

Stability Analysis of SiO₂ /SiC Multilayer Coatings

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Abstract: The stability behaviours of SiC coatings and SiO₂/SiC coatings in helium with little impurities are studied by HSC Chemistry 4.1, the software for analysis of Chemical reaction and equilibrium in multi-component complex system. It is found that in helium with a low partial pressure of oxidative impurities under different total pressure, the key influence factor controlling T_{cp} of SiC depends is the partial pressure of oxidative impurities; T_{cp} of SiC increases with the partial pressure of oxidative impurities. In helium with a low partial pressure of different impurities, the key influence factor of T_{cs} of SiO₂ are both the partial pressure of impurities and the amount of impurities for 1mol SiO₂; T_{cs} of SiO₂ increases with the partial pressure of oxidative impurities at the same amount of the impurities for 1mol SiO₂ while it decreases with the amount of the impurities for 1mol SiO₂ at the same partial pressure of the impurities. The influence of other impurities on T_{cp} of SiC in He-O₂ is studied and it is found that CO₂, H₂O and N₂ increase T_{cp} of SiC in He-O₂ while H₂, CO and CH₄ decrease T_{cp} of SiC He-O₂. When there exist both oxidative impurities and reductive impurities, their effect on T_{cs} of SiO₂ can be suppressed by the other. In HTR-10 operation atmosphere, SiO₂/SiC coatings can keep stable status at higher temperature than SiC coatings, so SiO₂/SiC coatings is more suitable to improve the oxidation resistance of graphite in HTR-10 operation atmosphere compared with SiC coatings.

Key words: SiC, SiO₂, Stability behaviour, Thermodynamics, Helium with little impurities

1. Introduction

Graphite is an important material for the construction of High Temperature

Gas-cooled Reactor (HTGR) as the matrix materials for fuel element and absorbing element, structural materials for reflector, discharge tube, support column and thermal barrier for it has high strength at high temperature, high heat conductivity, high stability at high temperature in inert environment and excellent nuclear properties. But it is apt to be oxidized in HTGR atmosphere at high temperature when air or water enter the primary circuit of HTGR, which causes the decline of its properties and even causes the radioactive products leakage. So it is essential to improve the oxidation resistance of graphite used in HTGR in order to further improve the safety of HTGR.

Amongst the methods to improve the oxidation resistance of graphite, the application of SiC coatings on graphite is the most effective method, for SiC coatings have an excellent consistence with graphite and a dense amorphous SiO₂ layer can be formed on the surface of SiC coatings at a high partial pressure of oxidative gas. Up to now, some researchers have fabricated SiC coatings on graphite by different methods and obviously improved the oxidation resistance of graphite in air. A. M. Hurtado, et al fabricated SiC coatings on graphite by chemical vapour deposition method and slip casting method, the mass loss rate of coated graphite ball was less than 1mg/(cm² · h) when the samples were oxidized in the air over 1 000 °C^[1]. C. Tang, et al. coated SiC coatings on graphite by the reaction between graphite and molten silicon and the oxidation experiment showed only 1.7% mass loss when the samples were heated at 1 000 °C in static air for 8h^[2]. Q. Zhu, et al. fabricated SiC coatings on graphite by slip-gelation process and an obtained excellent oxidation resistance too^[3].

In order to exert the protection of coatings for graphite under oxidative atmosphere, the coatings material should be stable at the service condition. However, many researchers studied the behaviour of SiC materials and found that there existed two kinds of oxidation mechanism: passive oxidation and active oxidation^[4-6]. When SiC is oxidized at high partial pressure of oxidative gas, a dense amorphous SiO₂ layer can be formed on the surface. The oxidation rate of SiC is very low for oxygen can only diffuse through SiO₂ layer at a very low rate. At this case, a little mass increase of SiC samples will be found. This kind of oxidation is called passive oxidation and is the important basis for the improvement of the oxidation resistance of graphite by SiC coatings. However, when SiC is oxidized at low partial pressure of oxidative gas, SiC is changed into

gaseous SiO and CO, so notable mass loss of the samples is found. This kind of oxidation is called active oxidation. At this case, SiC coatings cannot protect graphite from oxidation for a long time since it may be consumed during the oxidation period.

The partial pressure of oxidative gas is very low at the normal service condition of graphite in HTGR, and it will be increased to a high level when air or water enters the primary circuit of HTGR. If SiC is oxidized in active oxidation mechanism under these cases, SiC coatings will have been consumed before the arrival of high partial pressure of oxidative gas and will not protect graphite well. Therefore, the determination of the condition for active oxidation or passive oxidation of SiC is required.

