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Fusibility of medical glass in hospital waste incineration: Effect of glass components

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ABSTRACT

Medical glass, which is the principal incombustible component in hospital wastes, has a bad influence on combustion. In a rotary kiln incinerator, medical glass melts and turns into slag, possibly adhering to the inner wall. Prediction of the melting characteristics of medical glass hence is important for preventing slagging. The effect of various glass components on fusibility has been investigated experimentally; that of Na_2O is the most marked. The softening temperature and flow temperature decrease 19.8 °C and 34.0 °C, respectively, with a rise of Na_2O content in the Basic Content (standard composition of medical glass) of 1%. Correlations between fusion temperatures and glass components have been investigated; predictive functions of four characteristic melting temperatures have been obtained by simplifying the multi-variant series and were verified by testing glass samples. Relative errors of fusion temperatures (computed vs. measured) are mostly less than 5%.

1. Introduction

Hospital wastes include radioactive wastes, pharmaceuticals and hazardous wastes, such as chemical wastes, infectious wastes, contaminated sharps and so on. Incineration has been identified as the best disposal option for hospital wastes because it is harmless and realizes a large reduction in volume as well as resources recovery [1,2]. Rotary kiln incineration has several advantages when used to dispose of hospital wastes, for example being adapted for various feeds and simple operation [1,3]. The combustion process of hospital wastes was tested and its kinetic parameters and mechanism were established [4]. Pyrolysis-gasification experiments of hospital waste materials were carried out on a rotary kiln incinerator [5]. The chemical composition, mineralogy and leaching behavior of heavy metals have been analyzed for fly ash and slag from hospital waste incineration [2,6]. The effects of the chemical components on the melting points of hospital waste slag were analyzed already; it was observed that fusion temperature increased with the CaO content [7].

The characteristics of hospital wastes are important parameters to optimize incineration. A large amount of medical glass is present in hospital wastes. Hospital waste samples have been collected from a hospital waste treatment center and statistical results show more than 11% of hospital wastes are medical glass bottles. Tube vials for antibiotics and ampoule bottles account for 69.1% and 15.5% of medical glass, respectively. The mass of a single glass bottle ranges from 3.0 to 83.0 g. Generally, medical glass has a rather low fusion temperature; fusion temperatures were determined as for coal ash. Results exhibit softening temperatures (*ST*) mostly ranging from 900 °C to 1000 °C and flow temperatures (*FT*) generally less than 1250 °C. When hospital wastes are incinerated in a rotary kiln incinerator, medical glass is heated and melted. Molten glass may adhere to the inner wall, leading to slagging. In other cases, the molten glass probably tumbles and rolls, bonding to other slag particles; finally large slag agglomerates are formed, blocking the exit of rotary kiln. Therefore, the melting characteristics of medical glass are important for optimizing hospital waste incineration and preventing slagging of rotary kiln incinerators.

In this paper, the effects of glass components on the melting characteristics of medical glass have been researched by the SiO_2 replacement method and quantitative correlations between fusion temperatures and components of medical glass have been obtained by simplifying the multi-variant Taylor series.

2. Experimental verification

The composition of medical glass samples, collected from hospital waste treatment center, is so variable that it is difficult to obtain quantitative correlations between fusion temperatures and components. Blending oxides (analytical reagent) and thus adjusting the ratio of components allows studying their effect on fusion temperatures. According to the composition of ampoule glass (G2 in Table 1), oxides (analytical reagent) were blended and marked as Sim-1. The corresponding carbonates substituted the instable oxides: Na_2O,

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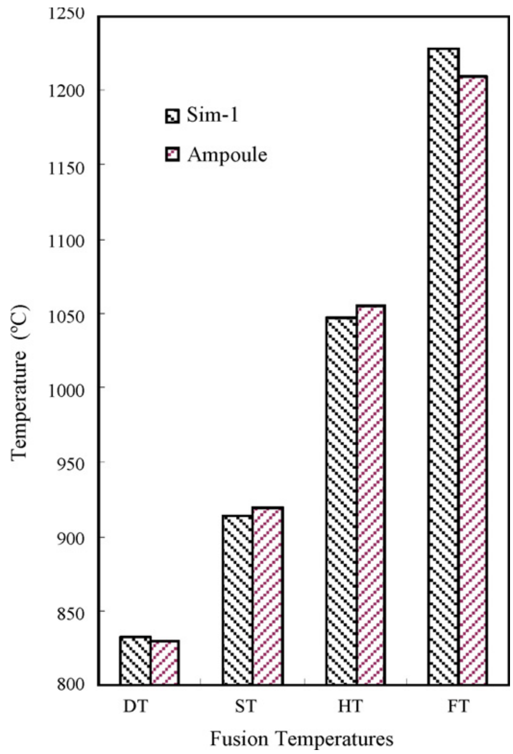

Fig. 1. Experimental verification.

