CO_2 放电初始反应集合

表 1 火星大气下 CO_2 放电初始反应集合中由 Bolsig+计算获得速率系数的电子碰撞反应，其中 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

Tab. 1 Electron impact reactions in the initial reaction set of CO_2 discharges on Mars with reaction rate coefficients obtained by Bolsig+, where CO_2v_x denotes symmetric stretching and bending modes, CO_2v_i and CO_2v_j denote asymmetric stretching modes, and CO_2e_i denotes electronically excited states

序号	反应	速率系数	参考	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 火星大气下 CO_2 放电初始反应集合中由 Bolsig+计算获得速率系数的电子碰撞反应，其中 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

Tab. 1 Electron impact reactions in the initial reaction set of CO_2 discharges on Mars with reaction rate coefficients obtained by Bolsig+, where CO_2v_x denotes symmetric stretching and bending modes, CO_2v_i and CO_2v_j denote asymmetric stretching modes, and CO_2e_i denotes electronically excited states (continued)

序号	反应	速率系数	参考	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 分子碰撞电离反应相同的横截面。
(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 火星大气下 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附着反应，以及相应的速率系数和参考文献。除非另有说明，反应中的 CO_2 代表各种状态的 CO_2。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}

Tab. 2 The electron-ion recombination reactions and electron attachment reactions included in the reaction set of CO_2 discharge on Mars, as well as the corresponding rate coefficients and references. Unless noted otherwise, CO_2 in the reaction represents all kinds of states of CO_2. In the rate coefficient expressions, T_e is the electron temperature in eV and T_g is the gas temperature in K. The units of rate coefficients for two-body reactions are cm^3s^{-1}, and for three-body reactions are cm^6s^{-1}

序号	反应	速率系数	参考	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 火星大气下 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附着反应，以及相应的速率系数和参考文献。除非另有说明，反应中的 CO_2 代表各种状态的 CO_2。在速率系数表达式中，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}

Tab. 3 The electron-ion recombination reactions and electron attachment reactions included in the reaction set of CO_2 discharge on Mars, as well as the corresponding rate coefficients and references. Unless noted otherwise, CO_2 in the reaction represents all kinds of states of CO_2. In the rate coefficient expressions, T_g is the gas temperature in K. The units of rate coefficients for two-body reactions are cm^3s^{-1}, and for three-body reactions

序号	反应	速率系数	参考	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]	

续表 3 火星大气下 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附着反应，以及相应的速率系数和参考文献。除非另有说明，反应中的 CO_2 代表各种状态的 CO_2。在速率系数表达式中，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}

Tab. 3 The electron-ion recombination reactions and electron attachment reactions included in the reaction set of CO_2 discharge on Mars, as well as the corresponding rate coefficients and references. Unless noted otherwise, CO_2 in the reaction represents all kinds of states of CO_2. In the rate coefficient expressions, T_g is the gas temperature in K. The units of rate coefficients for two-body reactions are cm^3s^{-1}, and for three-body reactions (continued)

序号	反应	速率系数	参考	备注
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
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 火星大气下 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。除非另有说明，反应中的 CO_2 代表各种状态的 CO_2。在速率系数表达式中，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}

Tab. 4 The neutral reactions included in the reaction set of CO_2 discharge on Mars, as well as the corresponding rate coefficients and references. Unless noted otherwise, CO_2 in the reaction represents all kinds of states of CO_2. In the rate coefficient expressions, T_g is the gas temperature in K. The units of rate coefficients for two-body reactions are cm^3s^{-1}, and for three-body reactions

序号	反应	速率系数	参考	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 火星大气下 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。其中 CO_2v_i 和 CO_2v_j 表示非对称拉伸模式在速率系数。表在速率系数表达式中，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是 cm^3s^{-1}

Tab. 5 The vibrational energy exchange reactions included in the initial reaction set of CO_2 discharges on Mars, as well as the corresponding rate coefficients and references, where CO_2v_i and CO_2v_j denote asymmetric stretching modes. In the rate coefficient expressions, T_g is the gas temperature in K, and the rate coefficients have the units of cm^3s^{-1} for two-body reactions

序号	反应	速率系数	参考	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)

续表 5 火星大气下 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。其中 CO_2v_i 和 CO_2v_j 表示非对称拉伸模式在速率系数。表在速率系数表达式中，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是 cm^3s^{-1}

Tab. 5 The vibrational energy exchange reactions included in the initial reaction set of CO_2 discharges on Mars, as well as the corresponding rate coefficients and references, where CO_2v_i and CO_2v_j denote asymmetric stretching modes. In the rate coefficient expressions, T_g is the gas temperature in K, and the rate coefficients have the units of cm^3s^{-1} for two-body reactions (continued)

序号	反应	速率系数	参考	备注
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$_i$	$CO_2v_i + M \rightarrow CO_2v_{i-1} + M$	$f(k(VT_{v1\rightarrow va}), k(VT_{v1\rightarrow vb}))$	[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]	
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]	

续表 5 火星大气下 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。其中 CO_2v_i 和 CO_2v_j 表示非对称拉伸模式在速率系数。表在速率系数表达式中，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是 cm^3s^{-1}

Tab. 5 The vibrational energy exchange reactions included in the initial reaction set of CO_2 discharges on Mars, as well as the corresponding rate coefficients and references, where CO_2v_i and CO_2v_j denote asymmetric stretching modes. In the rate coefficient expressions, T_g is the gas temperature in K, and the rate coefficients have the units of cm^3s^{-1} for two-body reactions (continued)

序号	反应	速率系数	参考	备注
$V39_i$	$CO_2v_i + CO_2 \rightarrow CO_2v_{i-1} + CO_2v_a$	$2.03\times10^{-5}\exp(-242T_g^{-1/3}-633T_g^{-2/3})$	[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]	
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]	

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Tab. 5 The vibrational energy exchange reactions included in the initial reaction set of CO_2 discharges on Mars, as well as the corresponding rate coefficients and references, where CO_2v_i and CO_2v_j denote asymmetric stretching modes. In the rate coefficient expressions, T_g is the gas temperature in K, and the rate coefficients have the units of cm^3s^{-1} for two-body reactions (continued)

序号	反应	速率系数	参考	备注
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。

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