At the conditions for active oxidation of SiC, if we can fabricate a SiO₂ layer with a suitable thickness on SiC coatings and the consumption rate of SiO₂ is slow enough, we can yet protect graphite from oxidation by SiO₂/SiC coatings. Hence, studying the stability of SiO₂ at different conditions, especially at the condition for active oxidation of SiC is also essential.

The SiC and SiO₂/SiC coatings services in high pressure helium with a small amount of impurities during the normal operation of HTGR while the usual high temperature corrosion apparatus in laboratory can only operate at normal pressure, so the analogy of the corrosion behaviours at service condition from those at normal pressure is necessary, which needs finding the key influence factor of the corrosion of SiC and SiO₂ at different pressure.

The equilibrium composition of the stable phases for SiC or SiO₂ in a certain gas is first obtained with HSC Chemical reaction and equilibrium software, and the critical temperature of passive oxidation for SiC or the critical temperature of stability for SiO₂ is determined from the equilibrium composition diagram; then the key influence factors controlling the critical temperature are found and their effect on the critical temperature is studied. The analysis procedure of finding the key influence factors of the critical temperature is demonstrated by an example of analysis of the stability of SiC and SiO₂ in He-O₂. Then the stability behaviours of SiC and SiO₂ in the atmosphere with a low partial pressure of oxidative species are studied.

2. Analysis of key influence factor of critical temperature for stability of SiC and SiO₂ in He-O₂ by thermodynamic diagram

2.1 Analysis of key influence factor of critical temperature of passive oxidation for SiC

The typical equilibrium composition diagram of the stable phases for SiC in He-O₂ is shown in Fig. 1. SiO₂ and C are stable phases at low temperature, SiO₂ and CO are stable phases at medium temperature, SiO and CO are stable phases at high temperature, and SiO₂, SiC will be decomposed at super-high temperature. Since the decomposition temperature of SiC and SiO₂ is much higher than the temperature for active oxidation, the active oxidation is dominating factor affecting the stability of SiC in He-O₂. The amount of SiO₂ and SiO of the equilibrium composition diagram in Fig. 1 is shown in Fig. 2. At low or medium temperature SiC undergoes passive oxidation for SiO₂ is stable, but SiC withstands active oxidation at high temperature for SiO is stable. With the rise of temperature from medium temperature to high temperature, the amount of SiO increases until it keeps almost constant. When the equilibrium composition diagrams of SiC in He-O₂ with different amount of oxygen are compared, it is found that with the augment of the amount of oxygen for 1mol SiC, the amount of SiO₂ and SiO increases also, i. e. more SiC is consumed. The temperature at which the amount of SiO is equal to 0.01% of the amount of SiO at high temperature is defined as the critical temperature of passive oxidation for SiC (T_{cp}), below which SiC is thought to undergo passive oxidation. If the SiC coatings are needed to service at a certain condition for a long time, the service temperature should not exceed the critical temperature of passive oxidation for SiC in the specific atmosphere.

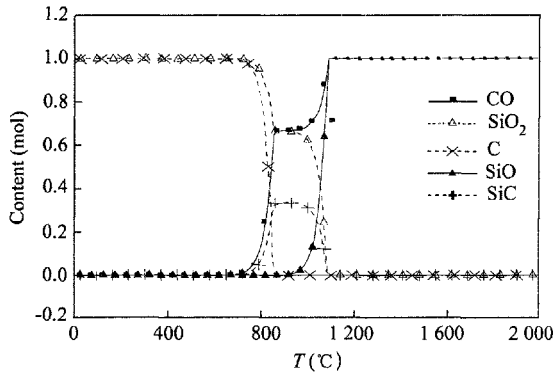


Fig. 1 Typical equilibrium composition diagram for SiC in He-O₂

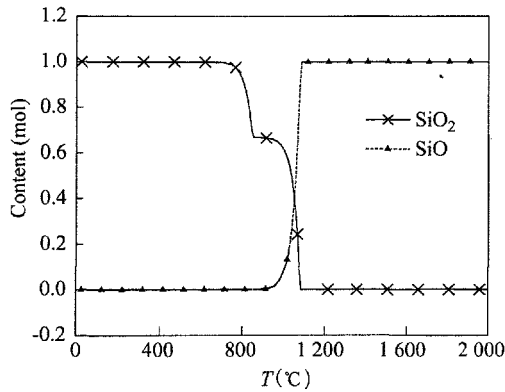


Fig. 2 Amount of SiO₂ and SiO in equilibrium composition diagram for SiC in He-O₂

There are 5 factors of gas affecting the critical temperature; they are the pressure of gas, the concentration of oxidative impurity, the partial pressure of oxidative impurity, the amount of gas, and the amount of oxidative impurity. The partial pressure of oxidative impurity is same as the product of the concentration of oxidative impurity and the pressure of gas; the amount of oxidative impurity is same as the product of the concentration of oxidative impurity and the amount of gas. The key influencing factors under different pressure of gas are the fewest required influence factors in order to determine T_{cp} when the pressure of gas is different.