K_2O, CaO and BaO. According to GB/T 219-1996 “Determination of Fusibility of Coal Ash” (China), four characteristic melting temperatures (Deformation Temperature *DT*, Softening Temperature *ST*, Hemisphere Temperature *HT* and Flow Temperature *FT*) of a medical glass sample (ampoule) and of a simulated composition (Sim-1) were determined using a 5E-AFIII Ash Fusion Determinator produced by Changsha Kaiyuan Instruments Co. Ltd. A reducing atmosphere was used in all experiments. The heating rate was set as 20 °C/min when temperature was lower than 750 °C and at 6 °C/min when it was higher than 750 °C. Fig. 1 exhibits the characteristic melting temperatures approximate very much between simulated composition and medical glass; the largest temperature deviation is no more than 20 °C. Therefore, in the following experiments a simulated composition is used to study the melting characteristics of medical glass.

3. Experiments

3.1. Selection of Basic Content

The composition of medical glass samples, collected from a hospital waste treatment center, is given in Table 1 on a wt% basis; MgO and Fe_2O_3 are negligible, due to their low contents (average content: MgO 0.39%, Fe_2O_3 0.09%). The seven principal components are averaged and normalized to obtain the Basic Content ($\boldsymbol{X}_{bc}$), as shown in Table 1; this Basic Content is used in the following experiments.

3.2. Methods

SiO_2 is the most abundant component in medical glass (about 72%); Si–O is the basic unit in the three-dimensional network structure of glass. Hence, the SiO_2 replacement method is used to study the effects of the relevant components on the melting characteristics of medical glass: if the content of any glass component (B_2O_3, Na_2O, K_2O, Al_2O_3, CaO and BaO) increases 1%, SiO_2 content will be cut down by 1%.

Four characteristic melting temperatures were determined from the above fusion experiments, with the content of six glass components (B_2O_3, Na_2O, K_2O, Al_2O_3, CaO and BaO) changing 2% every time (CaO changing 3%). So, the data of fusion temperatures with the changes of glass components are shown in Tables 2–7.

4. Results and discussion

4.1. The effect of glass component

Table 2 shows the effect of B_2O_3 on the melting characteristics of medical glass. All four characteristic melting temperatures fall sharply when the content of B_2O_3 increases. In these experiments, *ST* decreases 152 °C and *FT* 278 °C when the percentage of B_2O_3 changes from 0 to 8. Hence, B_2O_3 plays the role of flux in glass. In the network structure of glass, B_2O_3 generally takes $[BO_3]$ or $[BO_4]$ as cell unit. Since the energy network structure of $[BO_3]$ or $[BO_4]$ is lower than that of $[SiO_4]$, B_2O_3 decreases the viscosity and fusion temperatures of medical glass [8].

Tables 3 and 4 display the effects of alkali metal oxides (Na_2O, K_2O). Again, all four characteristic melting temperatures sharply drop with raising percentage of alkali metal oxides. The effect of Na_2O on the fusion temperature of medical glass is the most marked: when the percentage of Na_2O changes from 4 to 6, the *DT* decreases 332 °C; when the percentage rises from 6 to 8, *ST* drops 310 °C, and when it increases from 8 to 10, *HT* falls 238 °C. Meanwhile also the flow temperature *FT* is reduced from higher than 1500 °C to 1041 °C. Obviously, also K_2O could decrease the fusion temperatures of medical glass. When alkali metal oxides are added, the Si–O network structure is ruptured by Na^+ and K^+ and becomes loose; hence fusions temperature visibly decrease [8–10].

