. The Journal of Physical Chemistry C, 2018, 122(45): 25869-25881.
[17] BERTHELOT A, BOGAERTS A. Modeling of CO_2 plasma: Effect of uncertainties in the plasma chemistry[J]. Plasma Sources Science and Technology, 2017, 26(11): 115002.
[18] BERTHELOT A, BOGAERTS A. Modeling of plasma-based CO_2 conversion: Lumping of the vibrational levels[J]. Plasma Sources Science and Technology, 2016, 25(4): 045022.
[19] MOSS M S, YANALLAH K, ALLEN R W K, et al. An investigation of CO2 splitting using nanosecond pulsed corona discharge: effect of argon addition on CO2 conversion and energy efficiency[J]. Plasma Sources Science and Technology, 2017, 26(3): 035009.
[20] BLAUER J, NICKERSON G. A survey of vibrational relaxation rate data for processes importantto CO_2-N_2-H_2O infrared plume radiation; proceedings of the 7th Fluid and PlasmaDynamics Conference, F, 1974[C].