The critical temperature of passive oxidation for SiC under different oxidation conditions is shown in Tab. 1. When the amount of oxygen is no more than that of SiC, T_{cp} of SiC is same when the concentration of oxygen and the pressure of gas are same, no matter when the amount of oxygen (or the amount of gas) increases or decreases.

When the concentration of oxygen is same, T_{cp} of SiC increases with the pressure of gas and the partial pressure of oxygen; while the change of the amount of gas or the amount of oxygen has no effect on T_{cp} of SiC when the pressure of gas or the partial pressure of oxygen keeps constant. When the amount of gas for 1mol SiC or the amount of oxygen for 1mol SiC is same, T_{cp} of SiC cannot always keep constant when the other factors change. But when the partial pressure of oxygen is same, T_{cp} of SiC always keeps constant no matter how the others influence factors change.

Tab. 1 T_{cs} of SiC under different oxidation condition/°C

Concentration of oxygen/ 10^{-6}	Pressure of gas/MPa	Amount of oxygen for 1mol SiC/mol			
		1×10^{-5}	1×10^{-3}	1×10^{-1}	1
0.1	0.01	672	672	672	672
	0.1	721.5	721.5	721.5	721.5
	1	776	776	776	776
	10	835	835	835	835
1	0.01	721.5	721.5	721.5	721.5
	0.1	776	776	776	776
	1	834.5	834.5	834.5	834.5
	10	900	900	900	900
10	0.01	776	776	776	776
	0.1	834.5	834.5	834.5	834.5
	1	900	900	900	900
	10	974	974	974	974
100	0.01	834.5	834.5	834.5	834.5
	0.1	900	900	900	900
	1	974	974	974	974
	10	1 058.5	1 058.5	1 058.5	1 058.5

From the discussion above, we can find that only when the partial pressure of oxygen keeps constant, T_{cp} of SiC in the gas, which has nothing to do with the change of any other influence factor, can be determined. Therefore, the key influence factor controlling T_{cp} is the partial pressure of oxygen. If we have only the apparatus which can test the oxidation behaviours of samples at normal pressure but want to simulate the oxidation behaviours of SiC under different pressure of gas, we should keep the partial pressure of oxygen same.

Similarly, we can also find the only key influence factor controlling T_{cp} in helium with other oxidative impurity is the partial pressure of oxidative impurity in helium.

2.2 Analysis of key influence factor of critical temperature of stability for SiO₂

The typical equilibrium composition diagram of the stable phases for SiO₂ in He-O₂ is shown in Fig. 3. The amount of SiO₂ and SiO of the equilibrium composition diagram in Fig. 3 is shown in Fig. 4. SiO₂ is stable at low

temperature, while it is decomposed into SiO and oxygen at high temperature. With the increase of temperature at high temperature range, the amount of SiO increases until it is almost equal to the amount of SiO₂, which means that SiO₂ is completely decomposed into SiO and oxygen. The temperature at which the amount of SiO is equal to 0.01% of the amount of SiO₂ is defined as the critical temperature of stability for SiO₂ (T_{cs}), below which SiO₂ is thought stable. If the SiO₂ coatings are needed to service at a certain condition for a long period, the service temperature should not exceed the critical temperature of stability for SiO₂.

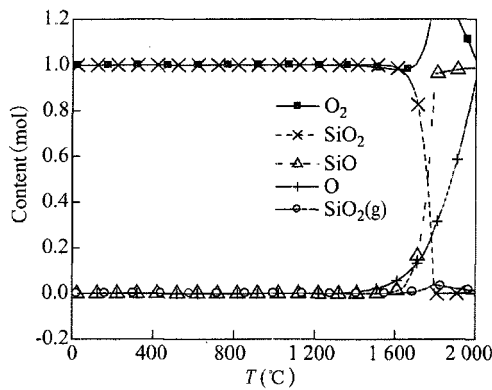


Fig. 3 Typical equilibrium composition diagram for SiO₂ in He-O₂

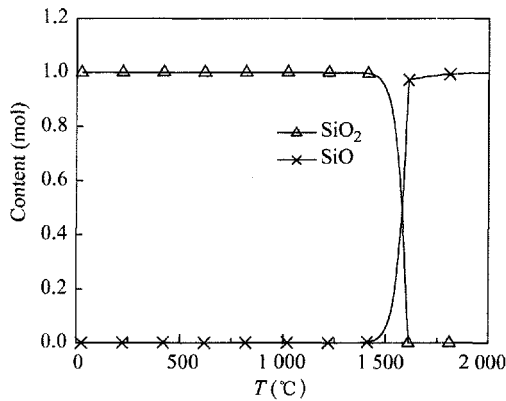


Fig. 4 Content of SiO₂ and SiO in equilibrium composition diagram for SiO₂ in He-O₂

The critical temperature of stability for SiO₂ in the gas at different conditions is shown in Tab. 2. It is can be seen that T_{cs} of SiO₂ decreases with

the increase of the amount of oxygen for 1mol SiO₂ or the amount of gas for 1mol SiO₂ when the pressure of gas and the concentration of oxygen are same, T_{cs} of SiO₂ increases with the increase of the pressure of gas or the concentration of oxygen when the others influence factors keep constant.