Al_2O_3 acts as an amphoteric oxide in the silicate system. Al^{3+} forms a tetrahedron $[AlO_4]^{5-}$ strengthening the network structure of glass. Hence the viscosity and fusion temperatures should increase with rising percentage of Al_2O_3. But Table 5 exhibits that, while Al_2O_3 content increases, the *ST* of medical glass indeed mounts but *FT* shows a sharp fall. Maybe Al_2O_3 participates in the formation of eutectic minerals such as anorthite ($CaO[Al_2Si_2O_3]$), gehlenite ($Ca_2[Al_2SiO_7]$) and albite [11,12]. The eutectic points of these minerals are about 1200 °C, i.e. between *ST* and *FT*. Therefore, adding Al_2O_3 increases *ST* and decreases *FT* in these experiments.

Table 1
The principal components and fusion temperatures of medical glass samples.

Sample	Content (wt%)							*FT* (°C)	*HT* (°C)	*ST* (°C)	*DT* (°C)
	SiO_2	B_2O_3	Na_2O	K_2O	Al_2O_3	CaO	BaO				
G1	72.94	1.33	10.82	0.78	6.57	3.32	2.45	1213	1095	1007	936
G2	72.95	5.78	8.70	1.59	1.74	10.88		1210	1055	919	830
G3	72.39	6.20	8.63	1.40	5.70	3.99	2.44	1246	1064	882	831
G4	69.39	6.52	9.39	2.35	4.94	4.05	2.30	1177	1017	907	815
G5	71.42	5.91	8.39	2.16	5.35	2.85	2.68	1212	1085	924	824
B1	72.95	2.44	10.29	0.98	5.36	5.21	1.84	1236	1075	997	895
Basic Content $\boldsymbol{X}_{bc}$	72.50	4.08	9.71	1.31	4.06	7.03	1.32	1248	1034	935	865

Table 2
Fusion temperatures and fitting equations of B_2O_3.

T (°C)	B_2O_3 content (wt%)					Quadratic polynomial equations	R^2
	0.00	2.00	4.00	6.00	8.00		
FT	1352	1344	1259	1181	1074	$FT = -34107\,\Delta x_1^2 - 3649.6\,\Delta x_1 + 1266.4$	0.9920
HT	1234	1170	1033	981	956	$HT = 29107\,\Delta x_1^2 - 3678.4\,\Delta x_1 + 1048.6$	0.9718
ST	1038	960	946	916	886	$ST = 14286\,\Delta x_1^2 - 1717.1\,\Delta x_1 + 936.39$	0.9587
DT	909	901	872	860	826	$DT = -6250\,\Delta x_1^2 - 1045\,\Delta x_1 + 877.77$	0.9810

Table 3
Fusion temperatures and fitting equations of Na_2O.

T (°C)	Na_2O content (wt%)								Quadratic polynomial equations	R^2
	0.00	2.00	4.00	6.00	8.00	10.00	12.00	16.00		
FT	>1500	>1500	1457	1384	1316	1250	1198	1041	$4\% \le x_2 \le 16\%$ $FT = -1547.6\,\Delta x_2^2 - 3388.2\,\Delta x^2 + 1264$	0.9977
HT	>1500	1493	1429	1337	1237	999	986	931	$2\% \le x_2 \le 10\%$ $HT = -63571\,\Delta x_2^2 - 10617\,\Delta x^2 + 1043.5$ $10\% < x_2 \le 16\%$ $HT = -12083\,\Delta x_2^2 - 338.25\,\Delta x^2 + 1000.1$	0.9898 1.0000
ST	>1500	1447	1385	1291	981	923	916	885	$2\% \le x_2 < 8\%$ $ST = -155000\,\Delta x_2^2 - 22061\,\Delta x^2 + 658.28$ $8\% \le x_2 \le 16\%$ $ST = 15455\,\Delta x_2^2 - 1830.5\,\Delta x^2 + 940.54$	0.9868 0.9454
DT	1463	1389	1284	952	898	864	838	827	$2\% \le x_2 < 6\%$ $DT = -161250\Delta x_2^2 - 29830\Delta x^2 + 77.062$ $6\% \le x_2 \le 16\%$ $DT = 16204\,\Delta x_2^2 - 1656.5\,\Delta x^2 + 867.27$	0.9874 0.9992

Table 4
Fusion temperatures and fitting equations of K_2O.