With the similar analysis with that of the key influence factor controlling T_{ep}, it can be seen that T_{cs} of SiO₂ cannot be determined if only one influence factor keeps constant. If the decomposition behaviour of SiO₂ under different pressure needs to be analogized with a usual high temperature corrosion apparatus at normal pressure, more influence factors should be controlled. There are five variables for the gas under different pressure, the pressure of gas is not considered to be controlled for the decomposition behaviour of SiO₂ under different pressure is needed to be analogized. When the correlation between the five variables of the gas is considered, there are only three independent combinations of two variables of gas under different pressure. The others combinations can be derived from these three combinations.

Tab. 2 T_{cs} of SiO₂ under different condition/°C

Concentration pressure of of oxygen/10 ⁻⁶ gas/MPa		Amount of oxygen for 1mol SiO ₂ /mol						
		1×10 ⁻⁵	1×10 ⁻⁴	1×10 ⁻³	1×10 ⁻²	1×10 ⁻¹	1	10
0.1	0.01	1 474	1 382.5	1 314.5	1 255	1 200	1 149.5	1 110
	0.1	1 593	1 489	1 412	1 345.5	1 284.5	1 227.5	1 174.5
	1	1 732	1 611.5	1 523	1 447	1 378	1 314	1 255.5
	10	1 893	1 752	1 649	1 563	1 484	1 412	1 345.5
1	0.01	1 593	1 489	1 412	1 345.5	1 284	1 227.5	1 174.5
	0.1	1 731	1 611.5	1 523	1 447	1 378	1 314.5	1 255.5
	1	1 893	1 752	1 649	1 563	1 484	1 412	1 345.5
	10	>2 000	1 918	1 797	1 695	1 605	1 523	1 447.5
10	0.01	1 731	1 611.5	1 523	1 447.5	1 378	1 314.5	1 255.5
	0.1	1 893	1 752	1 649.5	1 563	1 484	1 412	1 345.5
	1	>2 000	1 918	1 797	1 695	1 605	1 523	1 447.5
	10	>2 000	>2 000	1 971	1 851.5	1 744.5	1 649.5	1 563
100	0.01	1 893	1 752	1 649	1 563	1 484	1 412	1 345.5
	0.1	>2 000	1 918	1 797	1 695	1 605	1 523	1 447.5
	1	>2 000	>2 000	1 971	1 851.5	1 744.5	1 649.5	1 563
	10	>2 000	>2 000	>2 000	>2 000	1 909.5	1 797	1 695.5

When the partial pressure of oxygen and the amount of gas for 1mol SiO₂ are same, T_{cs} of SiO₂ increases with the pressure of gas while it decreases with the increase of the concentration of oxygen and the amount of oxygen for 1mol SiO₂. When the concentration of oxygen and the amount of oxygen are same, T_{cs} of SiO₂ increases with the pressure of gas and the partial pressure of oxygen. When the partial pressure of oxygen and the amount of oxygen for 1mol SiO₂ are same, T_{cs} of SiO₂ always keeps constant, independent of the change of the others influence factors.

According to the discussion above, we can find T_{cs} of SiO₂ can be determined when the partial pressure of oxygen and the amount of oxygen for 1mol SiO₂ are known. So we conclude that the key influence factors controlling T_{cs} of SiO₂ are the partial pressure of oxygen and the amount of oxygen for 1mol SiO₂. If we have only the apparatus which can test the oxidation behaviours of samples at normal pressure but want to simulate the decomposition behaviours of SiO₂ under different pressure of gas, we should keep both the partial pressure of oxygen and the amount of oxygen for 1mol SiO₂ same as the service conditions.

Similarly, we find the key influence factors controlling T_{cs} of SiO₂ in helium with a small amount of other oxidative impurity are the partial pressure of oxidative impurity and the amount of oxidative impurity for 1mol SiO₂.

3. Comparison of T_{cp} of SiC and T_{cs} of SiO₂ in helium with a small amount of oxidative impurities

T_{cp} of SiC and T_{cs} of SiO₂ in He-O₂ at 0.1MPa are shown in Fig. 5, the number following T_{cs} in the legend indicating the total amount of gas (mol) for 1mol SiO₂ (for example, T_{cs} , 10² means T_{cs} of SiO₂ in the helium whose amount is 100 times of that SiO₂). It can be seen that the critical temperature of passive oxidation for SiC is much lower than the critical temperature of stability for SiO₂, which means SiO₂ can be stable at some condition for active oxidation of SiC. Therefore, SiO₂/SiC coatings can improve the oxidation resistance of graphite in He-O₂ at low partial pressure of O₂ more greatly than SiC coatings.

It can be found also from Fig. 5 that T_{cs} of SiO₂ increases with the decrease of amount of gas for 1mol SiO₂, that is to say, SiO₂/SiC coatings can service in He-O₂ with oxygen at low partial pressure at higher temperature when the thickness of SiO₂ layer is increased.

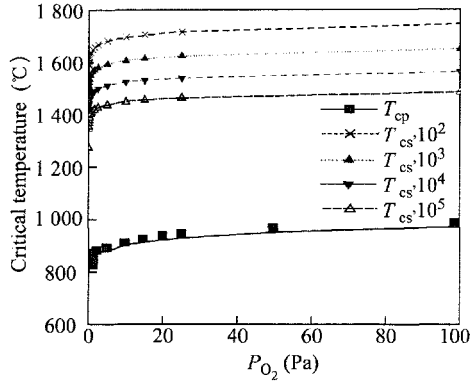


Fig. 5 T_{cp} of SiC and T_{cs} of SiO₂ with in He-O₂

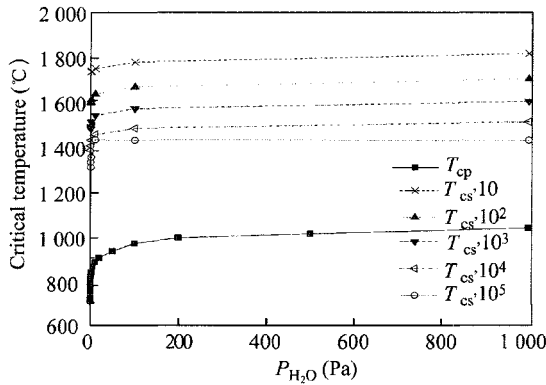


Fig. 6 T_{cp} of SiC and T_{cs} of SiO₂ with in He-H₂O

T_{cp} of SiC and T_{cs} of SiO₂ in He-H₂O at 0.1MPa are shown in Fig. 6, the number in the legend indicating the total amount of gas (mole) for 1mol SiO₂. T_{cp} of SiC and T_{cs} of SiO₂ in He-CO₂ at 0.1 MPa are shown in Fig. 7, the number in the legend indicating the total amount of gas (mol) for 1mol SiO₂. The similar conclusion can be obtained from these figures. Therefore, SiO₂/SiC coatings can improve the oxidation resistance of graphite in helium with a small amount of oxidative impurities more greatly than SiC coatings; and SiO₂/SiC coatings can service in helium with a small amount of oxidative impurities at higher temperature when the thickness of SiO₂ layer is increased.

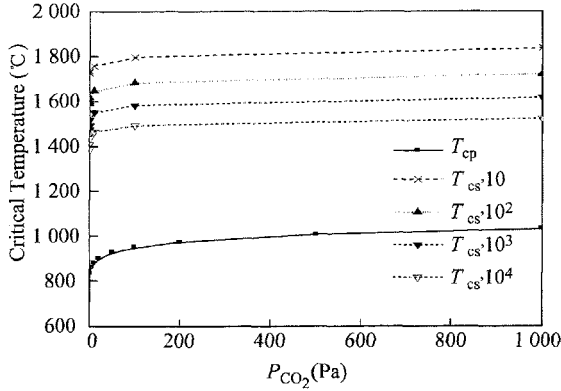


Fig. 7 T_{cp} of SiC and T_{cs} of SiO₂ with in He-CO₂

4. Influence of different impurities on T_{cs} of SiO₂ in helium

The influence of different impurities in helium at 0.1 MPa on the T_{cs} of SiO₂ is shown in fig. 8. When the amount of gas for 1 mol SiO₂ is small, the decrease of T_{cs} of SiO₂ by introducing reductive impurities such as CO, H₂, and CH₄ at low partial pressure is not evident while the influence is enhanced at high partial pressure; the influence of nitrogen and oxidative impurities such as O₂, H₂O, and H₂O on T_{cs} of SiO₂ is un conspicuous at any partial pressure. However, when the amount of gas for 1 mol SiO₂ is large, T_{cs} of SiO₂ decreases sharply with the partial pressure of reductive impurities at low partial pressure while the influence becomes not so obvious when the partial pressure is high; T_{cs} of SiO₂ increases obviously with the partial pressure of oxidative impurities at low partial pressure but the influence is not so obvious at high partial pressure; the influence of nitrogen on T_{cs} of SiO₂ is yet not obvious in any partial pressure range. The decrease of T_{cs} of SiO₂ by reductive impurities is more obvious than the rise of T_{cs} of SiO₂ by oxidative impurities. When the influence of different impurity on T_{cs} of SiO₂ is compared, it is found that the rise of T_{cs} of SiO₂ by oxygen is the most obvious amongst the oxidative impurities; the decrease of T_{cs} of SiO₂ by methane is the most prominent amongst the reductive impurities.