T (°C)	K_2O content (wt%)					Quadratic polynomial equations	R^2
	0.00	2.00	4.00	6.00	8.00		
FT	1283	1224	1167	1128	1108	$FT = 17143\Delta x_3^2 - 3152.3\Delta x_3 + 1240.7$	0.9984
HT	1045	1016	1009	984	962	$HT = -714.29\Delta x_3^2 - 951.57\Delta x_3 + 1029.9$	0.9777
ST	957	947	918	906	857	$ST = -10893\Delta x_3^2 - 618.96\Delta x_3 + 950.25$	0.9762
DT	878	854	851	844	832	$DT = 3571.4\Delta x_3^2 - 702.14\Delta x_3 + 865.25$	0.9338

Table 5
Fusion temperatures and fitting equations of Al_2O_3.

T (°C)	Al_2O_3 content (wt%)					Quadratic polynomial equations	R^2
	0.00	2.00	4.00	6.00	8.00		
FT	1357	1283	1250	1232	1227	$FT = 27321\Delta x_4^2 - 1522.2\Delta x_4 + 1247$	0.9924
HT	998	1011	1022	1026	1048	$HT = 1964.3\Delta x_4^2 + 577.36\Delta x_4 + 1019.8$	0.9618
ST	898	902	930	928	998	$ST = 18214\Delta x_4^2 + 1151.9\Delta x_4 + 917.31$	0.9101
DT	847	867	876	874	878	$DT = -7678.6\Delta x_4^2 + 335.79\Delta x_4 + 874.75$	0.9485

Table 6
Fusion temperatures and fitting equations of CaO.

T (°C)	CaO content (wt%)					Quadratic polynomial equations	R^2
	0.00	3.00	6.00	9.00	12.00		
FT	1354	1281	1250	1227	1153	$FT = 476.19\,\Delta x_5^2 - 1510.2\,\Delta x_5 + 1236.5$	0.9597
HT	1051	1038	1026	1037	1050	$HT = 5952.4\,\Delta x_5^2 + 112.62\,\Delta x_5 + 1030.2$	0.9382
ST	890	904	924	967	978	$ST = 1349.2\,\Delta x_5^2 + 824.46\,\Delta x_5 + 938.52$	0.9633
DT	838	844	853	899	922	$DT = 5634.9\,\Delta x_5^2 + 859.41\,\Delta x_5 + 869.31$	0.9649

Table 7
Fusion temperatures and fitting equations of BaO.

T (°C)	BaO content (wt%)					Quadratic polynomial equations	R^2
	0.00	2.00	4.00	6.00	8.00		
FT	1263	1250	1220	1198	1183	$FT = 714.29\,\Delta x_6^2 - 1098.3\,\Delta x_6 + 1251.1$	0.9853
HT	1028	1039	1041	1014	993	$HT = -16607\,\Delta x_6^2 + 415.14\,\Delta x_6 + 1037.1$	0.9586
ST	927	932	938	924	913	$ST = -9285.7\,\Delta x_6^2 + 317.71\,\Delta x_6 + 932.38$	0.9200
DT	847	841	832	836	848	$DT = 8750\,\Delta x_6^2 - 484\,\Delta x_6 + 840.49$	0.9036

The effects of alkaline earth metal oxides (CaO, BaO) on the melting characteristics of medical glass are relatively complex, as shown in Tables 6 and 7. CaO increases *ST* and decreases *FT*. In fusion experiments, *ST* increases 88 °C and *FT* decreases 201 °C. But the effect of BaO on the melting characteristics is not so obvious; BaO only decreases *FT* slightly, as shown in Table 7. CaO is a network modifier oxide and its ionic potential is higher, so it restricts the activity of Na^+ and strengthens the network structure of glass [8].

Generally CaO plays a role of flux in coal ash. When heated, CaO easily forms eutectic minerals such as anorthite, gehlenite, monocalcium aluminate ($CaO(Al_2O_3)$ and wollastonite ($3CaO(SiO_2)$ with silicate minerals in coal ash, and these eutectic minerals have a rather low melting point and decrease fusion temperatures of coal ash [11–13]. Therefore, the effect of CaO on the melting characteristics of medical glass is different from that on coal ash.