In the normal operation atmosphere of high temperature reactor, there are both oxidative impurities and reductive impurities. The influence of a kind of impurities can be affected by the other kind of impurities, so the influence of the introduction of both oxidative impurity (O₂, CO₂ and H₂O) and reductive

impurity (CO , H_2 , and CH_4) into helium on T_{cs} of SiO_2 should be studied. The influence of the introduction of both oxygen and reductive impurities in helium on T_{cs} of SiO_2 is shown in Fig. 9. The influence of the introduction of both CO_2 (or H_2O) and reductive impurities in helium on T_{cs} of SiO_2 is studied also. It is found that when the amount of gas for 1mol SiO_2 is small and the partial pressure of impurities is low, simultaneous introduction of both oxidative impurities and reductive impurities has little influence on T_{cs} of SiO_2 . However, when the amount of gas for 1mol on SiO_2 is large or the partial pressure of impurities is high, the influence of simultaneous introduction of oxidative impurities and reductive impurities on T_{cs} of SiO_2 becomes obvious; T_{cs} of SiO_2 decreases with ratio between partial pressure of oxidative impurity to that of reductive impurity.

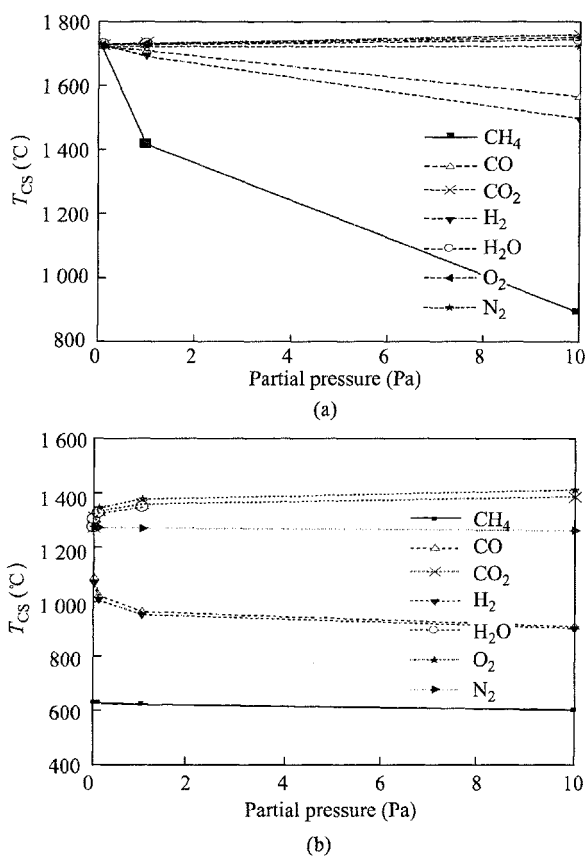
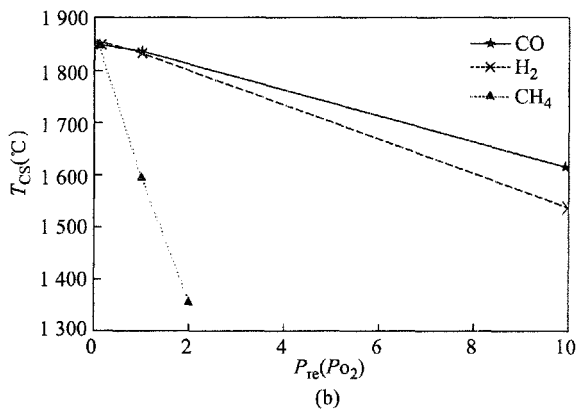
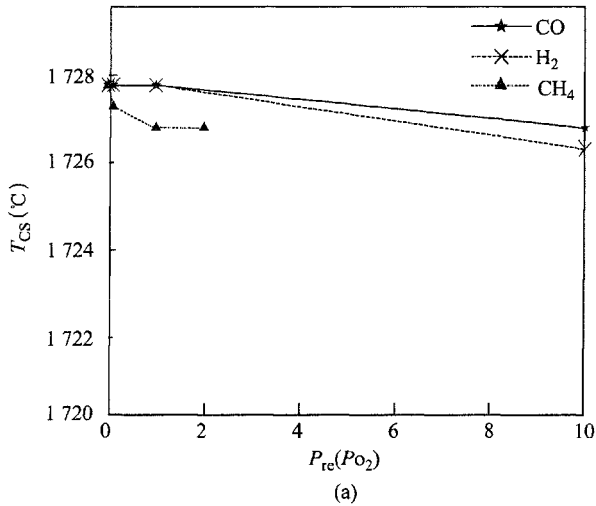
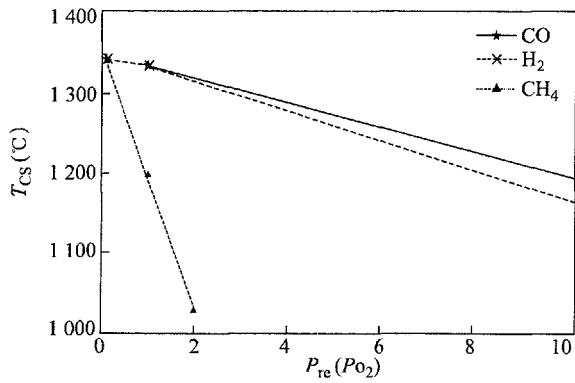


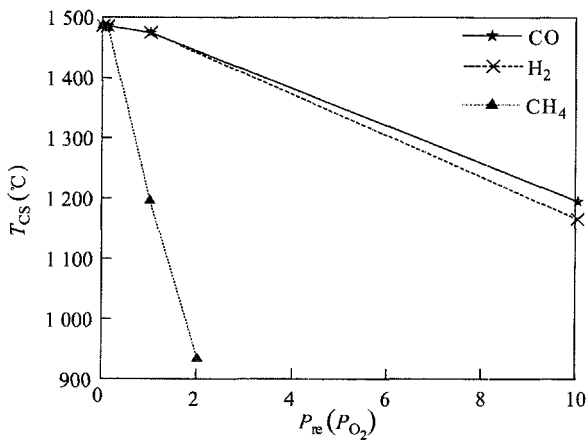
Fig. 8 The influence of impurities in helium at 0.1 MPa on the T_{cs} of SiO_2
 (a) the amount of gas for 1 mol SiO_2 is 10 mol;
 (b) the amount of gas for 1 mol SiO_2 is 100 000 mol

For a certain gas, there exists a critical ratio between partial pressure of oxidative impurity to that of reductive impurity, below which T_{cs} of SiO_2 is higher than that in pure helium and above which T_{cs} of SiO_2 is lower than that in pure helium. With the increase of the amount of gas for 1mol SiO_2 or the partial pressure of oxidative impurities, the critical ratio appreciably increases.





(c)



(d)

Fig. 9 Influence of the introduction of both oxygen and reductive impurities in helium

(a) $P_{O_2} = 0.01$ Pa, amount of gas for 1 mol SiO_2 is 10 mol;

(b) $P_{O_2} = 100$ Pa, amount of gas for 1 mol SiO_2 is 10 mol;

(c) $P_{O_2} = 0.01$ Pa, amount of gas for 1 mol SiO_2 is 100 000 mol;

(d) $P_{O_2} = 100$ Pa, amount of gas for 1 mol SiO_2 is 100 000 mol

5. Influence of other impurities on T_{cp} of SiC in He- O_2

The influence of the introduction of different impurities into He- O_2 on T_{cp} of SiC is shown in Fig. 10. It can be found that the introduction of other oxidative impurities and nitrogen will increase T_{cp} of SiC in He- O_2 ; the decrease of T_{cp} of SiC in He- O_2 by the introduction of reductive impurities except methane is not very obvious.

When compared with the influence of introducing different impurities on T_{cs}

of SiO_2 , it is found that nitrogen increases T_{cp} of SiC while it has little effect on T_{cs} of SiO_2 . This is because $\text{Si}_2\text{N}_2\text{O}$ can be formed when nitrogen is introduced into He-O_2 (shown in Fig. 11), which can suppress the formation of gaseous silicon compounds. However, T_{cs} of SiO_2 is so high that $\text{Si}_2\text{N}_2\text{O}$ is not stable, so the introduction of nitrogen has little effect on T_{cs} of SiO_2 .

6. T_{cp} of SiC and T_{cs} of SiO_2 in helium for HTR-10 coolant

The measured data of impurities in helium coolant for 10 MW High Temperature Gas-Cooled Reactor (HTR-10) is shown in Tab. 3. The operation pressure is 3 Mpa, the flow rate of helium is 3.99 kg/s, and the operation temperature is 700°C now and the operation temperature will be further increased in future.