4.2. Polynomial equations on glass components

Fusion temperatures of coal ash are important indices for determining the quality of coals; especially *ST* and *FT* are helpful in predicting the slagging and fouling potentials of coals in boilers. Therefore predictive functions of fusion temperatures have been obtained by a polynomial or neural network model [14,15]. However, there are still little data about the melting characteristics of medical glass. In the following, the data derived from the SiO_2 replacement experiments are analyzed, and several functions about predicting fusion temperatures are obtained by simplifying the multi-variant Taylor series.

The above fusion experiments have been conducted by the SiO_2 replacement method. So, the contents of B_2O_3, Na_2O, K_2O, Al_2O_3, CaO and BaO (except SiO_2) are marked as x_1, x_2, x_3, x_4, x_5 and x_6, respectively; their partial content (Δx) is defined as $\Delta x = x - \boldsymbol{X}_{bc}$. For example, the partial content of B_2O_3 is: $\Delta x_1 = x_1 - \boldsymbol{X}_{bc.1} = x_1 - 0.0408$; that of other five glass components can be also performed by the same method. With the partial content ($\Delta x_1, \Delta x_2, \ldots, \Delta x_6$) as independent variables and four characteristic melting temperatures (*FT*, *HT*, *ST*, *DT*) as dependent variables, the quadratic polynomial equations have been fitted by using no-linear regression analyses, and described by the same form, as shown in Eq. (1).

$$T = a_i\,\Delta x_i^2 + b_i\,\Delta x_i + c_i \tag{1}$$

where *T* refers to the characteristic melting temperature (*FT*, *HT*, *ST* or *DT*); *i* ranges from one to six; Δx_i represents the partial content of glass component and a_i, b_i, c_i refer to the equation parameters.

The data higher than 1500 °C is not included when fitting the Eq. (1). The effect of Na_2O on fusion temperatures of medical glass is so severe that *DT*, *ST* and *HT* fall sharply when its content changes from 4% to 10%, and consequently the fusion temperatures of Na_2O are piecewise fitted.

The quadratic polynomial equations of fusion temperatures, which have the same form as Eq. (1), are shown in Tables 2–7. The parameters of quadratic polynomial (a_i, b_i and c_i) are also displayed in Tables 2–7. The correlation coefficients (R^2) of all the equations are more than 0.9; and these reveal good correlations between partial content of glass components and the characteristic melting temperatures. Among the six components, Na_2O plays the most remarkable role on the melting characteristics while BaO influences the least. *ST* and *FT* decrease 19.8 °C and 34.0 °C, respectively, while Na_2O content in the Basic Content increases 1%. And *ST* increases 2.2 °C and *FT* decreases 10.9 °C while BaO content increases 1%. Furthermore the contribution of SiO_2 to the melting characteristics of medical glass could be derived from Tables 2–7; fusion temperatures increase slightly with a rise of SiO_2 content.

4.3. Predictive functions of fusion temperatures

Quadratic polynomial equations of fusion temperatures on partial content of single glass component have been obtained and predictive functions of fusion temperatures on all glass components need to be further researched. A point set of 6-dimensional space $\boldsymbol{X} = (x_1, x_2, \ldots, x_6)$ ($\boldsymbol{X}^2 \le 1$) is defined to represent all possible compositions of medical glass, and $x_1, x_2, \ldots, x_6$ are still the contents of six glass components, i.e. B_2O_3, Na_2O, ..., BaO (except SiO_2), respectively. Hence the Basic Content ($\boldsymbol{X}_{bc}$) is represented as a point in a 6-dimensional space. Due to the SiO_2 replacement experiments, the sum of all glass components should always be 100% while $\boldsymbol{X}$ varies. Similarly, the partial content of glass composition in a 6-dimensional space ($\Delta\boldsymbol{X} = \boldsymbol{X} - \boldsymbol{X}_{bc}$) is defined. Thereby the characteristic melting temperature *T* (represents *FT*, *HT*, *ST* or *DT*) of medical glass is a function of the glass composition $\boldsymbol{X}$. It is supposed that the function *T* is continuous in the neighborhood of the Basic Content and thus it has continuous three-order partial derivatives; so, *T* can be expanded into a second-order Taylor series at the point $\boldsymbol{X}_{bc}$, as shown in Eq. (2).