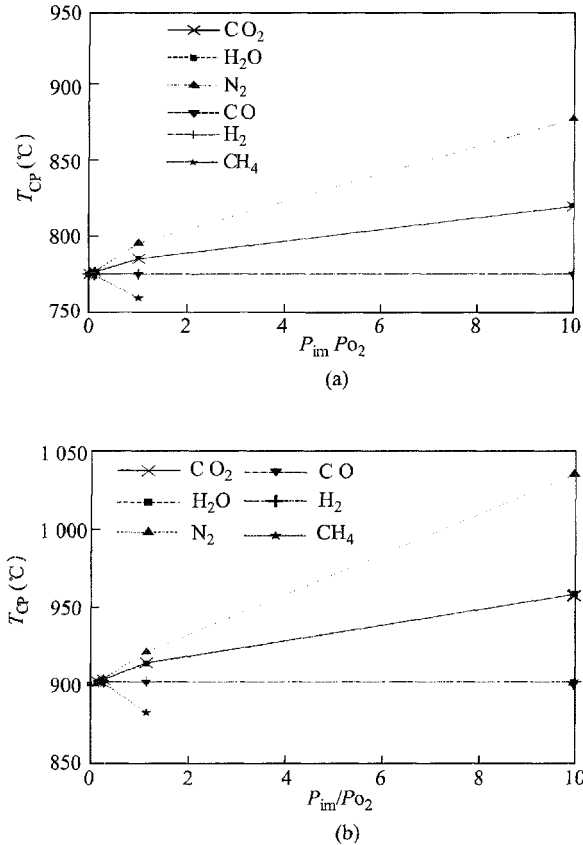


Fig. 10 Influence of the introduction of different impurities into He-O_2 of T_{cp} of SiC

(a) P_{O_2} is 0.1 Pa; (b) P_{O_2} is 10 Pa

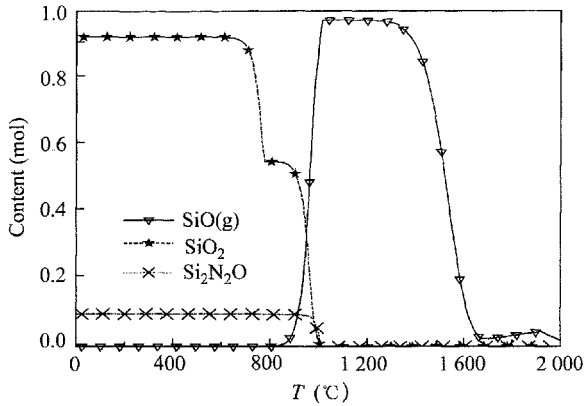


Fig. 11 Main silicon compounds formed from SiC in He-O₂-N₂ gas

Tab. 3 Measured data of impurities in helium coolant for HTR-10

Impurity	H ₂	O ₂	N ₂	CH ₄	CO	CO ₂	H ₂ O
Measured value /vpm	4.39	0.5	1.86	0.41	8.84	5.23	3

Tab. 4 T_{cs} of SiO₂ in helium coolant for HTR-10

Total amount of helium for 1mol SiO ₂ /mole	10	100	1 000	10 000	100 000
T_{cs} of SiO ₂ /°C	1 940.5	1 712	1 569	1 450	1 345

T_{cp} of SiC in helium for HTR-10 coolant at 3 MPa is 929 °C. T_{cs} of SiO₂ in helium for HTR-10 coolant at 3 MPa is shown in Tab. 4. It can be seen that SiC coatings can protect graphite from oxidation in HTR-10 operation atmosphere at nowadays operation temperature; but it cannot be used if the operation temperature is increased above 950 °C in future while SiO₂/SiC coatings can still protect graphite from oxidation during a long period even at a much higher temperature. So SiO₂/SiC coatings is more suitable than SiC coatings for the improvement of the oxidation resistance of graphite used in HTR.

7. Conclusions

1) In helium with a small amount of oxidative impurities, T_{cp} of SiC depends only on the partial pressure of oxidative impurities; T_{cp} of SiC increases with the partial pressure of oxidative impurities.

2) In helium with a small amount of oxidative impurities, T_{cs} of SiO_2 depends on both the partial pressure of impurities and the amount of oxidative impurities for 1mol SiO_2 ; T_{cs} of SiO_2 increases with the partial pressure of oxidative impurities while it decreases with the amount of reductive impurities for 1mol SiO_2 .

3) When other impurities are introduced into He-O_2 , CO_2 , H_2O and N_2 increase T_{cp} of SiC while H_2 , CO and CH_4 decrease T_{cp} of SiC .

4) When there exist both oxidative impurities and reductive impurities, their effect on T_{cs} of SiO_2 can be suppressed each other.

5) In HTR-10 operation atmosphere, SiO_2/SiC coatings are more suitable than SiC coatings to improve the oxidation resistance of graphite.

Note

This work was performed by Dr. Zhiqiang Fu during his visit in CEA (Cadache) from November, 2003 to June, 2004.

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