$$\begin{aligned} T &= T(\boldsymbol{X}) = T(\boldsymbol{X}_{bc} + \Delta\boldsymbol{X}) = T(\boldsymbol{X}_{bc}) + \frac{\partial T(\boldsymbol{X}_{bc})}{\partial x_1}\,\Delta x_1 + \cdots \\ &\quad + \frac{\partial T(\boldsymbol{X}_{bc})}{\partial x_6}\,\Delta x_6 + \frac{1}{2}\left[\frac{\partial^2 T(X_{bc})}{\partial x_1^2}\,\Delta x_1^2 + \frac{\partial^2 T(\boldsymbol{X}_{bc})}{\partial x_1 \partial x_2}\,\Delta x_1\,\Delta x_2 + \cdots\right. \\ &\quad + \frac{\partial^2 T(\boldsymbol{X}_{bc})}{\partial x_1 \partial x_6}\,\Delta x_1\,\Delta x_6 + \frac{\partial^2 T(X_{bc})}{\partial x_2 \partial x_1}\,\Delta x_2\,\Delta x_1 + \frac{\partial^2 T(\boldsymbol{X}_{bc})}{\partial x_2^2}\,\Delta x_2^2 \\ &\quad + \cdots + \frac{\partial^2 T(\boldsymbol{X}_{bc})}{\partial x_2 \partial x_6}\,\Delta x_2\,\Delta x_6 \ldots + \frac{\partial^2 T(\boldsymbol{X}_{bc})}{\partial x_6 \partial x_1}\,\Delta x_6\,\Delta x_1 \\ &\quad \left. + \frac{\partial^2 T(\boldsymbol{X}_{bc})}{\partial x_6 \partial x_2}\,\Delta x_6\,\Delta x_2 + \cdots + \frac{\partial^2 T(\boldsymbol{X}_{bc})}{\partial x_6^2}\,\Delta x_6^2\right] + R_n(\Delta\boldsymbol{X}) \end{aligned} \tag{2}$$

where $T(\boldsymbol{X}_{bc})$ is a constant and represents the characteristic melting temperatures at the Basic Content composition.

If the disturbance caused by simultaneous changes of several components could be negligible, the second-order Taylor series is able to be simplified. Now, the Lagrange remainder and thirty second-order mixed partial derivative terms are omitted from the complex Eq. (2), so that only a constant term, six first-order partial derivative terms and six second-order partial derivative terms still remain as shown in Eq. (3).

$$T = T(\boldsymbol{X}_{bc}) + \sum_{i=1}^{6}\left(\frac{\partial T(X_{bc})}{\partial x_i}\,\Delta x_i + \frac{1}{2}\,\frac{\partial^2 T(X_{bc})}{\partial x_i^2}\,\Delta x_i^2\right) \tag{3}$$

As yet the values of six first-order partial derivative and six second-order partial derivative need to be calculated by using the data derived from experiments. The difference between Eqs. (1) and (3) is whether the partial contents ($\Delta x_2, \ldots, \Delta x_6$) are supposed to be variable (although these five values are constant and equal to zero). Therefore, $\Delta x_2, \ldots, \Delta x_6$ could be set equal to zero; Δx_1 is still reserved, and Eq. (3) is simplified to the following equation.

$$T = T(\boldsymbol{X}_{bc}) + \frac{\partial T(\boldsymbol{X}_{bc})}{\partial x_1}\,\Delta x_1 + \frac{1}{2}\,\frac{\partial^2 T(\boldsymbol{X}_{bc})}{\partial x_1^2}\,\Delta x_1^2 \tag{4}$$

where Δx_1 refers to the B_2O_3 partial content.

Comparing Eq. (4) with Eq. (1) and considering the coefficients of fitting equations on B_2O_3 in Table 2, the values of first-order partial derivative and second-order partial derivative of *T* on x_1 are obtained, i.e. $\partial T(\boldsymbol{X}_{bc})/\partial x_1 = b_1$, $\partial^2 T(\boldsymbol{X}_{bc})/\partial x_1^2 = 2a_1$. So the values of first-order partial derivative and second-order partial derivative of *T* on the content of the other five glass components can be performed by the similar method. Finally, introducing twelve partial derivative

Table 8
Calculated values and relative errors of fusion temperatures.

Sample	*FT*		*HT*		*ST*		*DT*	
	Calculated value (°C)	Relative error (%)	Calculated value (°C)	Relative error (%)	Calculated value (°C)	Relative error (%)	Calculated value (°C)	Relative error (%)
G1	1309	−7.33	1115	1.83	989	−1.79	914	−2.35
G2	1235	−2.02	1094	3.70	916	−0.33	834	0.48
G3	1212	2.81	1085	1.97	916	3.85	837	0.72
G4	1142	3.06	1007	−0.98	914	0.77	809	−0.74
G5	1206	0.50	1112	2.49	932	0.87	841	2.06
B1	1296	−4.63	1062	−1.21	959	−3.81	889	−0.67

values into Eq. (3), predictive functions of fusion temperatures of medical glass are obtained and described by Eq. (5).

$$T = T(\boldsymbol{X}_{bc}) + \sum_{i=1}^{6}(a_i\,\Delta x_i + b_i\,\Delta x_i^2) + r \tag{5}$$

where T refers to the characteristic melting temperature (*FT*, *HT*, *ST* or *DT*); $T(\boldsymbol{X}_{bc})$ is the characteristic melting temperature at the Basic Content composition and the experimental values are $FT_{bc} = 1248\,°C$, $HT_{bc} = 1034\,°C$, $ST_{bc} = 935\,°C$, $DT_{bc} = 865\,°C$; a_i and b_i refer to the equation parameters of glass components (B_2O_3, ..., BaO) and their values are shown in Tables 2–7, Due to piecewise fitting of Na_2O, the correction factor (r) is introduced. While $10\% < x_2 \le 16\%$, in *HT* function, $r = -34$; while $2\% \le x_2 < 8\%$, in *ST* function, $r = -277$; while $2 \le x_2 < 6\%$, in *DT* function, $r = -788$; in the other cases, $r = 0$.

4.4. Verification of the predictive functions

Five medical glass samples (G1–G5), collected from a hospital waste treatment center, were analyzed for their content of seven principal glass components and the four characteristic melting temperatures (*FT*, *HT*, *ST* and *DT*); the experimental data are exhibited in Table 1. Furthermore the characteristic melting temperatures could be calculated by predictive functions of Eq. (5); the calculated values and relative errors are displayed in Table 8. B1 is a blend of G1 and G2 in proportion of 75%:25%. Table 8 indicates that the predictive functions fit well; relative errors of four characteristic melting temperatures of a blended glass sample and of five glass samples are less than 5%, except for that of G1's *FT*. In addition, Table 8 exhibits that relative errors of *ST* derived from predictive functions are less than those of *FT*; and the overall results reveal that the more the composition of medical glass approximates the Basic Content, the less relative error occurs.

The error is composed of experimental error and mathematical model error. In fusion experiments, the reproducibility of fusion temperatures for a given specimen in different laboratory may differ by ±20–100 °C [11,16]. On the other hand, the omitted second-order mixed partial derivatives in Taylor series represent the combined effect caused by simultaneous changes of two components; and thus the mathematic model needs to be improved in this field. Moreover the mutation of fusion temperatures caused by component change needs to be further researched.

5. Conclusions

The following results can be concluded from this work:

- The effects of alkali metal oxides (Na_2O, K_2O) and B_2O_3 on the melting characteristics of medical glass is more marked and these components could decrease the characteristic melting temperatures sharply. The contribution of alkaline earth metal oxides (CaO, BaO) and Al_2O_3 to the melting characteristics is relatively complex and these components increase *ST* and decrease *FT*.
- Predictive functions of fusion temperatures are obtained by simplifying a multi-variant Taylor series and verified by testing medical glass samples. Relative errors of fusion temperatures are mostly less than 5%. These are important for optimizing hospital waste incineration and preventing slagging of rotary kiln incinerator.
- *ST* and *FT* decrease 19.8 °C and 34.0 °C, respectively, with a rise of Na_2O content in the Basic Content of 1%. Whereas *ST* rises 2.2 °C and *FT* falls 10.9 °C when BaO content in the Basic Content increases 1%.

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